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An extended global foresight report with regional and stakeholders' insights

Shaping sustainable agrifood futures: pre-emerging and emerging technologies and innovations for impact

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Revised

Nevena Alexandrova-Stefanova, Kacper Nosarzewski, Zofia Krystyna Mroczek,
Norbert Kolos and Jieqiong Wan
Food and Agriculture Organization of the United Nations, Rome
Sarah Audouin and Patrice Djamen
International Cooperation Centre of Agricultural Research for Development, Paris

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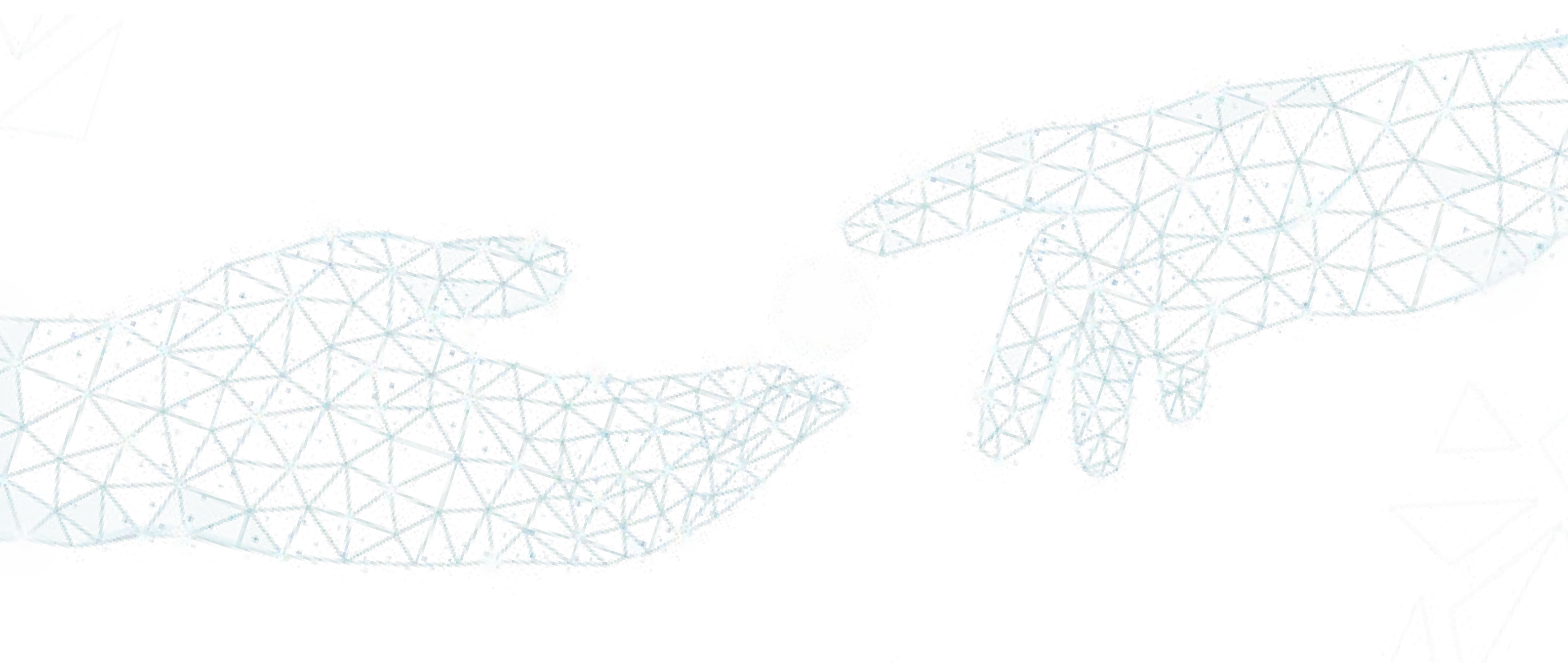

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Foreword

Shaping a sustainable agrifood future with emerging technologies and innovations:
A call to action

The Summit of the Future (2024) has set a bold vision for a more sustainable, inclusive, and resilient world. Science, technology, and innovation (STI) are key to achieving this vision.

This foresight report, "Shaping the Sustainable Agrifood Futures: pre-emerging and emerging technologies and innovations for impact", provides insights into how emerging technologies and innovations can advance our agrifood systems. In a data-limited world driven by uncertainties, foresight is crucial for navigating complexities.

This initiative of the FAO Office of Innovation sheds light on the innovation process, revealing how to accelerate the journey from lab to field. It presents a tool to navigate emerging solutions, such as AI, environmental biology, frugal innovations, and innovation policy labs, and harness their potential for a tangible impact in different contexts.

Successful integration of these technologies requires strong human and social capital, ethics, and governance. By investing in skills, knowledge, and networks, we can ensure effective implementation and positive outcomes.

Addressing global disparities in technological advancement requires international cooperation and open innovation. By fostering partnerships and sharing knowledge, we can bridge gaps, leverage regional strengths, and ensure equitable access to transformative solutions.

By tapping into global knowledge and expertise, we can fast-track the development and adoption of transformative technologies and innovations. The future is not far off - it is a reality we can shape now. Let us seize the opportunities before us to build a sustainable agrifood future for generations to come.

Vincent Martin
Director, Office of Innovation, UN FAO


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Abbreviations

AGI	Artificial general intelligence
AKIS	Agricultural knowledge and innovation system
AI	Artificial intelligence
AIS	Agricultural innovation system
AR	Augmented reality
ASI	Artificial super intelligence
AWG	Atmospheric water generator
CACFRAS	Central Asian and Caucasus Forum for Rural Advisory Services
CIRAD	French Agricultural Research Centre for International Development
CSO	Civil society organizations
DACC	Direct air carbon capture
EAS	Extension and advisory services
ETM	Earliest time to mature
ETSI	Estimated timeframe to significant impact
FAO	Food and Agriculture Organization of the United Nations
FOFA	Future of food and agriculture publication series of FAO
FSN	FAO Food Security and Nutrition Forum
GIS	Geographic information system
HICs	High-income countries
IAFN	International Agrifood Network
IDIs	In-depth interviews
IO	International organizations
LMICs	Low and mid-income countries
PETIAS	Pre-emerging and emerging technologies and innovations in agrifood systems
PS	Private sector
R&D	Research and development
RA	Relative advantage
RELASER	Red Latinoamericana de Extensión Rural
RIPS	Research and innovation paradigm shifts
RNA	Ribonucleic acid
SDGs	Sustainable Development Goals
STI	Science, technology and innovations
VR	Virtual reality
4CF	Foresee the Future

Glossary

Agricultural innovation: the process whereby individuals or organizations bring existing or new products, processes and forms of organization into social and economic use to increase effectiveness, competitiveness, resilience to shocks or environmental sustainability, thereby contributing to food and nutritional security, economic development and sustainable natural resource management (FAO Science and innovation strategy).

Innovation (in agrifood systems) is used as a verb (to innovate) referring to the process by which individuals, communities or organizations generate changes in the design, production or recycling of goods and services, as well as changes in the surrounding institutional environment, that are new to their context and foster transitions towards sustainable agrifood systems for food security and nutrition. Innovation is also used as a noun to refer to the changes generated by this process. Innovation includes changes in practices, norms, markets and institutional arrangements, which may foster new networks of food production, processing, distribution and consumption that may challenge the status quo.

Agricultural technologies: the application of scientific knowledge to develop techniques to deliver a product and/or service that enhances the productivity and sustainability of agrifood systems.

Agrifood innovation system (AIS): a network of actors or organizations, and individuals, together with supporting institutions and policies in the agricultural and related sectors, that brings existing or new products, processes, and forms of organization into social and economic use (TAP, 2016).

Agrifood systems: encompass the entire range of actors, and their interlinked value-adding activities, engaged in the primary production of food and nonfood agricultural products, as well as in storage, aggregation, post-harvest handling, transportation, processing, distribution, marketing, disposal and consumption of all food products including those of non-agricultural origin.

Areas of application: specific domains within agrifood systems where technologies and innovations are applied for impact.

Backcasting: backcasting engages people in creating pathways to a desired future. It starts the conversation assuming that the preferred future or a certain set of changes in society have been achieved and works backwards to the present to outline what might have happened to get there (UN Futures Lab, 2023).

Change agenda: the change agenda identifies the transformations needed to achieve the desired future. If you are using foresight to inform a set of decisions, the first step is to outline the change agenda. The change agenda plays a crucial role in answering the "so what" of foresight (UN Futures Lab, 2023).

Clusters: groups of related technologies and innovations of a similar nature.

Emerging innovation fields: areas of technology and innovation that are rapidly evolving, interdisciplinary, and have the potential to significantly impact various aspects of society, economy and culture, including agrifood systems.

Emerging technologies and innovations: technologies and innovations that are developing, have moved away from their origin (often but not always) research stations or living labs and may substantially evolve through cycles of adaptation.

Enabling environment: the context in which individuals and organizations put their capabilities into action, and where capacity development processes take place. It includes the institutional set-up of a country, its implicit and explicit rules, its power structures, and the policy and legal environment in which individuals and organizations function.

Earliest time to mature (ETM): the minimal amount of time needed for the large application of a solution or reaching full maturity over which it may become obsolete. This criterion takes into consideration aspects such as delays caused by technological, financial, social, or legal barriers. The moment of large application is defined as the time when a solution is largely available and accessible (in terms of distribution, but also e.g. financially) to the majority of the target group. ETM and ETSI are typically estimated in years, with an upper limit determined in advance on a scale of 0-45, where 0 means that the solution is already largely available on the market and accessible to the majority of the target group (globally, in all regions), while 45 means that 45 years or more are needed for it to become globally available and accessible.

Estimated timeframe to significant impact (ETSI): Estimated timeframe for impact for pre-emerging and emerging technologies and innovations to achieve significant impact on the agrifood system globally.

Foresight: science-based collectively informed systematic approach to inform taking actions in presence of uncertainties for longterm planning by drawing upon analytical and anticipatory tools to understand the past and present, while providing insights about the future.

Horizon scanning is a foresight method to envisage weak signals and potentially very important technological developments and anticipate their impact, threats, and opportunities.

Pre-emerging technologies and innovations: Technologies and innovations in the early stages of development, not yet used outside the community of developers.

Preferred future: a set of characteristics, not a specific scenario. As it is used in this report, the preferred future is not a selection of one of the scenarios or a highly detailed narrative about what the future could look like. Focusing on characteristics of the future allows to work on multiple visions of what is desired and means that there are different ways of achieving this preferred future (UN Futures Lab, 2023).

Relative advantage (RA): the degree of improvement that the proposed solutions might bring to the realization of a particular need. This is contrasted with today's most popular solutions as well as with hypothetical future ones. The relative advantage is typically evaluated on a scale of 0–10, where 0 means lack of improvement in the realization of a need, while 10 means major improvement - a "gamechanger". The relative advantage evaluation should not take into consideration the time needed for implementation or barriers to entry. Both of these are included in the next criterion. In this particular case, positive impact on challenge areas was taken into consideration.

Research and innovation paradigm shifts (RIPS): Tipping points where a broad spectrum of synergetic technological or innovation advancements can elevate agrifood systems to new levels of resilience, inclusivity and sustainability.

Scenarios: scenarios are provocations to broaden our understanding of how the future may evolve, which allows to prepare not for one but multiple ways the future might unfold. In the foresight process, scenarios are generated by identifying emerging drivers of change that may affect the future. Stakeholders identify these drivers of change through a horizon scanning activity which is often conducted prior to the scenario development exercise (UN Futures Lab, 2023).

Trend: trend is a general tendency or direction of a development or change over time. It can be called a megatrend if it occurs at global or large scale. In contrast of the stable over long periods of time megatrends, the trends are emerging patterns of change likely to have large impact. A trend may be strong or weak, increasing, decreasing or stable. There is no guarantee that a trend observed in the past will continue in the future.

Drivers: drivers are defined as developments causing change, affecting or shaping the future. A driver is the cause of one or more effects, e.g. increasing sugar intake in our daily food consumption is a driver for obesity.

Triggers: triggers of change are hypothetical future events (e.g. emergence of a new technology, idea or other sort of opportunity or threat) which can potentially affect the strength of currently observable drivers and the course of trend.

Weak signals: weak signals of possible futures are existing indicators for events or phenomena actually observed that may reveal important features of possible medium- to long-term futures.

Wild cards: refer to low-probability and high-impact events, that are sudden, unique, and surprising incidents. They could constitute turning points in the evolution of a certain trend or system. Wild cards may or may not be announced by weak signals.

Executive summary

In response to the increasing frequency of economic, social, political and environmental upheavals and rising uncertainties faced by agrifood systems, new technologies and innovations can offer promising solutions. However, these technologies and innovations may not fulfill their potential unless the underlying changes are thoroughly understood, supported and anticipated. Recent crises and forecasts indicate a need to break with certain mainstream features of agrifood systems that fail to provide sustainable solutions to current and future challenges. FAO and CIRAD embarked on a new foresight study focusing specifically on pre-emerging and emerging technologies and innovations in agrifood systems (PETIAS) to explore their potential in addressing agrifood challenges and the transformative changes required.

This report builds on previous joint work, particularly the foresight synthesis report (Alexandrova-Stefanova N., *et al.*, 2023) and emphasizes the benefits of using foresight as a new, transformative approach to inform policies through forward-thinking applied to technologies and innovations for the future of agrifood systems. Through a multistakeholder approach, we received substantial contributions from various partners, including research and education organizations, extension and advisory services, International Agrifood Network (IAFN), private business organizations, policymakers and public institutions.

The report introduces the imperative of technology and innovation for agrifood systems transformation to fuel the implementation of the Sustainable Development Goals (SDGs), as well as the holistic approach and new elements studied. (Chapter 1). The methodology includes a number of foresight approaches, such as horizon scanning, scenario building, preferred future, change agenda, backcasting and policy games that in combination with other methods, integrate anticipation as a new mindset (Chapter 2).

This report provides practical and analytical results regarding a set of 32 promising pre-emerging and emerging technologies and innovations, of which 20 are most capable of addressing agrifood systems challenges. It discusses potential opportunities and trade-offs to anticipate or avoid, outlines plausible future scenarios for the emergence of agrifood technologies and innovations and presents regional and stakeholders' perspectives.

The next section summarizes the report results in numbers.

20	Pre-emerging and emerging technologies and innovations	**selected with potential to address multiple challenges in the future. (Chapter 3).**
7	Clusters	**grouping PETIAS of similar nature. Clusters (Chapter 4) include:** • Advanced biotechnologies; • Advanced digital technologies and innovations; • Advanced geospatial technologies and innovations; • New renewable energy and transportation; • Micro- and nanotechnology and nanobiotech; • Market and financial innovations; and • Policy and organizational innovations.
10	Emerging innovation fields	**significantly impacting** various aspects of society, the economy and culture, as well as agrifood systems (Chapter 4), including: • Metaverse in agriculture (agriverse); • Omics-based tailored solutions (cell-based food, precision fermentation, bioprinting and personalized nutrition); • Vertical farming; • Circular agriculture; • Precision agrifood systems; • Molecular computers in agrifood systems; • Next-gen gene editing; • Web3.0; • Nature-positive agriculture; and • Grassroot innovation in agrifood systems.
10	Areas of application in the agrifood systems	**bringing systemic impact (Chapter 5)** • Production systems; • Processing systems; • Value chains and services; • Energy and transportation; • Food waste; • One health and nutrition; • Governance and trade; • New materials, new proteins, and circular economy; • Blue economy; • Inclusion of the most vulnerable.
8	Agrifood systems challenges	**can be addressed by PETIAS (Chapter 5 and Annex 1):** • Population and development dynamics, food and nutrition security, sustainable diets; • Climate change, disasters, conflicts and protracted crises; • Erosion of natural resource base, loss of biodiversity; • Food loss and waste; • Energy demand and use in agrifood systems; • Inclusion of the most vulnerable; • Transboundary and emerging agrifood system threats; • National and international governance.
8	Research and innovation paradigm shifts (RIPS)	**necessary for closing the science and technology gap** and enabling these technologies and innovations to emerge in a sustainable and inclusive manner (Chapter 7), including: • Convergence of pre-emerging and emerging technologies and innovations from diverse fields; • Biomimicry through nature-inspired solutions for sustainable agrifood systems; • Open source and open innovation; • Citizen science; • Geoengineering to modify weather and climate; • Quantum computers and AI dominance; • Emergence of plant and animal diseases; • Agrifood farm: a holistic agrifood system.

6	Key global drivers for technology and innovation	**shaping the emergence of technologies and innovations** (Chapter 6) and (FAO, 2022a), including: • climate change; • population dynamics and urbanization; • economic growth; • structural transformation and the macroeconomic outlook, • public investment in agrifood systems; • innovation and science.
3	Internal blended trends	**driving** technology and innovation emergence: sustainability, democratization and efficiency (Chapter 6).
5	Triggers of technology and innovation transformation	**boosting the impact of technology and innovation,** including (Chapter 6): • governance and business environment related to agrifood emerging technologies in place; • rapid acquiring of new skills and rise of human capital; • removed barriers for technology adoption: improved mechanisms for intellectual property rights, knowledge flow and dissemination; • societal consensus and ethical standards in place; • achieving true circularity and sustainability.
10	Wild cards (low probability events with high potential impact)	**changing the direction** of global drivers (Chapter 6).
5	Future scenarios	**exploring diverse alternative and plausible global futures** for technology and innovation, based on drivers, trends, triggers and wild cards (Chapter 6).
1	Preferred future	**featuring preferred characteristics** for technology and innovation emergence and impact in agrifood systems for strategic planning (Chapter 7).
5	Key transformation areas	**help** achieve the preferred future (Chapter 7): • Governance and participation; • Ethical and social considerations; • Integrated, fact-based, and fit-for-purpose knowledge; • Incentives and investment for impact; • Fostering systemic changes.
6	Regions	**showing challenges and opportunities** (Chapter 8). Europe and Central Asia; North America, Latin America and Caribbean; Norh Africa and Near East; Sub-Saharan Africa) were analyzed with respect to their dominant drivers, the regional strengths and time lags of technology and innovation emergence and reaching significant impact, as well as regionalized pathways and levers to accelerate impact of innovation.
8+1	Stakeholders' groups	**analyzed** in each scenario, providing insights into mechanisms for stakeholder empowerment and multilateral governance (Chapter 9). stemming from the report: AI, and governance and policy innovation. They are discussed horizontally, across several chapters.
2	Cross-cutting highlights	**stemming** from the report: AI, and governance and policy innovation. They are discussed horizontally, across several chapters.

By exploring the two important cross-cutting highlights, we came to the conclusion that:

- **Artificial Intelligence** (AI, AGI, ASI) has potential to connect and process information, develop complex thinking, and select optimized solutions. However, there is a need for relevant regulation and control, particularly to ensure inclusion for small-scale farmers and areas lacking data and investment. This discussion positions AI as a future non-human stakeholder, potentially exerting either light or significant influence on the agrifood systems, depending on scenarios and pathways of change.

- **Policy and organizational innovations** are highlighted as the most promising innovations with the highest potential to address multiple challenges, in combination with other technologies and innovations. They are able to empower stakeholders, drive innovation processes and respond to local context, while addressing sustainability, inclusion and resilience issues. Efficient and balanced innovation **governance**, deploying multilateral approaches is essential to close the science, technology and innovation divide between regions and countries, and among stakeholders.

The findings indicate that no single technology can adequately address future challenges; sustainable and inclusive solutions will typically emerge from packages of technologies and innovations that target multiple challenges, in different regions and serve various users (farmers, agrifood processors, etc.). It provides insights on the mechanisms to anticipate and drive positive impact, that include strategic planning and transformative changes.

To anticipate strategic planning and transition to more resilient, sustainable and inclusive agrifood systems, the report offers (Chapter 10):

- A foresight-informed and typology-based toolkit to screen, target and support new technologies and innovations and their ecosystems, through a six-step approach;

- Monitoring and evaluation framework for sustainable and responsible uptake of innovation;

- A helical model to stimulate reflection on systemic transformation and participatory governance of innovation processes; and

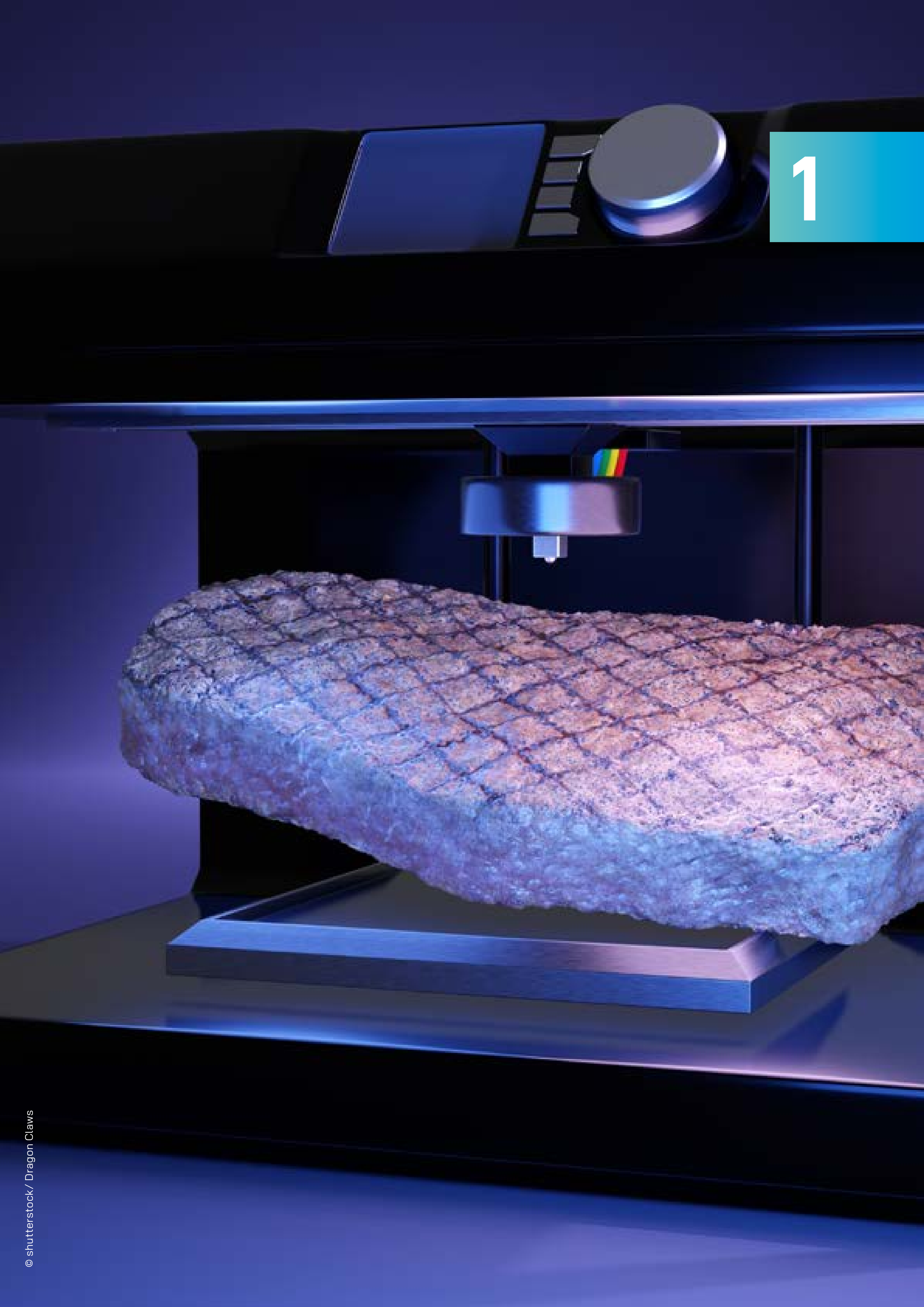
- Actionable recommendations that translate foresight into impactful strategic planning tailored to key stakeholders and aligned with the key transformation areas. They focus on pre-emerging and emerging technologies and innovations that tackle agrifood systems challenges ang go beyond problem-solving towards transformative impacts.

The main learning from this report is that the future of agrifood systems is not predetermined. Therefore, discussions around the pathways of change towards a "preferred future" must occur within multistakeholder spaces at local, regional and international levels, allowing for anticipation and transformation into relevant and coherent actions and policy instruments tailored to specific regions.

A mission-oriented approach to shaping the future agrifood systems will draw attention to the roles and functions of technologies and innovations. To bridge the technological and innovation divide, relevant and continuous monitoring, evaluation and learning need to be established to ensure inclusivity, address shortcomings and incrementally increase impacts. Capacity development emerges as a key takeaway, requiring attention at multiple levels (enabling environment, organizational and individual) and across various domains – from technological skills to the ability to innovate, collaborate and engage in multistakeholder approaches.

In conclusion, this report offers a framework for developing effective strategies that accelerate the impact, support the responsible use of pre-emerging and emerging technologies and innovations, address societal challenges, and promote a sustainable future.

As a way forward, this report lays the groundwork for further foresight studies that enhance stakeholders' future literacy, ensuring that foresight approaches not only positively influence long-term strategic planning and policies but also drive transformative actions for the agrifood systems of the future.



1

Introduction

1.1 FROM POLYCRISIS TO OPPORTUNITY: THE INNOVATION IMPERATIVE FOR THE TRANSFORMED AGRIFOOD SYSTEMS

The pursuit of sustainable development, as outlined in the Sustainable Development Goals (SDGs), requires profound transformations across various sectors. Agrifood systems, central to human civilization and one of the key transition areas highly interconnected with numerous SDGs, can facilitate their success, playing a critical role in achieving these global targets. As highlighted in the recent UN report (United Nations, 2024), innovation is pivotal in this process. Decision-makers must integrate current socio-economic, political and environmental challenges increasingly affecting agrifood systems worldwide – such as climate change, extreme weather events, armed conflicts, pandemics and economic crises – into their strategies to address, mitigate or adapt to these realities. Agrifood system development paths must undergo radical transformations, as current trends are leading agrifood-related targets off-track, with growing populations, urbanization, macroeconomic instability, poverty, inequalities, geopolitical tensions and natural resource depletion exacerbating these issues (FAO, 2022a).

The transformative potential of pre-emerging and emerging technologies and innovations in reshaping agrifood systems is immense. As stated in the Pact of the Future, "Science, technology and innovation have the potential to accelerate the realization of the aspirations of the United Nations across all three pillars of its work." By leveraging these advancements, we can build more sustainable, resilient and equitable agrifood systems that meet the needs of a growing global population while protecting our planet's resources.

Technology and innovation – across social, market, financial, policy and institutional dimensions – are key in driving sustainable economic growth, increasing productivity and sustainability, creating new job opportunities and fostering inclusivity. These advancements modernize production methods, making them more efficient and cost-effective, which boosts economic output with the same or fewer inputs. Innovations in food, education and communication improve quality of life and address environmental challenges. Although some jobs may be replaced by technologies and innovations, new opportunities arise in emerging industries such as IT and cybersecurity. Furthermore, technology and innovation expand economic participation, potentially reducing inequality and contributing to a more dynamic, resilient and prosperous society. In agrifood systems, such advancements are particularly relevant for enhancing food production efficiency, improving supply chain management and promoting sustainable agricultural practices – thereby ensuring food security and reducing environmental impact. For example, digital agriculture harnesses advanced data analytics and automation to optimize resource use, reduce environmental impact and enhance crop yields. Similarly, sustainable food processing technologies and innovations can minimize waste, conserve energy and enhance food safety. Blockchain technology improves transparency and traceability throughout the food supply chain, reducing losses from spoilage and inefficiencies. Meanwhile, Artificial Intelligence and policy innovations can optimize logistics and transportation networks to ensure that food reaches those in need more efficiently.

In an age of polycrisis, where challenges are interconnected and often escalate, simply minimizing inputs and optimizing outputs is not enough. Beyond their traditional roles in food production and processing, technologies and innovations must catalyze systemic change, with ethical and sustainable use at the forefront. The Pact for the Future emphasizes that science, technology and innovation must not exacerbate inequalities; they must protect human rights and ensure equitable distribution of benefits. Addressing the gender digital divide, promoting inclusive innovation and safeguarding human rights in the development and deployment of these technologies and innovations are critical. To achieve this, creating an enabling environment for scientific and technological development is essential. This includes investing in research and infrastructure, promoting open science and innovation and facilitating knowledge sharing between high-income (HICs) and low and middle-income countries (LMICs). Strengthening international collaboration and capacity development will ensure that the benefits of these advancements reach all parts of the world.

Despite their potential, technologies and innovations may fall short of delivering on their promises to boost economies, improve livelihoods and reduce inequalities. This often results from significant time lags – sometimes decades – between their inception and their ability to make a significant impact and be scaled up, compounded by challenges in infrastructure, policy and societal readiness. Additionally, differing rates of scaling up across regions, coupled with varying stakeholder needs and demands, create complexities in achieving the global sustainable use of these technologies and innovations. Failure to address these challenges not only leads to economic losses, but also missed opportunities for a more equitable, resilient and sustainable future.

Achieving these ambitious goals is a complex task that, despite some positive examples, has yet to be realized on a global scale. This calls for innovative, out-of-the-box approaches to navigate the path forward.

Forecasting approaches have been used for decades to assess and extend hypotheses based on current and known metrics. However, these methods fall short when it comes to supporting strategic planning, especially in the context of disruptive changes required for transforming agrifood systems. Achieving sustainable agrifood systems necessitates decisions informed by future scenarios, which open the door to new paradigms for managing social, environmental and economic dimensions at different scales and across value chains and within territories.

Foresight approaches serve various purposes, including exploration, strategic decision-making, system transformation, strategic planning and participatory dialogue among stakeholders (Djamen *et al.,* 2023). They can also foster future literacy and contribute to the decolonization process (Bourgeois *et al.,* 2022). Strategic foresight, which helps navigate the complexity, uncertainty, volatility and ambiguity of challenges and trends (Miller 2018), is vital for anticipating future trends and scenarios. This ability to foresee and guide actions is crucial in understanding pre-emerging and emerging technologies and innovations, assessing their potential benefits and risks, identifying the trends and drivers behind their emergence and taking informed actions to scale them up equitably.

By analyzing pre-emerging and emerging technologies and innovations, market dynamics and societal shifts, policymakers and stakeholders can pinpoint promising innovations and guide their development and scaling up. Strategic foresight thus provides a valuable tool, among many, for shaping the future of agrifood systems in a sustainable, resilient and inclusive manner.

1.2 DRIVING AGRIFOOD TECHNOLOGIES AND INNOVATIONS FOR IMPACT: OBJECTIVES AND SCOPE OF THIS FORESIGHT REPORT

This comprehensive foresight report aims to provide a robust framework for harnessing science, technology and innovation (STI) to transform agrifood systems in response to global challenges. By identifying pre-emerging and emerging technologies and innovations, analysing their potential impacts and developing actionable strategies, this report seeks to empower policymakers, industry leaders, researchers and other stakeholders to shape a more sustainable, resilient and inclusive future for all those involved in agrifood systems.

Building upon the foundation of the 2023 report

The report builds on the findings of the 2023 synthesis report, *Harvesting Change: Harnessing Emerging Technologies and Innovations for Agrifood System Transformation* (Alexandrova-Stefanova N., *et al.*, 2023). It reaffirms the importance of the 32 key pre-emerging and emerging technologies and innovations, as well as the 20 areas warranting special attention identified in the previous study. This report revisits and expands on future scenarios, delving deeper into perceived impact, benefits and challenges of pre-emerging and emerging technologies and innovations in agrifood systems, exploring the trends, drivers, and triggers, and potential wild cards that may shape their emergence.

Beyond sharing observations and recommendations, this report strives to foster a more profound and holistic understanding of innovation processes and pathways. It aims to provide a future-informed technology and innovation toolbox – a typology framework – relevant to various futures, agrifood system challenges, stakeholders, regions and timelines. The ultimate goal is to offer a strategic plan for scaling up technologies and innovations that drive real impact.

Specific objectives of this foresight report include:

- Identifying emerging innovation fields and paradigm shifts in the areas of democratization, efficiency and sustainability.
- Developing a typology framework for investments and decision-making in agrifood STI.
- Identifying key transformation areas (change agenda foresight) to achieve the desired future for agrifood technologies and innovations.
- Creating a strategic action plan to guide agrifood science, technology and innovation (STI) towards a more sustainable, resilient and inclusive future.

The scope of this report extends beyond the 2023 report, encompassing:

- A deeper exploration of the hopes and concerns associated with each of the 32 identified technologies and innovations.
- A deeper analysis of clusters, response to challenges and application areas of the pre-emerging and emerging technologies and innovations, alongside actionable insights for ensuring a balanced acceleration of innovation pathways.
- A revisited and enriched set of five scenarios addressing the emergence of technologies and innovations, incorporating perspectives from stakeholders.
- An enhanced understanding of regional aspects and timelines for achieving meaningful impact through agrifood technologies and innovations in pre-emerging and emerging stage of development.

Paradigm shifts for agrifood innovation:

The findings of the 2023 report, supported by additional participatory research on the prioritization of policy and other non-technological innovations conducted in 2023–2024, have unequivocally highlighted the need for a fundamental reassessment of the current STI paradigm. This paradigm has proven inadequate for generating and scaling the right innovations at the right time and place, particularly in the face of increasingly complex global and regional challenges.

A key contribution of this foresight report is the identification of emerging STI paradigm shifts. These shifts, inspired by Kuhn's vision of scientific revolutions (Kuhn,1962/1970), offer new approaches to address key transformation areas differently, and guide the way towards a preferred future. Known as RIPS by the authors, these paradigm shifts are considered instrumental in anticipating and initiating transformative changes rather than merely reacting to external pressures.

A comprehensive and inclusive analysis

To ensure a comprehensive and inclusive analysis, the report incorporates regional perspectives and diverse stakeholder viewpoints. It advocates for systemic and inclusive approaches that take into account the specific drivers and opportunities within different regions. By doing so and considering the insights of numerous stakeholders, it develops tailored recommendations that can be applied to a wide range of contexts.

Through this multifaceted approach, the report seeks to break free from the status quo and actively shape the future of agrifood systems through technology and innovation. This transformative approach is essential for addressing the complex challenges facing agrifood systems today, ensuring a sustainable, resilient and inclusive future for all.

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Methodology

2.1 THE FORESIGHT METHODOLOGY

Through a multistakeholder approach, FAO has collaborated with CIRAD to develop a viable foresight methodology, with substantial contributions from research and education organizations, extension and advisory services, civil society organizations, IAFN, private business organizations, policymakers and public institutions.

The findings of this comprehensive report were generated from July 2023 to mid-2024, and involved more than 300 participants. This process combined quantitative and qualitative methods, along with a comparative analysis of findings from various sources.

Using a combination of methods within a foresight approach is crucial, as it allows for a more comprehensive and robust understanding of potential future developments. Each step of the methodology and tools employed offer unique strengths and perspectives, contributing to cohesion and robust analysis. For example, literature reviews provide a foundation of existing knowledge, expert interviews offer in-depth insights and surveys capture a broader range of opinions. Participatory workshops facilitate the development of hypotheses about the future, scenario development covers diverse stakeholders' perceptions, knowledge and disruptive views. Validation workshops aim at enriching and complementing the outputs. Combining these tools helps mitigate the limitations of any single approach, ensuring that the foresight is based on a diverse and reliable set of information. The initiative's nature was highly participatory to ensure the inclusion of varied expertise and viewpoints, fostering the co-creation of impactful strategic planning.

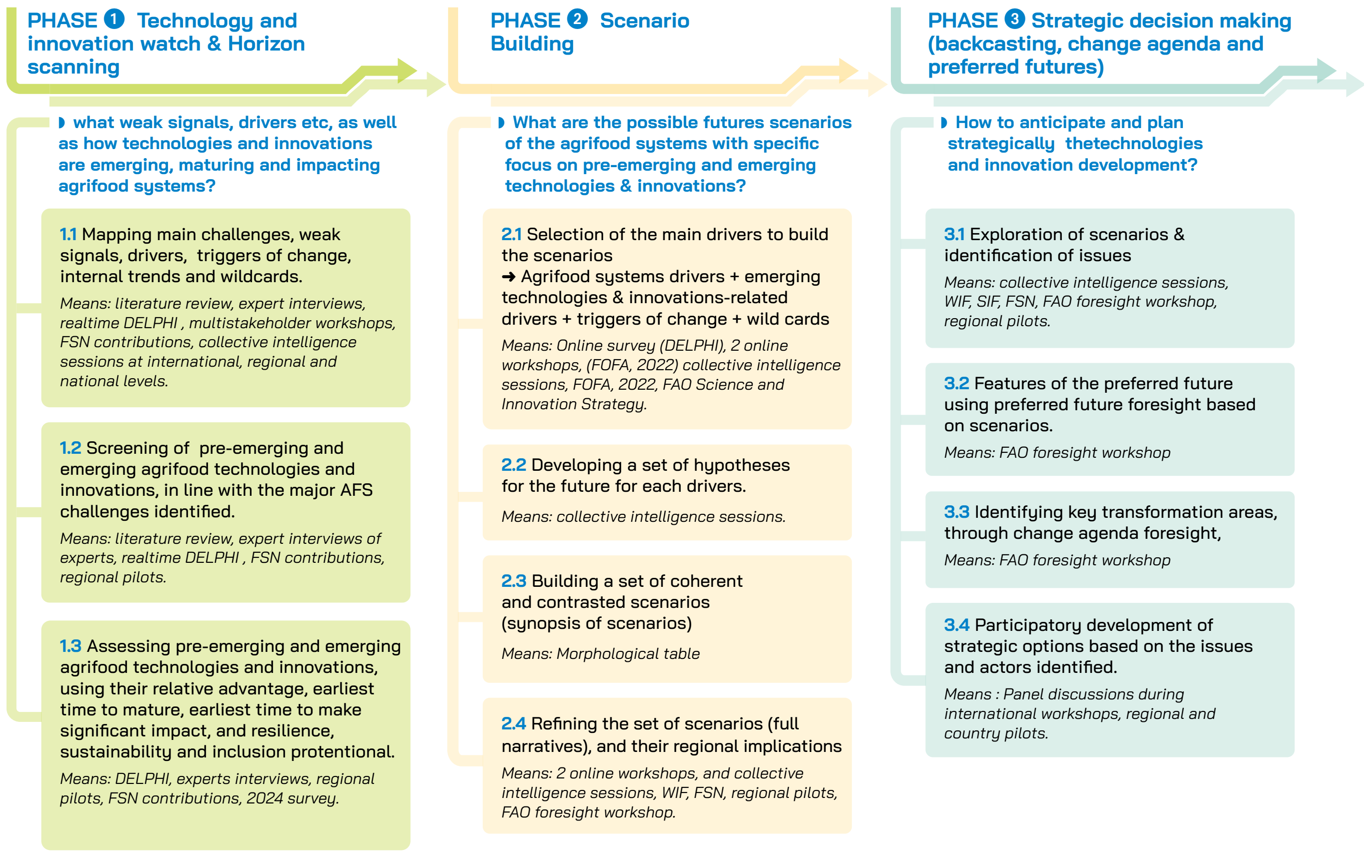
The approach consists of three phases:

- **Technology and innovation watch & horizon scanning phase:** this phase aims to screen key pre-emerging and emerging technologies and broader innovation areas based on the key challenges of agrifood systems (technology and innovation watch). It also identifies drivers, triggers of change, trends and wildcards (see the Glossary) through expert and multistakeholder consultation (horizon scanning). This phase is rooted in the previous FAO work on foresight (FAO, 2022a).

- **Scenario building phase:** this phase aims to develop a set of plausible, coherent and transformative narratives about the future of agrifood systems, with a specific focus on pre-emerging and emerging technologies and innovations. This is achieved through a multistakeholder and participatory approach. The process is not arbitrary but based on a thorough analysis of identified drivers and triggers, aiming to inform strategic planning.

- **Strategic planning phase:** this phase aims to explore and elaborate recommendations for using scenarios in strategic planning at regional and country levels. It includes exercises for preferred futures and backcasting, a change agenda, and governance role play and policy game foresights to empower concrete actions for impact.

Figure 1. The three sequential phases of the foresight process on emerging agricultural technologies and innovations for agrifood systems of the future.



As mentioned, a rich combination of foresight methods has been employed to leverage collective intelligence, generate more robust findings and ensure that every voice is heard in building the future. These methods include (for more in-depth explanation of each, please see the Glossary): technology watch and sensemaking; horizon scanning; scenario building; preferred futures; change agenda; backcasting; and simulated scenario role plays and policy games (UN Futures Lab, 2023).

Each foresight method was conducted in a highly participatory manner, involving experts from various fields and stakeholders, including those from the private sector and smallholder farmers. The details of each method, including the means and steps involved, are described below.

2.2 THE PROCESS

2.2.1 Literature review

We began by combining foresight literature along with agricultural and agrifood systems literature to build a multi-level and multistakeholder foresight approach. A diverse range of publications – including academic journals, private sector reports, industry documents, governmental publications, international organizations reports, websites, online databases and grey literature – were reviewed. The literature review served several purposes:

- *Technology and innovation watch:* The process involved identifying promising pre-emerging and emerging technologies and innovations in agrifood systems, including technological and non-technological solutions like policy and nature-positive approaches. This information was synthesized into a comprehensive database, categorized by innovation type and refined into specific clusters, forming the basis for selecting the most promising technologies and developing the PETIAS typology, along with a preliminary assessment of their potential to address agrifood system challenges.

- *Horizon scanning:* While a wealth of publications was reviewed, the horizon scanning process is firmly rooted in the FAO Future of Food and Agriculture reports (FAO, 2018, 2022a) and identifies key challenges, external drivers, internal trends, triggers of change and wildcards.

- *Emerging innovation fields:* A substantial number of recent publications were reviewed to identify weak signals and describe emerging fields of technologies and innovations, including examples, potential areas of application and possible benefits and trade-offs.

- *RIPS:* A thorough literature review forms the basis for identifying existing and potential new paradigms in agrifood systems (or influencing them), along with concrete examples of the main PETIAS under each RIPS. This includes potential benefits and trade-offs, as well as the dynamics of co-existence or shifts between different paradigms.

2.2.2 In-depth interviews (IDIs) with experts

The IDIs were conducted to further identify and discuss pre-emerging and emerging technologies and innovations in agrifood systems that have the potential to address significant challenges by 2030, 2040, 2050 and beyond.

Interviewees were encouraged to focus on technologies and innovations within their area of expertise but were also invited to speculate on potential solutions that may still be in early development or even purely theoretical.

The IDI methodology followed a semi-structured format, where the interviewer guided the conversation with predetermined questions while allowing flexibility to explore unexpected insights. The goal was to foster a dynamic and open exchange of ideas, capturing both mainstream perspectives and unconventional, pre-emerging or emerging technological and innovative solutions for agrifood systems.

The interviewees represented a diverse group of internationally recognized experts. The IDIs took place in August 2023 and included participants from organizations such as International Atomic Energy Agency (IAEA), FAO, Toronto Metropolitan University and International Agri-food Network (IAFN) scientists.

2.2.3 Delphi

The survey was developed by FAO's Office of Innovation and CIRAD's Innovation Research Unit and was conducted using the 4CF HalnyX real-time Delphi platform. The Delphi method was deemed appropriate as it facilitates dialogue among participants, allowing them to revisit the survey several times, adjust their opinions based on other participants' inputs and ultimately build consensus.

The primary objective of the study was to assess a selection of technologies and innovations, as well as the most significant internal and external drivers, triggers of change and wildcards influencing the emergence of agrifood technologies and innovations.

The Real-time Delphi survey focused on a pre-selected list of agrifood technologies and innovations, developed by the FAO team through internal research and expert interviews. These were evaluated based on their potential to address the most pressing challenges facing agrifood worldwide. While the list was comprehensive, it was not exhaustive. Participants were encouraged to suggest additional pre-emerging and emerging agrifood technologies and innovations for potential analysis in future FAO studies. The challenges included (Alexandrova-Stefanova *et al.,* 2023, adapted from FOFA, FAO, 2017):

- Population and development dynamics, food and nutrition security, sustainable diets;
- Climate change, disasters, conflicts and protracted crises;
- Erosion of natural resource base, loss of biodiversity;
- Food loss and waste;
- Energy demand and use in agrifood systems;
- Inclusion of the most vulnerable;
- Transboundary and emerging agrifood system threats;
- National and international governance.

Participants were also tasked with evaluating regional advantages and challenges regarding the scaling up of these pre-emerging and emerging technologies and innovations. Additionally, they were asked to identify key drivers, triggers of change and overarching trends influencing the evolution and scaling of agrifood technologies and innovations. They also provided insights on the potential for significant breakthroughs in specific application areas. Detailed parameters and scales were provided for each question. Participants were not required to provide feedback on topics outside their areas of expertise, particularly those related to regional specificities. Efforts were made to ensure diverse regional expertise from various fields.

The challenges, triggers of change, drivers and trends assessed were based on previous FAO foresight work, particularly The future of food and agriculture (FAO, 2022a) report.

2.2.4 Multistakeholder survey 2024

This section presents the results of an additional survey circulated among participants of the FAO Multistakeholder Workshop on foresight, as well as a broader group of stakeholders. The survey aimed to gather perspectives on pre-emerging and emerging agrifood technologies and innovations, with a focus on sustainability, inclusion and resilience. It also included an assessment of the identified RIPS from the perspective of these key principles. The findings enabled quantitative analysis, presented in numerous graphs throughout this report, and were combined with results from other participatory exercises, such as the FAO Food Security and Nutrition (FSN) Forum.

2.2.5 Scenario building

The scenario-building process was conducted using a participatory, multistakeholder approach, along with experts back-office sessions. Building on FAO's extensive work in developing scenarios for the report The future of food and agriculture (FAO, 2022), we chose to expand on the set of five scenarios, placing a specific focus on pre-emerging and emerging technologies and innovations. Special attention was given to the role of the private sector, farmers' organizations and research institutions highlighting the potential of co-creation, uptake conditions and policy recommendations for new technologies and innovations.

The drivers and triggers of change came from the FOFA (FAO, 2022a), the DELPHI tool, relevant literature, high-level documentation (such as the FAO Strategy for Science and Innovation (FAO, 2022b) and the thematic expertise of the co-authors. To ensure a systemic approach, drivers and triggers were divided into two categories: (1) drivers related to agrifood systems (top-five drivers and top triggers), and (2) trends related to pre-emerging and emerging technologies and innovations. Additionally, scenario building requires contrasted and imaginative assumptions, as well as relevant use of the wild cards, in order to "envisage a clear break in the logic of growth that dominates the current functioning of our human societies" as outlined by Jahel et al (2023). Hence, three wildcards were incorporated to introduce disruptive thinking and challenge the current paradigms, influencing the state of the drivers.

To translate this analysis into a narrative, we used a morphological table. Each FOFA scenario was supplemented with an additional matrix, where selected drivers were broken down into alternative hypotheses about their future states. By combining the hypotheses, each scenario was formed.

Each scenario offers a distinct and plausible narrative, some more optimistic and others more pessimistic. While some scenarios may reflect specific views, they all represent plausible futures. The purpose of using scenarios is to emphasize potential changes towards either desirable or undesirable futures, including disruptive shifts, to "provoke" stakeholders out of conventional paths of change. These scenarios are not forecasts or set predictions but are tools to stimulate reflection on various potential future developments. They serve as starting points for informing strategic planning through methods such as preferred futures, change agendas and backcasting.

2.2.6 Multistakeholder workshops, conferences and seminars

FAO organized three (online and in-person) workshops to enrich the findings and incorporate a diverse range of perspectives, including those from experts across different fields and stakeholders with balanced geographical representation. Additionally, three conferences in which FAO participated were used to gather further insights into various components of the work.

- **Scenarios co-creation workshops:** two online workshops were held on 5 and 14 September 2023, in collaboration with IAFN. These workshops brought together a group of international experts from diverse regions and domains, including the private sector, academia, farmers' organizations and policy makers. Participants were asked to refine the set of drivers and hypotheses for each selected driver's future state, anchored in the FAO Science and innovation strategy output matrix (FAO, 2022b). Their input contributed to refining five distinct scenarios, with particular focus on technologies and innovations, as well as transformative partnerships and innovation financing, including the role and importance of partnerships and types of innovation funding mechanisms.

- **Validation and strategic planning workshops:** the scenarios have been validated during the World Investment Forum, Abu Dhabi (October 2023), the Science and Innovation Forum, Rome (FAO, 2023), and the multistakeholder and expert foresight workshop (17–18 June 2024). Backcasting and preferred future foresight have been performed to reflect regional specificities.

- **Multistakeholder and expert foresight workshop (17–18 June 2024):** titled "FutureFood-I Lab in action: Cultivating Innovation for Agrifood Systems' Transformation", this workshop (i) gathered feedback and ideas to improve the methodology; (ii) presented the scenarios, identify common "preferable" features and develop a "preferred future" and change agenda, discussing the transformations needed to achieve a desirable future; (iii) showcased various initiatives aimed at democratizing science, technology and innovation; and (iv) tested and learn from innovative participatory governance exercises. One such exercise was the Samoa Circle (Hernandez, 2012), which allowed participants to simulate the introduction of new technologies and innovations and explore ways of managing power dynamics to create an inclusive, transparent and responsible governance process that could be applied to real-life situations.

- **FAO special session during IFSA in Trapani (June–July, 2024):** focused on the Samoa circle exercise, providing further insights into the complex dynamics of participatory governance processes. It also included a general discussion on the foresight methodology and its application. The outcomes from this conference, along with the role plays conducted during the FAO workshop, informed reflections on the STI democratization and governance in agrifood innovation systems (AIS). These reflections contributed to the final recommendations included in this report.

2.2.7 Regional foresights with strategic impact

In 2024, FAO collaborated with two regional organizations – Red Latinoamericana de Extensión Rural (RELASER) and Central Asian and Caucasus Forum for Rural Advisory Services (CACFRAS) – to apply strategic foresight to innovation system policies, including extension and advisory services (EAS) at both regional and country levels in Uzbekistan, Kazakhstan, Paraguay and Bolivia. This combined methodology aimed not only to envision possible future developments for regional science, technology and innovation (STI) systems – covering governance, drivers, triggers, scenarios and the change agenda – but also to explore the critical role that EAS could play in the (co)creation, (co)implementation and scaling of the promising technologies and innovations.

The initiative involved the application of strategic foresight tools, including the adaptation of global scenarios, as well as country-specific drivers, triggers, trends and wildcards. The goal was to influence policy, particularly in relation to research, EAS and innovation systems. Key methods included horizon scanning, scenario building, preferred future development and backcasting.

2.2.8 FAO Food Security and Nutrition Forum

The FAO Food Security and Nutrition (FSN) Forum issued a call for submissions that ran from 10 May to 10 June 2024, accepting responses in Arabic, Chinese, English, French, Russian and Spanish. A total of 51 responses were received from a diverse array of global stakeholders in the six studied regions and covered a broad stakeholder representation.

The structured questionnaire featured a series of open-ended questions designed to gather detailed input on key topics, including: the potential of pre-emerging and emerging technologies and innovations in agrifood systems to enhance inclusion, sustainability, and resilience; identifying capacity gaps in technology development and adoption in low-income countries; discussing plausible regional scenarios and anticipating technological breakthroughs over the next 10-20 years; exploring triggers for rapid technological development; interpreting and implementing foresight synthesis report recommendations at national and regional levels; and examining women's roles in innovation and promoting gender equality within agrifood systems.

The collected submissions were analyzed and integrated into various thematic chapters of this report, and their results were compared with findings from other participatory exercises conducted by FAO and CIRAD for this report.

2.2.9 Back office team

The analysis for this report was conducted by a multi-institutional and multidisciplinary team, consisting of FAO, CIRAD and colleagues from 4CF, a company specializing in future studies. The team brought together expertise in foresight, mission-oriented agricultural innovation systems, technology and innovation policies and governance. The team members collaborated and exchanged on regular basis, co-organized all the above-mentioned initiatives, as well as ensured the participatory revision of each chapter of the report.

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Pre-emerging and emerging technologies and innovations (PETIAS) addressing agrifood systems challenges and driving transformative outcomes

3.1 INTRODUCING A FORESIGHT-INFORMED TYPOLOGY

Our findings allowed us to develop a typology of pre-emerging and emerging technologies and innovations within agrifood systems. As a means to group possible technology and innovation changes, this typology is vital for accelerating their full potential and impact. By understanding their characteristics, dynamic interactions and synergies of these technologies and innovations at global, regional and national levels, we can facilitate strategic planning, foster collaboration with farmers and local communities, guide research and development, inform policy decisions, raise awareness and proactively take action.

The main categories of the typology are:

1. Pre-emerging and emerging technologies and innovations (PETIAS);
2. Technology and innovation clusters;
3. Emerging innovation fields;
4. Areas of agrifood system application;
5. Research and innovation paradigm shifts (RIPS).

Table 1 presents definitions, examples, key features and criteria, as well as the relationships and added value of these categories.

Table 1. Typology categories

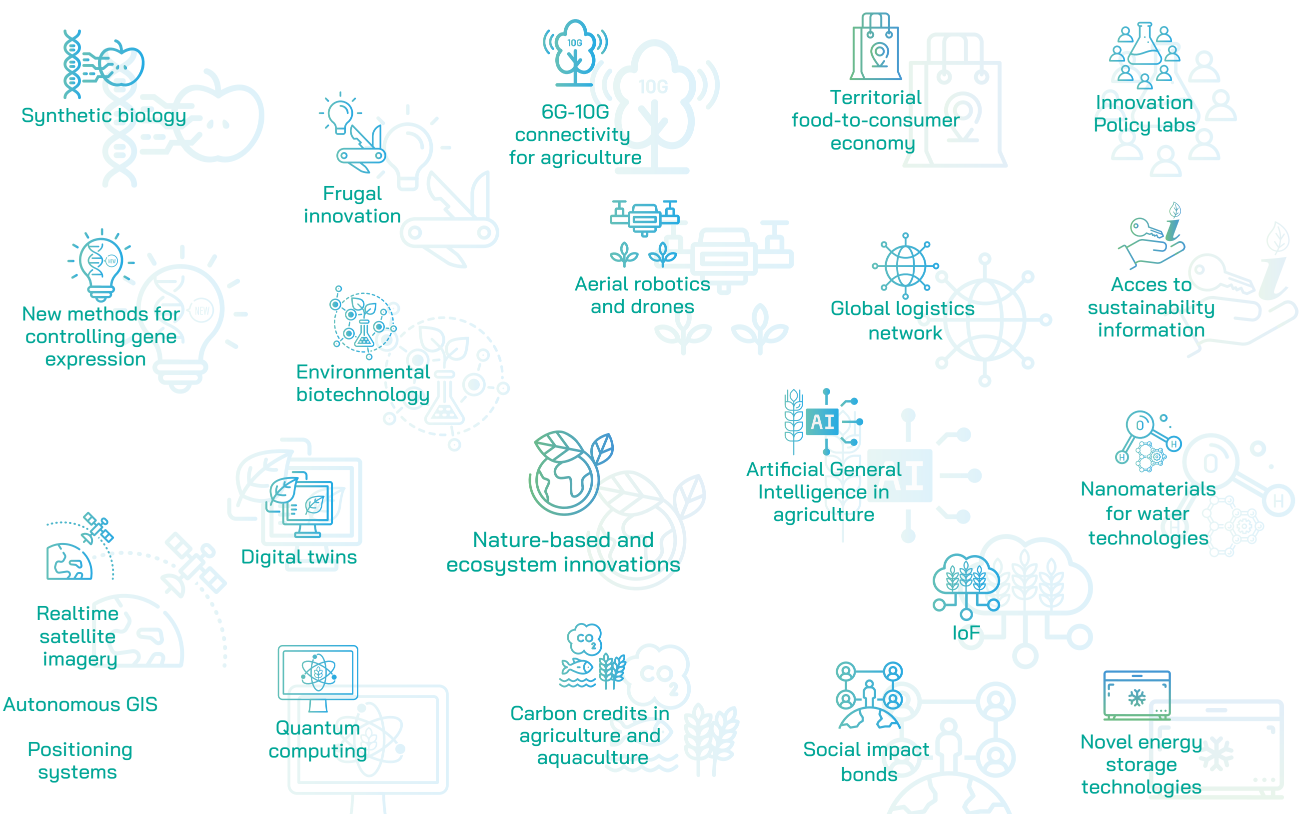
Category	Definition	Examples	Criteria				Linkages with other categories
			Scope/pace	Maturity	Uncertainty	Innovation/ impact	
Pre-emerging technologies and innovations	Technologies and innovations in the early stages of development, not yet used outside the community of developers	Teleportation of complex molecules; AGI, Quantum Computing, Synthetic Biology, Internet of Food	Single technology	Early research stages, not applied in practice	High	High impact, often disruptive	Refer to single technologies and innovations, or small groups of related ones. Often foundational for emerging technologies, requiring significant R&D
Emerging technologies and innovations	Technologies and innovations that are developing, have moved away from their origin (often but not always) research stations or living labs and may substantially evolve through cycles of adaptation	Nature-based and ecosystem innovations, digital twins, environmental biotechnology, social impact bonds	Single technology, rapid growth	Emerging with increasing adoption	Relatively high medium	Diverse/both incremental and disruptive	Refer to single technologies and innovations or small groups of related ones. Increasing adoption, significant investment and policy and innovation system support Build on pre-emerging technologies, drive innovation in various fields
Clusters	Groups of related technologies and innovations of a similar nature	Advanced digital technologies, advanced biotechnologies, micro-nanotechnology and nano-biotech, advanced geospatial technologies, food manufacturing, nutrition, social/financial innovation/policy and organizational innovation	Closely related technologies or innovations, focused on a specific theme or domain, sharing similar innovation ecosystems with synergies	Often well-established	Low	Disruptive and incremental	Facilitate synergetic actions and enhance innovation potential within a specific discipline or domain, increasing specialization and depth. While they may involve ongoing research and development, they generally experience less uncertainty and rapid change compared to emerging fields. Some clusters may evolve into emerging fields and be applied in specific areas.

Category	Definition	Examples	Criteria				Linkages with other categories
			Scope/pace	Maturity	Uncertainty	Innovation/ impact	
Emerging innovation fields	Areas of technology and innovation that are rapidly evolving, interdisciplinary, and have the potential to significantly impact various aspects of society, economy and culture, including agrifood systems	Metaverse (agriverse); new gene editing, omics-based solutions, nature-positive agriculture, vertical farming, circular agriculture, precision agrifood systems, molecular computers, Web3.0, grassroots innovations	Rapid advancement, faster pace than traditional technologies, Interdisciplinary in nature	Early stages	High	Disruptive	Clusters can encompass a broader range of technologies and innovations within a specific area, while emerging fields tend to focus more narrowly on particular advancements. Emerging fields often experience rapid innovation and disruption, whereas clusters typically develop at a more stable pace. Emerging fields can also stimulate related and complementary innovation ecosystems, fostering synergies across technologies and diverse innovations to ensure their rapid and safe development.
Areas of application	Specific domains within agrifood systems where technologies and innovations are applied for impact	Production systems, processing, energy, transportation, value chains, governance, trade, One Health nutrition, inclusion, new materials, proteins circular economy, Blue Economy (oceans) and food waste	Focus on functions, end-use, sector-specific impact	Well-established, emerging and mature	Moderate to low	Diverse impact; incremental and disruptive	A broader category focused on the specific purpose or area of the agrifood system where a technology or innovation is (or will be) applied
Research and innovation paradigm shifts (RIPS)	Tipping points where a broad spectrum of synergetic technological or innovation advancements can elevate agrifood systems to new levels of resilience, inclusivity and sustainability	Convergence, biomimicry, open innovation, citizen science, geoengineering, quantum computing, AGI and disease breakthroughs	Transdisciplinary, transcends the current paradigm	Early stages, rapid development	Moderate to high	Great transformative and disruptive potential	Induces fundamental changes in the underlying assumptions, methodologies and practices within agrifood science, technology and innovation. Disrupts existing trends and steers technology and innovation onto new pathways. Unlike other categories, it embraces multi-, inter- and transdisciplinary approaches, often incorporating elements from all other categories, leading to significant transformations.

3.2 ANALYZING THE PROMISING PRE-EMERGING AND EMERGING TECHNOLOGIES AND INNOVATIONS IN THE AGRIFOOD SYSTEMS

3.2.1 Top 20 pre-emerging and emerging technologies and innovations with highest potential to address agrifood system challenges.

Pre-emerging and emerging technologies and innovations represent the bridge between theoretical concepts and practical applications, spanning the gap between their origins in various places (research stations, laboratories, and academic journals, online forum, multistakeholder dialogues, co-innovation processes as living and policy labs, innovation platforms, traditional knowledge etc.) and including a broad range of stakeholders, interacting through various intensity and modalities and their integration into use. These technologies and innovations, while promising, are still in the nascent stages of development and have not yet scaled out. In the Harvesting Change synthesis report (Alexandrova-Stefanova N., *et al.*, 2023), we have meticulously identified 32 such pre-emerging and emerging technologies and innovations in the agrifood systems, with 20 of those deserving special attention according to our survey results and hence described in more detail ("Top 20" PETIAS). This chapter aims to provide a more comprehensive examination of each of these identified items, delving into both the potential benefits they offer and the associated challenges and trade-offs. To place the potential concerns and benefits into context, we attempted to provide a comparator – a technology or practice used currently and widely. While choosing the comparator is of paramount importance in a proper

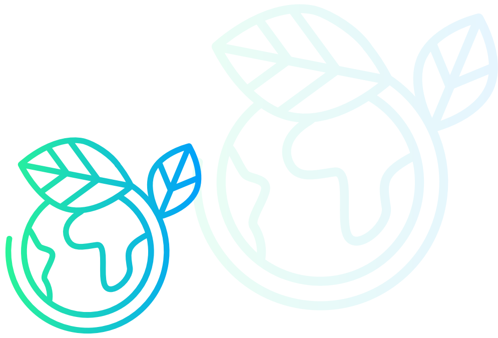


risk-benefit analysis, meticulous accuracy was not a goal in this study.

By exploring these multifaceted aspects, we aim to foster a nuanced understanding of the complexities surrounding the integration of these pre-emerging and emerging technologies and innovations into agrifood systems. With these considerations we aim not only to highlight the transformative potential of these advancements but also to shed light on the potential complications and unintended consequences that need to be carefully considered to ensure their responsible, just and sustainable deployment.

The list of pre-emerging and emerging technologies and innovations spans a broad spectrum, intentionally encompassing both singular technologies with disruptive potential, like 3D food printing, and expansive clusters of interrelated innovations, such as nature-based and frugal innovations. This diversity reflects the multifaceted nature of the agrifood sector and the varied pathways through which transformative change can emerge. Our definition of "emerging" is deliberately inclusive, acknowledging the different maturity levels of these technologies and innovations. Some are already making their mark in real-world applications, while others remain theoretical concepts confined to research labs. This breadth allows us to capture the full scope of innovation, from the cutting-edge to the visionary. Despite their varying stages of development, these pre-emerging and emerging technologies and innovations share common threads. They are not yet widely adopted, holding untapped potential for growth and impact. Moreover, they often exhibit a degree of novelty and complexity, demanding rigorous assessment to fully grasp their potential benefits and implications. By examining these diverse technologies and innovations individually, we aim to illuminate their capacity to address the intricate challenges confronting agrifood systems and their role in shaping a sustainable, inclusive, resilient and efficient agrifood system transformation.

In 2023 we surveyed the earliest time of each technology and innovation to reach maturity (ETM), which indicates peak of adoption after which the technology may become obsolete. Additionally, in 2024 we surveyed the perceived earliest time of a technology or innovation to reach a significant impact (ETSI). Naturally, ETM would require a longer timeline in most of the cases. While the first unit of measurement provides better understanding of the inclusivity potential of a PETIAS, the second provides more nuanced information on its use to boost sustainable development: similar and early ETM and ETSI would denote a PETIAS that is seen as inclusive and impactful and could be prioritised, especially if the trade-off level is low. More specifically, the 2024 survey explored participants' views on the conduciveness of pre-emerging and emerging technologies and innovations in fostering inclusive, sustainable, and resilient agrifood systems. It is important to note that a few questions have not been answered by all, as we made answers to specific questions contingent on the participants' decision to respond to them, trying to avoid a situation where an expert less confident in one area would be forced to weigh in on them.



Nature-based and ecosystem innovations

Nature-based and ecosystem innovations encompass a range of sustainable solutions that leverage natural processes and resources to enhance land and water management, promote biodiversity and mitigate climate change impacts, contributing to global food security and improved human well-being.

Summary

Nature-based and ecosystem innovations offer transformative potential for agrifood systems by leveraging natural processes to improve biodiversity and soil and water health and mitigate climate change. Examples include agroforestry, biochar-based soil amendments and precision biofertilizers. These approaches align with sustainability goals by promoting low-input, high-output systems that foster environmental resilience and food security.

However, challenges remain, including balancing ecosystem preservation with agricultural production, which requires secure land tenure, labour investment and community engagement. Regulatory barriers, technological needs and the time-intensive nature of these practices further hinder adoption. Monitoring systems are crucial to assess their impact on biodiversity and social equity.

According to the survey results, this technology is expected to make an impact before 2040.

Examples: agroecology, biochar-based soil amendments and precision application of biofertilizers.

Comparators (examples of contemporary solutions): conventional farming practices (tillage, synthetic fertilizers and pesticides), conventional livestock production.

Main hopes: improved water/soil quality, biodiversity, cost-effectiveness, safe and nutritious food, reduced emissions, harmony with nature and community growth.

Some concerns: balancing preservation and agriculture, time and labour investment for which tenure rights need to be reinforced.

Nature-based and ecosystem innovations offer a holistic approach to addressing pressing global challenges, particularly in sustainable land and water management, climate change mitigation and food security. These innovations provide a long-term, cost-effective approach to environmental protection and resource preservation by harnessing ecosystems' inherent resilience and functionality (IUCN, 2016). The direct benefits are improved water availability and quality, soil restoration and biodiversity enhancement. Furthermore, nature-based solutions offer significant co-benefits for human well-being, including improved air quality, safe and nutritious food (HLPE, 2017), greater biodiversity and reduced heat island effects (Gill *et al.,* 2007). In the context of food security, these innovations can improve agricultural productivity and resilience through practices like agroforestry, regenerative agriculture and ecosystem-based pest control. Moreover, nature-based solutions can be cost-effective and adaptable to local contexts, decreasing dependency on external inputs and valuing traditional knowledge, making them particularly suitable for implementation in resource-constrained regions and marginalized communities. Moreover, approaches such as agroecology also encompass the social dimension, empowering smallholders and women and giving them agency (HLPE, 2019).

However, the widespread scaling up of nature-based and ecosystem innovations is not without its challenges. Balancing ecosystem preservation with agricultural needs can require intensive work, substantial time investment and secure land tenure (Iseman and Miralles-Wilhelm, 2021). Various factors, including the specific ecosystem, the scale of implementation and the level of community engagement, may influence the effectiveness of these innovations. Regulatory barriers and policy frameworks may need to be adapted to support and incentivize the scaling up of nature-based solutions. Potential trade-offs between short-term economic gains and long-term ecological benefits must also be carefully considered. Monitoring and evaluation systems are essential to assess the impacts of these innovations on biodiversity, food security and social equity, particularly in remote and marginalized communities. Ensuring equitable access to the benefits of nature-based solutions and addressing potential impacts on local livelihoods and traditional practices are crucial for a just and inclusive transition. Technological barriers, such as the need for specialized knowledge and tools, may also hinder the widespread adoption of these innovations. Therefore, capacity development and knowledge sharing initiatives are essential to empower stakeholders and promote the successful implementation of nature-based and ecosystem innovations (OECD, 2020).

As far as the results of the 2024 survey go, nature-based and ecosystem innovations were met with a generally positive reception, particularly in terms of its potential for sustainability, with an average rating of 1.36 out of 3. It also scored favourably on inclusivity (0.97) and resilience (1.42), suggesting that participants see it as contributing positively to all three dimensions of a sustainable agrifood systems. However, the relatively high standard deviations for all three dimensions indicate a range of opinions among participants, highlighting the need for further discussion and exploration of potential trade-offs or challenges associated with this technology/innovation.

The survey findings suggest that this emerging technology holds promise for contributing to more inclusive, sustainable and resilient agrifood systems.

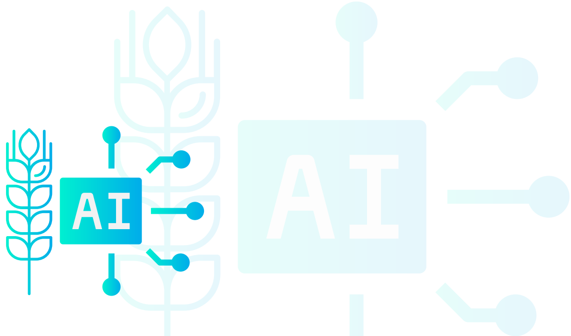
Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- The 2023 synthesis report based on the initial Delphi and the 2024 survey recognizes the high potential of nature-based and ecosystem innovations for sustainability in agrifood systems. In addition, the FSN Forum participants ranked them also high in terms of a positive impact on resilience and inclusion.
- The 2023 report focuses on the holistic benefits and challenges of adoption, highlighting a longer-term maturity timeline around 2043.
- The 2024 survey indicates a more immediate positive reception with a generally optimistic impact timeline, before 2040.
- While the 2023 report emphasizes the need for balancing preservation and agriculture, the 2024 survey reflects this through the diversity of opinions and the importance of further discussion on potential trade-offs or challenges.
- According to the survey results, this technology is expected to make an impact before 2040.

Main areas of application

The main areas of application for nature-based and ecosystem innovations listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Agroforestry, integrated pest management, pollinator habitats, cover cropping and crop rotation in precision, vertical and regenerative farming.
Processing systems	Utilize natural processes like fermentation, composting and anaerobic digestion for food processing and waste management, reducing reliance on synthetic chemicals and enhancing sustainability.
Value chains and services	Develop sustainable packaging, eco-labels and fair-trade certifications.
Energy and transportation	Integrate renewable energy sources like wind and solar and bioenergy from agricultural waste.
Food waste	Compost organic waste for fertilizer, where feasible, create biogas for energy and promote circular systems.
Governance and trade	Develop policies that support sustainable practices, biodiversity and equitable access to resources.
New materials, new proteins and circular economy	Utilize bio-based materials, restore degraded lands and promote closed-loop systems for nutrients and water.
One health and nutrition	Promote diverse diets, integrate livestock and crop production and improve soil health for nutrient-rich food.
Blue economy	Restore coastal ecosystems, promote sustainable fishing practices and develop marine-based products.
Inclusion of the most vulnerable	Empower marginalized groups through sustainable practices, promote traditional knowledge and ensure equitable resource access.



Artificial General Intelligence in agriculture

Artificial General Intelligence (AGI) in agriculture envisions the development of highly adaptable AI systems capable of surpassing human capabilities in various agricultural tasks.

Summary

Artificial General Intelligence (AGI) holds the potential to revolutionize agriculture by surpassing human capabilities in complex tasks such as precision agriculture, pest management and climate resilience. AGI's ability to independently learn and adapt can optimize decision-making, improve yields, reduce resource wastage and promote sustainability and food security.

However, AGI's development and deployment face concerns. Ethical considerations around human oversight, data privacy and the potential for job displacement require robust regulatory binding and non-binding mechanisms. Energy inefficiency is another challenge, as current AI models consume substantial computational power, potentially conflicting with sustainability goals. Widespread adoption may be hampered by the high costs of AGI technologies and limited access for marginalized communities, which could exacerbate existing inequalities.

AGI's full potential is expected to be realized by 2040. Ensuring inclusive access and ethical governance will be critical for AGI's responsible agricultural deployment.

Examples: AI is capable of independently learning and adapting to new agricultural challenges, such as predicting and responding to pest outbreaks or optimising irrigation schedules in real time based on changing weather patterns.

Comparators (examples of contemporary solutions): rule-based AI systems for specific tasks (e.g., crop identification), human expert consultation for complex decision-making and precision agriculture technologies with limited adaptability.

Main hopes: optimized decisions, enhanced productivity, sustainable practices, climate resilience and decision-making in complex scenarios.

Some concerns: AGI overshadowing humans, energy inefficiency, biases, data privacy and ownership, job losses, ethical considerations and the need for regulation.

Artificial General Intelligence (AGI) in agriculture holds immense potential to revolutionize the agrifood systems. By surpassing human capabilities in most cognitive tasks, AGI and its ASI evolution can process vast agricultural datasets, including images and natural language, to provide farmers with actionable insights. This can optimize decision-making, enhance productivity and promote sustainable practices (Liakos *et al.*, 2018). AGI's applications in precision agriculture, pest and disease management and supply chain optimization increase yields, reduce resource wastage and minimize environmental impact (Monteiro and Barata, 2021). Additionally, AGI could contribute to food security by improving agricultural efficiency and adaptability to changing climate conditions.

However, the development and deployment of AGI in agriculture also raises significant concerns. The potential for ASI to overshadow human decision-making brings ethical questions and necessitates robust governance frameworks to ensure human oversight and control. The current energy inefficiency of AI systems, requiring substantial computational power, already poses a challenge to sustainability goals, so it is vital to ensure far better energy efficiency in potential future AGI models. Ensuring the scalability and affordability of AGI/ASI technology for all farmers, including those in marginalized communities, is crucial to prevent exacerbating existing inequalities. Without it, AGI could quickly become a tool for the most significant and strongest entities to consolidate their market dominance. The lack of established ethical guidelines for AGI/ASI development and the potential social and psychological impacts on populations further underscore the need for careful consideration and regulation. The "black box" nature of AI algorithms raises concerns about transparency and accountability, particularly in the event of unforeseen consequences or systemic biases (Burrell, 2016). These challenges can be far more pronounced with AGI/ASI. Regulatory barriers, such as data privacy, intellectual property rights and biosafety, must be addressed to facilitate responsible AGI adoption. The long-term effects on the agricultural workforce, including potential job displacement and the need for new skill sets, must also be carefully evaluated and managed (The World Bank, 2019).

To ensure a sustainable agrifood systems transformation through AGI/ASI, ethical considerations such as prioritising equitable access, promoting energy efficiency and fostering collaboration among diverse stakeholders should be at the forefront.

Concerning AGI in agriculture, it was approached with caution, with an average conduciveness score of 0.08 for inclusivity, 0.89 for sustainability, and 0.63 for resilience. These scores, coupled with a relatively high relative advantage of the technology to address agrifood challenges, and along with relatively low standard deviations, suggest a general consensus about an urgent call for attention and to policy action that would allow maximizing opportunities for positive impact on sustainable development and minimising challenges associated with this powerful technology.

The estimated timeframe for significant impact varies across regions, with a majority of respondents in most regions anticipating an effect before 2040.

Altogether, the survey results do not paint a promising picture for AGI, with the lowest overall assessment.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: the 2023 report acknowledge AGI's transformative potential in agriculture acknowledges. The report emphasizes its role in surpassing human capabilities in complex decision-making, while the survey results are negative regarding AGI's contribution to inclusivity, sustainability and resilience. Likewise, the FSN Forum participants ranked AGI quite low in terms of a positive impact on these three dimensions.
- Concerns and challenges: the 2023 report raises concerns about ethical implications, energy inefficiency and potential job losses.
- Impact timeline: optimistic predictions of AGI by 2040 from the 2024 survey which may contradict the widely held belief that AGI is still a future hypothesis and lend toward a more generous interpretation that the present AI advances are actually on par with human cognitive level in several tasks or sets of functions relevant for agrifood systems. This contrasts with the 2023 report's implied longer-term view due to the need to address ethical and regulatory challenges.

Main areas of application

The main areas of application for Artificial General Intelligence in agriculture listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Optimize precision agrifood systems, land management, vertical farming and regeneration.
Processing systems	Enhance quality control and optimize processes.
Value chains and services	Improve supply chain management and financial services.
Energy and transportation	Optimize renewable energy use and transportation efficiency, explore new energy sources.
Food waste	Predict spoilage and develop new preservation techniques.
Governance and trade	Streamline customs procedures, ensure compliance with regulations and predict market trends.
New materials, new proteins and circular economy	Design bio-based materials and proteins.
One health and nutrition	Monitor diseases and develop personalized nutrition.
Blue economy	Optimize fishing quotas and protect marine ecosystems.
Inclusion of the most vulnerable	Create user-friendly interfaces and tools for farmers in developing countries.

Agricultural innovation policy labs

Agricultural innovation policy labs are collaborative platforms that foster evidence-based, participatory and behaviourally informed policymaking in the agrifood systems. These labs aim to co-create inclusive and impactful policies that address complex agricultural challenges by engaging diverse stakeholders throughout the policy process.

Summary

Agricultural innovation policy labs are collaborative platforms designed to revolutionize agricultural policymaking. Their participatory approach can optimize decision-making, promote innovation, and enhance the resilience of agrifood systems.

However, the widespread adoption of these labs faces challenges. Concerns include potential policy capture by dominant groups, high resource demands, and ensuring inclusivity for marginalized communities. Balancing participatory decision-making with efficient policy implementation is crucial. Overcoming these barriers will require effective governance, skilled facilitation, and a willingness to embrace new approaches to policymaking.

Agricultural innovation policy labs are expected to show their potential globally before 2040.

Examples: policy labs focused on developing and implementing policies that support regenerative agriculture practices or promote the use of AI in smallholder farming.

Comparators (examples of contemporary solutions): traditional top-down policymaking and limited stakeholder engagement.

Main hopes: evidence-based, participatory and responsive policy, inclusivity, stakeholder buy-in and addressing complex challenges.

Some concerns: policy capture, resource intensity, inclusivity for marginalized communities, the potential for slow decision-making, the need for skilled facilitation and difficulty in shifting from conservative policies.

Agricultural innovation policy labs represent a promising approach to decision-making in the agrifood systems, characterized by evidence-based, participatory foresight – and behaviourally informed co-creation. This model aims to empower diverse stakeholders, including farmers, consumers, researchers and policymakers, to engage actively in all phases of the policy process (Toffolini *et al.*, 2023). By fostering inclusivity and leveraging a wide range of perspectives and expertise, these labs have the potential to make decisions or resolve barriers to innovation within their level of control that are more responsive to the needs of the agrifood system, increase their buy-in by stakeholders, promote sustainable practices and drive innovation. Moreover, integrating foresight and behavioural insights can enhance the adaptability and effectiveness of policies in addressing complex and evolving challenges (OECD, 2017). This approach can also contribute to closing the gap between policy formulation and implementation, particularly in innovation domains characterized by novelty, complexity and uncertainty.

Expanding agricultural innovation policy labs on a larger scale poses inherent challenges. Establishing effective oversight and ensuring the availability of experts across numerous labs can be difficult. This may lead to inconsistencies in policy outcomes. The threat of policy capture by powerful interest groups is a concern, especially if labs lack transparency in their decision-making processes. Therefore, a skilled facilitation of the process is key. Additionally, the participatory nature of these labs may require significant time and resources, potentially slowing down the policymaking process. The need for a dramatic shift from conservative policies and establishing proper incentives are crucial for this approach's widespread adoption and success. Furthermore, the impact of these labs on remote and marginalized communities requires careful consideration to ensure that their voices are heard and their specific needs are addressed (FAO, 2021a). Regulatory barriers, such as existing bureaucratic structures and resistance to change, may also hinder the adoption of this innovative policymaking model.

As far as agriculture innovation policy labs go, 2024 survey evaluations were positive with average conduciveness scores of 1.47 for inclusivity, 1.69 for sustainability, and 1.72 for resilience. These scores, coupled with moderate standard deviations, suggest a very favourable perception of this, innovation's potential to contribute to inclusive, resilient and sustainable agrifood systems. On average, and in terms of inclusivity this PETIAS is definitely assessed as one of the most conducive to desirable change in global agrifood systems. The survey results indicate that participants view it positively, although with some reservations and uncertainties. The varying estimated timeframes for significant impact highlight the importance of considering context-specific factors and potential barriers to adoption when promoting and implementing this innovation.

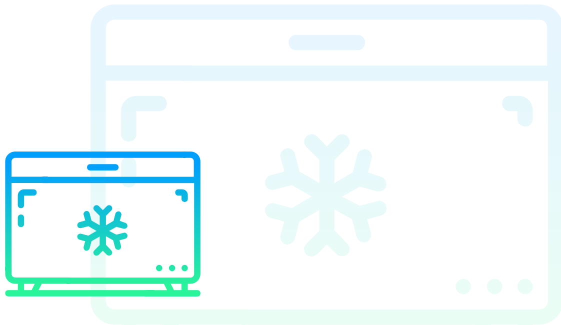
Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on purpose and potential: the 2023 report, the FSN Forum and the 2024 survey recognize the value of agricultural innovation policy labs in fostering inclusive and responsive policymaking. The report highlights their role in creating evidence-based policies with stakeholder engagement, while the survey participants also see their positive potential in promoting sustainability and resilience.
- Concerns and reservations: the 2023 report stresses challenges like policy capture, resource intensity and the need for skilled facilitation, less visible in the 2024 survey's ratings. This indicates optimism among survey participants, while acknowledging the potential complexities and barriers to effective implementation.
- Impact timeline: the 2024 survey shows a more nuanced perspective compared to the average ETM of 2035 that featured in the synthesis report.

Main areas of application

The main areas of application for agricultural innovation policy labs listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Based on evidence (data, digital) and collective intelligence (foresight, behavioural insights), multistakeholder groups remove policy barriers to innovate by supporting system shifts towards more sustainable, equitable and resilient agricultural production models in a community, institution or nationally.
Processing systems	Develop policy, institutional and operational innovations to reduce post-harvest losses, improve nutritional content and diversify product offerings.
Value chains and services	Remove policy and operational barriers to transparent value chains new farmer business models and support small-scale farmers.
Energy and transportation	Co-create new policy and operational frameworks for sustainable energy and transportation in a participatory and inclusive manner.
Food waste	Design innovative solutions, incentivize waste reduction and empower consumers.
Governance and trade	Develop evidence-based anticipatory and behaviourally informed policies and decisions, create dialogue platforms and design fair trade policies.
New materials, new proteins and circular economy	Analyse paradigmatic shifts related to circular economy, cell-based food and other new concepts in a particular country or local context and promote informed and inclusive decision-making.
One health and nutrition	Manage food safety and nutrition risks and promote healthy diets.
Blue economy	Promote responsible decision-making for sustainable aquaculture and protect marine ecosystems.
Inclusion of the most vulnerable	Design and implement policies that promote gender equality in agriculture, empower youth and elderly farmers and support indigenous communities in preserving their traditional agricultural practices.



Energy storage technologies

Emerging energy storage technologies encompass a range of cutting-edge solutions that enable the capture and storage of energy for later use. In agrifood systems, these technologies facilitate efficient energy management, enhance the utilisation and potential of renewable energy sources and ensure reliable power supply.

Summary

Energy storage technologies offer a transformative opportunity for agrifood systems by enabling better management of renewable energy sources like solar and wind. These technologies provide reliable power for farming operations, ensuring resilience during outages and reducing reliance on fossil fuels. Energy storage also enhances productivity by powering essential systems like cold storage and processing facilities, especially in remote or off-grid regions.

However, challenges include high upfront costs, environmental impacts from material extraction and the need for adapted regulatory frameworks. Equitable access remains a concern, as smaller farmers and marginalized communities may struggle to afford these systems. Addressing energy justice is crucial to prevent deepening inequalities in energy access.

Widespread global impact will depend on technological improvements, cost reductions and policy support. Energy storage is essential for transitioning to a more resilient and sustainable agrifood system but requires careful consideration of its social and environmental impacts.

Examples: Gravity-based energy storage systems for off-grid farms and solar-powered cold storage units for perishable produce.

Comparators (examples of contemporary solutions): Diesel generators for backup power and traditional cold storage relying on grid electricity or fossil fuels.

Main hopes: Better renewable energy use, lower emissions, resilience and energy independence for remote communities.

Some concerns: Environmental impacts of material extraction, high costs, equitable access, need for adapted regulations and incentives and energy justice.

Integrating energy storage technologies within agrifood systems presents significant opportunities for enhancing efficiency, resilience and sustainability. By providing a buffer for energy supply and demand fluctuations, storage solutions enable better utilisation of renewable energy sources like solar and wind power, even in remote or marginalized communities. This can lead to reduced reliance on fossil fuels, decreased greenhouse gas emissions and improved air quality, contributing to environmental conservation. For farmers and food producers, energy storage offers uninterrupted power supply, which is critical for maintaining operations during grid outages or peak demand periods. This can safeguard production processes, prevent spoilage of perishable goods and enhance overall productivity. Moreover, energy storage facilitates the adoption of decentralized energy systems, empowering communities to generate and manage their energy resources fostering energy independence and economic resilience.

While energy storage technologies hold immense promise, their implementation in agrifood systems faces challenges and potential drawbacks. The extraction and life-cycle management of materials used in energy storage devices raises environmental concerns, including habitat destruction, pollution and resource depletion. Addressing these issues through responsible sourcing, recycling and end-of-life management is essential for a sustainable energy transition. Additionally, the high upfront costs of energy storage systems can be a barrier to adoption, particularly for small-scale farmers and communities with limited financial resources (Olabi *et al.,* 2021). Regulatory frameworks and policies need to be adapted to facilitate the integration of energy storage into existing energy grids and incentivize their widespread deployment. The potential shift towards a more globalized system or increased storage capacity raises questions about energy justice and equitable access to energy resources. It is crucial to ensure that the benefits of energy storage are distributed fairly and that marginalized communities are not left behind in the transition to a more sustainable energy future.

In the 2024 survey, it garnered positive feedback, with average conduciveness scores of 1.14 for inclusivity, 1.42 for sustainability, and 1.42 for resilience. These scores, along with slightly higher than average standard deviations, suggest a generally favourable perception of this technology/innovation's potential to contribute to sustainable agrifood systems.

The estimated timeframe for significant impact shows a relatively optimistic outlook, with most respondents in most regions anticipating an impact before 2040.

The relatively consistent positive views across regions suggest that these technologies might be well-positioned for widespread adoption and impact. However, further research and monitoring will be necessary to track its progress and address any unforeseen challenges or trade-offs.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential and benefits: the 2023 report, the FSN Forum and the 2024 survey acknowledge the potential of energy storage technologies to facilitate renewable energy adoption, reduce emissions and enhance resilience in agrifood systems. While the report emphasizes their role in energy independence and sustainability, the survey highlights their positive contribution to resilience. In addition, the FSN Forum participants consider this PETIAS important for sustainability.
- Concerns and challenges: the 2023 report raises concerns about environmental impacts, costs and equitable access that are not prominently discussed in the 2024 survey results. This difference could indicate a greater focus on the benefits or the perception that some of these concerns have been addressed in the survey context.
- Impact timeline: the 2024 survey participants express optimism about the near-term impact of energy storage technologies. In contrast, the 2023 report suggests a similar medium-term horizon for maturity (2038), implying a possible acceleration in the technologies' development and adoption.

Main areas of application

The main areas of application for energy storage technologies listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Supporting energy-intensive processes like hydroponics and aquaponics to produce nutritious food.
Processing systems	Reducing energy costs and ensuring uninterrupted operation of food processing facilities during grid fluctuations or outages.
Value chains and services	Enable refrigerated storage and transportation and extend shelf life.
Energy and transportation	Integrating energy storage into smart grids improves energy management and creates new market opportunities for farmers.
Food waste	Powering refrigeration systems, food preservation technologies and innovations to extend shelf life and reduce waste.
Governance and trade	Streamline customs procedures, ensure compliance with regulations and predict market trends
Inclusion of the most vulnerable	Increasing energy access and affordability for marginalized communities, enabling them to participate in the agricultural economy.

Social impact bonds

Social impact bonds (SIBs) are outcome-based financing mechanisms that leverage private investment to address social and environmental challenges in agriculture. Repayment to investors is contingent upon achieving predefined outcomes and promoting innovation and accountability in project implementation.

Summary

Social impact bonds offer an innovative financing model for agricultural development by attracting private investment to fund projects that address sustainability and social challenges. Investors are repaid based on the achievement of predefined outcomes, promoting accountability and encouraging the adoption of sustainable practices in areas like resource management and smallholder farming.

However, SIBs face hurdles such as complex impact measurement, regulatory constraints and high development costs. Focusing on measurable outcomes can sometimes lead to narrow definitions of success, potentially overlooking broader social and environmental benefits. Ensuring equitable distribution of investments and preventing the exclusion of marginalized communities is key to their effectiveness.

Despite these challenges, SIBs present a valuable mechanism to complement traditional public funding, driving innovation and sustainability. While their full impact may take time to materialize, particularly in underdeveloped regions, they hold promise for fostering collaboration and delivering tangible outcomes by 2040, provided supportive policies and impact measurement frameworks are in place.

Examples: SIBs that fund the development and scaling of sustainable aquaculture practices or support the adoption of precision agriculture technologies and innovations by smallholder farmers.

Comparators (examples of contemporary solutions): traditional grant funding and philanthropy, government-led social and environmental programmes.

Main hopes: private capital for sustainability, outcome-based funding for social/environmental benefits, collaboration and complementing public funding.

Some concerns: impact measurement, narrow success definitions, workforce implications, complexity, time-consuming development, need for adapted regulations and ensuring equitable outcomes.

Social impact bonds (SIBs) offer a promising approach to financing agricultural innovation while promoting sustainability and social responsibility. By attracting private capital to address public issues, SIBs can drive a shift towards outcome-based funding, where success is determined by measurable impact. This model can potentially enhance the efficiency and effectiveness of agricultural initiatives focused on sustainable practices, resource conservation and food security. Additionally, SIBs can foster collaboration and systemic change by aligning the interests of investors, service providers and government agencies. In marginalized communities, SIBs can provide crucial capital for projects to improve livelihoods, expand market access and promote sustainable farming practices. Focusing on measurable outcomes helps ensure that investments deliver tangible social and environmental benefits (Carè, 2021). By leveraging private capital and expertise, SIBs can complement public funding and accelerate the adoption of sustainable agricultural practices in underserved areas.

Robust impact measurement and evaluation frameworks are essential to assess the effectiveness of SIB-funded projects and ensure accountability. Transparency and oversight mechanisms are crucial to prevent misuse of funds and guarantee that projects deliver on their intended outcomes. SIB development and implementation's complexity and time-consuming nature can pose challenges, particularly for smaller organisations or those operating in resource-constrained environments (Millner and Meyer, 2021). Regulatory frameworks and legal structures must be adapted to support SIBs, providing clarity on investor rights, risk allocation and performance measurement. Additionally, focusing on measurable outcomes may sometimes lead to a narrow definition of success, potentially overlooking broader social and environmental impacts. Workforce implications, such as potential job displacement or the need for new skills, must be considered and addressed through appropriate support and training programmes. Ultimately, the success of SIBs hinges on effective collaboration and communication among diverse stakeholders.

In the survey, SIBs present a generally positive picture, with average conduciveness scores of 1.25 for inclusivity, 1.53 for sustainability, and 1.50 for resilience. Standard deviation was generally low, which points to a favourable perception of this PETIAS. The estimated timeframe for significant impact also reflects this uncertainty, with a broader range of responses compared to the previous technologies and innovations. While some respondents anticipate an impact before 2035, a significant proportion predicts a longer timeframe, extending beyond 2040. This suggests that these innovations' adoption and impact might be subject to more complex and uncertain factors, including market dynamics and social acceptance.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on concept and potential: both the 2023 report and the 2024 survey recognize the innovative approach of SIBs in attracting private investment for sustainable agricultural practices. The report emphasizes their role in fostering outcome-based funding and accountability, while the survey and the FSN Forum reflect a cautious view of their inclusivity, sustainability and resilience.
- Concerns and challenges: the 2023 report outlines challenges like impact measurement, complexity and regulatory barriers, which seem to align with the 2024 survey's more reserved ratings and variability in participant opinions. This suggests ongoing concerns about the practicality, scalability and equitable implementation of SIBs.
- Impact timeline: the 2024 survey shows a slightly more uncertain outlook on the impact timeline for SIBs – the original ETM being 2036 – with some participants anticipating a longer timeframe or complex and uncertain factors influencing their adoption.

Main areas of application

The main areas of application for social impact bonds listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Fund sustainable land management, urban farming, regenerative practices, as well as paradigmatic shifts related to new ways of producing food.
Processing systems	Promotes energy-efficient technologies and innovations, sustainable sourcing and transparent labelling.
Value chains and services	Incentivize fair trade, ethical sourcing, fund traceability and technologies and innovations.
Energy and transportation	Finance renewable energy projects and low-carbon transportation.
Blue economy	Finance initiatives that protect marine ecosystems and biodiversity.
Inclusion of the most vulnerable	Empower women farmers through financial and technical support. Create training and employment opportunities for young people in agriculture. Support elderly people and Indigenous peoples' traditional knowledge and practices, ensuring their inclusion in the agrifood systems.

Real-time satellite imagery, positioning systems and autonomous GIS

Real-time satellite imagery, positioning systems and autonomous GIS combine to provide dynamic geospatial data and analysis for informed decision-making in agrifood systems. These technologies and innovations enable precise monitoring, efficient resource management and automation of various agricultural operations.

Summary

Real-time satellite imagery, positioning systems and autonomous GIS offer significant advancements for agrifood systems by providing precise, up-to-the-minute data on crop health, soil conditions and weather patterns. These technologies and innovations enable better decision-making, improve resource management and help farmers address pests and nutrient deficiencies, driving sustainability and efficiency.

Challenges include the high costs of deploying and maintaining these technologies and innovations, particularly for small-scale farmers and marginalized communities. There are also concerns over data privacy and the specialized skills required to operate these systems. Additionally, ensuring equitable access to these technologies and innovations is essential to avoid widening the agricultural digital divide.

While these technologies and innovations show strong potential for short-term impact by 2035, global scaling will depend on lowering costs, addressing infrastructure gaps and providing training. These systems are poised to transform precision agriculture but must overcome barriers to achieve widespread, equitable use.

Examples: AI-powered analysis of satellite imagery to detect early signs of crop stress swarms of autonomous drones for precision pollination.

Comparators (examples of contemporary solutions): periodic aerial surveys, manual field inspections, ground-based sensors and traditional GIS mapping and analysis.

Main hopes: informed decisions, early problem detection, efficiency, monitoring for sustainability and crucial data for decision-making.

Some concerns: high costs, data privacy, equitable access, need for technical skills, overreliance on technologies and innovations, the environmental impact of infrastructure and the potential digital divide.

Fusing real-time satellite imagery, precise positioning systems and autonomous Geographic Information Systems (GIS) offers an unprecedented opportunity to transform the agricultural landscape. This integrated system empowers farmers and stakeholders to make informed decisions that optimize resource allocation, minimize environmental impact and enhance productivity by providing up-to-the-minute, high-resolution data on crop health, soil conditions and weather patterns. Monitoring vast agricultural areas in real time allows for early detection of pests, diseases and nutrient deficiencies, enabling timely interventions and reducing crop losses (Jin *et al.,* 2024). This can significantly contribute to food security, especially in remote and marginalized regions with limited access to agricultural expertise and resources. Additionally, precise positioning systems enable autonomous farming operations, improving efficiency and reducing labour requirements. Integrating citizen science and participatory approaches can further enhance the accuracy and relevance of the collected data, empowering communities and fostering a sense of ownership over their agricultural practices.

While the benefits of real-time satellite imagery and autonomous GIS are undeniable, several challenges and potential trade-offs need consideration. The deployment and maintenance of the necessary infrastructure, including satellite networks and ground-based sensors, require significant investment, potentially limiting accessibility for small-scale farmers and marginalized communities. Ensuring equitable access and affordability is crucial to avoiding the digital divide within the agrifood systems. The vast amounts of data these systems generate necessitate robust cybersecurity measures and data privacy safeguards to protect sensitive information and prevent misuse (Wolfert *et al.,* 2017). The need for specialized expertise and technical skills to operate and maintain these systems may also pose a barrier to adoption, requiring significant investments in education and training. Finally, the environmental impact of satellite infrastructure and data centres, including their energy consumption and carbon footprint, needs to be carefully assessed and mitigated to ensure the sustainable integration of these technologies and innovations into agrifood systems.

In the 2024 survey, this technology received mixed praise with average conduciveness scores of only 0.75 for inclusivity, 1.29 for sustainability, and 1.25 for resilience, remaining among the most voted PETIAS for sustainability and resilience. These scores, along with higher than average standard deviations, indicate some optimism mixed with a degree of uncertainty and divergence in opinions among participants, based on the anticipated low accessibility of this PETIAS for important groups of agrifood systems' actors. The estimated timeframe for significant impact also reflects this uncertainty, with a broader range of responses ranging from 2035 to 2050.

Although recognized for its potential to enhance precision agriculture and resource management, concerns persist regarding its inclusivity. The high infrastructure and data access costs could create barriers for small-scale farmers, limiting their ability to benefit from these technologies and innovations. Furthermore, over-reliance on these systems could lead to a neglect of traditional ecological knowledge and practices, potentially undermining the resilience of agrifood systems in the face of unforeseen challenges.

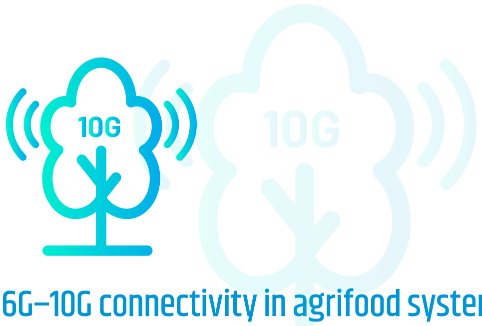
Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: both the 2023 report and the 2024 survey acknowledge the transformative potential of real-time satellite imagery and autonomous GIS in agriculture for improving resource management, decision-making and sustainability. The report emphasizes their role in early problem detection and efficient resource management, while the survey participants recognize their contribution to inclusivity, sustainability and resilience, albeit with some reservations. The FSN Forum participants considered this PETIAS important for resilience, while less impactful on sustainability and inclusion.
- Concerns and challenges: the 2023 report highlights challenges such as high costs, data privacy and equitable access, less visible in the survey's ratings. This indicates ongoing concerns about the practical implementation, accessibility and potential overreliance on technologies and innovations.
- Impact timeline: the 2024 survey shows uncertainty regarding the impact timeframe. Still the 2023 report's implied 2036 short-term horizon seems realistic, acknowledging the need for infrastructure development and addressing associated challenges.

Main areas of application

The main application areas for real-time satellite imagery, positioning systems and autonomous GIS listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Optimize irrigation, fertilizer use, pest control and crop health monitoring. Enables efficient land management and supports regenerative agriculture practices.
Processing systems	Ensures traceability, supply chain optimization and crop insurance.
Energy and transportation	Optimizes energy consumption on farms and monitors renewable energy sources.
Food waste	Monitor shipments and optimize waste collection.
Governance and trade	Provides data for policymaking, monitors regulatory compliance and facilitates fair trade. Ensures regulatory compliance and fair-trade practices.
Blue economy	Track marine ecosystems, identify pollution and monitor fishing activities.
Inclusion of the most vulnerable	Monitor weather patterns and extreme events, helping vulnerable communities prepare and adapt.



6G–10G connectivity in agrifood systems

6–10G connectivity refers to the broad application of advanced communication technologies and innovations, specifically from the sixth to tenth generation, to enable seamless and real-time data exchange, analysis and decision-making within the agricultural sector.

Summary

6G–10G connectivity promises to revolutionize agrifood systems by enabling seamless, real-time data exchange and advanced communication technologies and innovations. This can enhance precision farming, optimize resource management, improve traceability and give farmers better access to services and market information. These technologies and innovations can drive efficiency and sustainability across the supply chain by connecting sensors, machinery and data-driven platforms.

However, significant challenges include high infrastructure costs, energy demands and potential cybersecurity vulnerabilities. Ensuring equitable access, especially for smallholder farmers and marginalized communities, is critical to prevent exacerbating the digital divide. Regulatory frameworks and international standards must also evolve to support the widespread adoption of 6G–10G connectivity.

The impact of these technologies and innovations is expected to materialize before 2040 in developed regions. Still, adoption in less connected areas will take longer, driven by infrastructure investment and policy support. Overall, 6G–10G connectivity could transform the future of agrifood systems if accessibility and security challenges are addressed.

Examples: IoT sensors for real-time livestock health monitoring and environmental conditions in remote pastures and blockchain-based traceability systems for food products.

Comparators (examples of contemporary solutions): slower and less reliable internet connections in rural areas, paper-based or centralized record-keeping for traceability, reliance on manual data collection and analysis.

Main hopes: better information/communication, precision agriculture, traceability, access to services and market opportunities.

Some concerns: inclusivity, cybersecurity, infrastructure's environmental impact, including energy use, the need for policies incentivizing deployment, international standards development and the potential for disruption in conflict areas.

6G–10G connectivity in agrifood systems holds the potential to revolutionize agricultural practices through real-time data exchange, analysis and decision-making. It can improve access to information and services: with better access to vital information, such as weather forecasts, market prices and agricultural advisory services, farmers can make more informed decisions and improve their productivity and livelihoods. The technologies and innovations can facilitate communication and collaboration among farmers, suppliers and buyers, even in remote areas (FAO, 2017). This can open up new market opportunities and reduce transaction costs. 6G–10G can facilitate precision agriculture techniques, such as site-specific nutrient management and pest control, improving sustainability and reducing environmental impact. Moreover, 6G–10G enhances traceability and food safety through improved monitoring and data sharing throughout the supply chain.

However, realising these benefits hinges on carefully considering potential trade-offs and challenges. Ensuring that the benefits of 6G–10G reach all farmers, including those in rural or marginalized communities, will be a significant challenge. Addressing this requires policies that incentivize infrastructure deployment in underserved areas.

Additionally, increased reliance on digital systems raises cybersecurity vulnerabilities, potentially disrupting critical agrifood operations. Data privacy concerns also arise due to collecting and analysing vast amounts of agricultural data. Furthermore, deploying and maintaining extensive 6G–10G infrastructure can have significant environmental implications, requiring sustainable practices to mitigate these effects. Developing international standards for 6G–10G technology and innovation is crucial for interoperability and widespread adoption (Sufyan *et al.,* 2023). However, reaching a consensus among different countries and stakeholders can be lengthy and complex. Moreover, in regions with political instability or conflict, the deployment and maintenance of 6G–10G infrastructure could be hindered.

In 2024 survey, 6G-10G connectivity received generally favourable responses, save for inclusivity which was rated at 1.22. The other average conduciveness scores were 1.50 for sustainability, and 1.47 for resilience. These scores are among the highest technological ones, coupled with higher than average standard deviations, indicate a mix of optimism and reservation among participants. While some respondents might see potential benefits in certain dimensions, others emphasize low inclusivity. In the 2024 survey, 6G–10G connectivity received the most mixed responses among the evaluated technologies and innovations.

The estimated timeframe for significant impact also reflects this uncertainty, with a wide range of responses across different regions, but 2035 horizon dominates across the answers.

While lauded for its potential to revolutionize communication and data exchange in agriculture, the high infrastructure costs and potential for exacerbating the digital divide raise concerns about equitable access, particularly for marginalized communities. Additionally, the reliance on complex digital systems increases vulnerability to cyberattacks, potentially disrupting critical agrifood operations and compromising resilience.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential and challenges: both the 2023 report and the 2024 survey acknowledge the revolutionary potential of 6G–10G connectivity in transforming the agrifood systems through real-time data exchange, precision agriculture and improved access to information. However, both also express concerns about inclusivity, infrastructure costs, cybersecurity and environmental impact. In fact, the FSN Forum participants did not include this PETIAS among the most impactful ones on inclusion, sustainability and resilience.

- Divergence in perception: the 2024 survey participants' views are more reserved about the potential of 6G–10G connectivity, with medium ratings across all dimensions and high response variability. This suggests some scepticism about its feasibility and effectiveness compared to the 2023 report, which emphasizes both the hopes and the considerable challenges associated with its deployment.

- Impact timeline: the survey aligns with the 2023 report's implication of a longer-term horizon due to the need for extensive infrastructure, policy development and addressing inclusivity issues, albeit with a hint of hope that this could emerge by 2035 in some regions.

Main areas of application

The main areas of application for 6G–10G connectivity in agrifood systems listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Optimizes irrigation, fertilization and pest control through real-time data, even in remote locations.
Processing systems	Improves quality control and integrates processing processes.
Value chains and services	Enables traceability, supply chain optimization and e-commerce for farmers.
Energy and transportation	6G–10G connectivity for agriculture: Optimizes farm energy management and potentially reduces carbon footprint.
Governance and trade	Informs policy decisions with real-time data and promotes fair trade. Transparent and verifiable information about origin and production methods can ensure fair prices for farmers.
Blue economy	Real-time monitoring of water quality, fish health and environmental impact.
Inclusion of the most vulnerable	Bridging the connectivity divide by providing affordable access to high-speed internet and digital tools for marginalized communities, women, youth, older people and people with disabilities.

Environmental biotechnologies

Environmental biotechnologies employ biological processes and organisms, including genetic engineering tools, to develop sustainable solutions for environmental challenges.

Summary

Environmental biotechnologies offer innovative solutions for agrifood systems by utilizing biological processes to address pollution, waste management, drought and resource conservation challenges. These technologies can enhance soil health, reduce the need for chemical inputs and contribute to sustainable practices like bioremediation and bioenergy production. Their ability to support ecosystem restoration and renewable energy aligns with the global push for sustainability.

However, adoption faces challenges including public scepticism, regulatory hurdles and the potential ecological hazards related to introduction into some environments. Ensuring these technologies and innovations are affordable and accessible, especially for smallholder farmers, is key to preventing inequities. There are also concerns about the scalability of some biotechnologies and the long-term environmental impacts they may have.

Broader global scaling up is expected by 2035. To fully realize their potential, biotechnologies must be supported by adequate policy frameworks and deployed with attention to social equity and environmental sustainability.

Examples: CRISPR-Cas9 gene editing for developing crops with enhanced drought resistance and biopesticides derived from naturally occurring microorganisms.

Comparators (examples of contemporary solutions): chemical-based pollution remediation, landfill and incineration for waste management.

Main hopes: sustainable practices, pollution remediation, waste management, renewable energy, soil health, reduced chemical inputs and ecosystem restoration.

Some concerns: public perception in some contexts, asynchronous adoption, regulations, ecological consequences such as potential disruption of existing ecosystems and biodiversity, equitable access, varying regulations across regions, unintended consequences, scalability and affordability.

Environmental biotechnologies, spanning a spectrum from simple to sophisticated, offer a transformative approach to addressing pressing environmental challenges. These technologies and innovations in agriculture can lead to more sustainable practices through improved soil health, reduced reliance on chemical inputs and enhanced crop yields. In the realm of pollution remediation, environmental biotechnologies can offer practical solutions for cleaning up contaminated sites mitigating the risks to human health and ecosystems. For waste management, these technologies and innovations can facilitate the development of more efficient and sustainable waste treatment and recycling processes. Additionally, environmental biotechnologies can contribute to renewable energy production by developing biofuels and other bio-based energy sources. These technologies and innovations, such as developing innovative ecosystem restoration and biodiversity preservation approaches, can also support the conservation of natural resources.

On the other hand, public perception and mistrust of genetically modified organisms in some contexts can hinder their acceptance and create barriers to adoption (Frewer *et al.,* 2003). Addressing these concerns through transparent communication, public engagement and education is vital for fostering trust and facilitating informed decision-making. Additionally, the broadness of the "environmental biotechnologies" category encompasses a wide array of techniques, each with its unique regulatory considerations. Policy and standards mismatch across different geographies can create challenges for international collaboration and equitable access to these technologies and innovations. Additionally, for some concrete cases, there might be a hazard of unintended ecological consequences, such as disrupting natural ecosystems or introducing invasive species. Regulated science-based risk assessments, management and communication are needed to address those challenges, including addressing social considerations.

Environmental biotechnologies garnered mixed feedback in the 2024 survey, with average conduciveness scores of 0.72 for inclusivity, 1.17 for sustainability, and 1.17 for resilience. These scores, along with slightly higher than average standard deviations, suggest lack of consensus among participants about the positive overall contribution of this technology/innovation to sustainable agrifood systems. The estimated timeframe for significant impact is before 2035.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: the 2023 report acknowledges the transformative potential of environmental biotechnologies in promoting sustainable agricultural practices and addressing key environmental challenges. The report emphasizes their role in pollution remediation, waste management and resource conservation, while the 2024 survey results are much more cautious regarding their contribution to inclusivity, sustainability and resilience. Likewise, among the FSN Forum participants only a few considered this PETIAS as impactful on resilience.
- Concerns and challenges: the 2023 report raises concerns about public perception, regulatory challenges and ecological consequences, which is also reflected in the 2024 survey's ratings. This could suggest a mixed acceptance of biotechnologies.
- Impact timeline: the 2024 survey indicates a more optimistic impact timeline, with many participants anticipating significant impact before 2035. This contrasts with the 2023 report's longer-term maturity estimates around 2043.

Main areas of application

The main areas of application for environmental biotechnologies listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Microbiome engineering enhances soil health, plant growth and pest control. Bioremediation cleans contaminated water for irrigation.
Food waste	Composting and anaerobic digestion valorize waste into animal feed or fertilizers.
New materials, new proteins and circular economy	Bio-based plastics and composites. Novel biopesticide substances.
One health and nutrition	Develop probiotics, vaccines and biosensors for disease detection.
Blue economy	Marine bioremediation and aquaculture disease control.
Blue economy	Real-time monitoring of water quality, fish health and environmental impact.
Inclusion of the most vulnerable	Bridging the connectivity divide by providing affordable access to high-speed internet and digital tools for marginalized communities, women, youth, older people and people with disabilities.

Synthetic biology

Synthetic biology is an interdisciplinary field that applies engineering principles to design and construct new biological parts, devices and systems or to redesign existing natural biological systems for various applications.

Summary

Synthetic biology can transform agrifood systems by engineering biological organisms for improved crop yields, enhanced resilience and sustainable production. It offers solutions like nitrogen-fixing crops, bio-based materials and microorganisms that can degrade pollutants or produce biofuels, contributing to food security and environmental sustainability.

However, synthetic biology is challenged by, mistrust, complex regulatory frameworks and potential ecological hazards. There are public concerns about unintended consequences, such as disrupting ecosystems or the ethical implications of engineering life forms. Transparency governance and risk assessments are critical for public acceptance and responsible use. Furthermore, equitable access must be prioritized.

While some regions, expect early benefits broader global scaling hinges on addressing regulatory, ethical and scalability issues and extends to 2040. Synthetic biology offers transformative potential, but its deployment must balance innovation with precautionary principles to ensure sustainable and equitable outcomes.

Examples: engineered microorganisms that can fix nitrogen in the soil, reducing the need for synthetic fertilizers, or bioengineered crops that sequester more carbon from the atmosphere.

Comparators (examples of contemporary solutions): traditional crop breeding and genetic modification techniques, reliance on chemical fertilizers, use of fossil fuels for energy and materials.

Main hopes: enhanced crops, sustainable biofuels, new waste solutions, addressing food security, economic growth, precision farming.

Some concerns: ecological consequences such as potential disruptions of existing ecosystems and biodiversity, regulations, public acceptance, responsible use, ethical concerns, dual-use, potential for disruption and workforce displacement and need for risk assessment and oversight.

Synthetic biology emerges as a groundbreaking field with transformative potential to revolutionize agrifood systems and address pressing global challenges. By engineering new organisms or modifying existing ones, synthetic biology offers the possibility of developing crops with enhanced nutritional value, disease resistance and tolerance to environmental stressors (Akbar *et al.*, 2022). These can contribute significantly to food security, especially in marginalized and resource-constrained regions. Moreover, these technologies and innovations could facilitate the production of sustainable biofuels and bio-based materials, reducing reliance on fossil fuels and promoting a circular economy. Synthetic biology's potential extends to waste management and environmental remediation through engineered microorganisms capable of degrading pollutants or converting waste into valuable resources. Developing novel bio-based products and processes could create new economic opportunities, stimulating innovation and job creation in various sectors. Synthetic biology could optimize resource utilisation and minimize environmental impact by enabling precision farming and tailored agricultural solutions.

Despite the promising prospects, applying synthetic biology in agrifood systems raises complex ethical, social and environmental considerations. The release of engineered organisms into the environment necessitates rigorous risk assessment and monitoring to prevent unintended ecological consequences and potential harm to biodiversity, which is nowadays a routine procedure in many places but may be a capacity issue in others. The development and commercialization of synthetic biology products face regulatory hurdles, including concerns regarding biosafety, intellectual property rights and public acceptance. Ensuring transparency and ethical oversight throughout the research and development process is crucial to fostering public trust and preventing the misuse of these powerful technologies and innovations. Synthetic biology applications' long-term environmental and health impacts warrant ongoing research and vigilance. It's essential to strike a balance between innovation and precaution, ensuring that the benefits of synthetic biology are realized responsibly and sustainably, while respecting natural processes and upholding ethical principles, aligned with well established international treaties.

In the 2024 survey, the average conduciveness scores for this technology were among the lowest in the set of 0.44 for inclusivity, 0.94 for sustainability, and 0.86 for resilience. These scores, suggest a negative perception of the participants about the positive contribution of this technology/innovation to all three dimensions of sustainable agrifood systems, although standard deviation was slightly higher than average, so there is no strong consensus about this. The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact before 2040.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: the 2023 report recognizes the transformative potential of synthetic biology in agriculture for enhancing crop yields, promoting sustainability and developing innovative solutions for environmental challenges. The report highlights the potential for revolutionizing agrifood systems, while the survey results reflect strong agreement on its weak impact on inclusivity, sustainability and resilience. The 2024 survey's and the FSN Forum participants were also cautious and did not rank high this PETIAS in terms of a positive impact on these three dimensions.

- Concerns and challenges: the 2023 report emphasizes ethical concerns, ecological consequences, regulatory hurdles and public acceptance, which are also prominent in the 2024 survey results.

- Impact timeline: the 2024 survey participants are more optimistic about the near-term impact, with many expecting significant developments before 2040. This is somewhat earlier than the 2046 horizon implied in our 2023 report.

Main areas of application

The main areas of application for synthetic biology listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Innovations in synthetic biology lead to microbes that can provide nitrogen directly to crops, reducing the need for synthetic fertilizers. This cuts costs for farmers and minimizes environmental harm from fertilizer runoff.
Processing systems	Design cell factories for bio-based production and bioremediation.
Energy and transportation	Engineer advanced biofuels and sustainable materials.
Food Waste	Reduce waste through enzyme and microbial engineering. Extend crop shelf life.
New materials, new proteins and circular economy	Design new biomaterials with improved properties, proteins and recycling processes.
One health and nutrition	Develop probiotics, vaccines and biosensors for disease detection.
Blue economy	Engineering marine organisms for biofuel and plastic production, improving aquaculture efficiency, developing microorganisms for environmental monitoring and remediation, creating sustainable fish feeds and supporting marine conservation efforts.

Access to science-based sustainability information

Access to science-based information on sustainability matters entails the development of systems and technologies and innovations that provide readily available, standardized and verifiable data on sustainable practices in individual institutions and companies as well as entire industries. This includes establishing science-based standards and facilitating transparent access to product-level sustainability information.

Summary

Providing access to science-based sustainability information is crucial for empowering stakeholders across the agrifood system. Transparent, verifiable data can drive informed decision-making, improve accountability and promote sustainable practices. By enabling stakeholders to track sustainability metrics, such systems foster trust, encourage innovation and support sustainable investments.

Challenges include ensuring the accuracy and reliability of the data, developing standardized metrics and avoiding the exclusion of smaller producers who may struggle with data collection requirements. There is also a risk of misinformation or biased data influencing decisions, making robust regulatory oversight essential. Ensuring accessibility to marginalized communities is key to promoting inclusivity.

Access to reliable sustainability information is fundamental to achieving more transparent, equitable and sustainable agrifood systems.

Examples: blockchain-based platforms for transparent and traceable sustainability data and AI-powered tools for assessing the environmental impact of agricultural practices.

Comparators (examples of contemporary solutions): reliance on traditional research publications and academic journals, expert consultations and industry-specific sustainability reports.

Main hopes: informed decisions, accountability, transparency-driven innovation, fostering trust, sustainable investments and an equitable agrifood system.

Some concerns: data reliability, biases, preventing new inequalities, the need for standardized metrics, the potential for misinformation, the need to consider diverse knowledge sources and inclusivity for smaller producers.

Establishing a system providing readily available, standardized and verifiable sustainability data presents a transformative opportunity for multiple sectors, including agriculture. This transparency fosters accountability, enabling producers and consumers to make informed choices aligned with sustainability goals. Governments and regulatory bodies gain the ability to monitor and enforce compliance with environmental standards, promoting fair competition for businesses and safeguarding natural resources. The availability of comprehensive, traceable product-level data could drive innovation and competition as companies strive to demonstrate their sustainability credentials. This system could empower marginalized communities and regions by providing them with the tools to assess products' environmental and social impact and make informed choices. Furthermore, access to science-based information facilitates the development of responsive and responsible technologies and innovations, promoting a shift towards sustainable production and consumption patterns. Consumers would also benefit from increased access to reliable information about the sustainability of products, empowering them to make informed choices. This increased transparency could foster public trust, encourage sustainable investments and contribute to a more equitable and resilient global agrifood system.

The implementation of such a system is not without challenges. The primary concern is ensuring the reliability and transparency of the information sources feeding into the system. Issues such as outdated data, misinformation, or biases could undermine the system's effectiveness and lead to misinformed decision-making. It is also important that the information provided considers different sources of knowledge and is open to feedback rather than delivering only one-way communications based on one paradigm. Establishing and maintaining standardized sustainability metrics and methodologies across diverse industries and regions is a complex task that requires collaboration and consensus-building. The system's implementation could have implications for the workforce, requiring new skills and potentially leading to shifts in job roles. Technological and innovation barriers, such as data management and accessibility, must be overcome to ensure the system's effectiveness and inclusivity. There is also the risk of creating new inequalities, particularly for smaller producers or those in remote regions who may lack the resources or capacity to meet stringent data reporting requirements. Addressing these challenges will require collaboration among scientists, policymakers, industry leaders, farmers and civil society to build a robust, transparent and equitable system that fosters sustainable transformation across sectors.

In the survey, it received very positive evaluations, with average conduciveness scores of 1.36 for inclusivity, 1.61 for sustainability, and 1.60 for resilience among top 5 PETIAS across all three dimensions. These scores, coupled with moderate standard deviations, suggest a very favourable perception of this technology/innovation's potential to contribute to sustainable agrifood systems, in fact this PETIAS was among 5 best in terms of average notes across the three dimensions. The estimated timeframe for significant impact leans towards a more optimistic outlook, with most respondents in most regions anticipating an impact before 2035.

Overall, the survey results indicate that participants view it positively, with a strong belief in its potential to foster inclusivity, sustainability and resilience in agrifood systems. The relatively consistent positive views across regions and dimensions, especially for sustainability, suggest that these technologies and innovations might be well-positioned for widespread adoption and impact. However, further research and monitoring will be necessary to track its progress and address any unforeseen challenges or trade-offs.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: both the 2023 report and the 2024 survey highlight the potential of providing access to science-based sustainability information to drive transparency, accountability and informed decision-making in the agri-food systems. The report emphasizes the role of standardized and verifiable data in fostering trust and promoting sustainable practices. At the same time, the survey results reflect strong support for its contribution to inclusivity, sustainability and resilience. The FSN Forum also reflects the high importance of this PETIAS for inclusion.

- Concerns and challenges: the 2023 report addresses challenges related to data reliability, biases, the risk of misinformation and inclusivity, which are much less emphasized in the 2024 survey. This may indicate a growing acceptance or confidence in addressing these concerns through technological advancements or frameworks.

- Impact timeline: the 2024 survey presents a more optimistic view, indicating before 2035 on average. This contrasts with the 2023 report's estimated time to mature in 2042.

Main areas of application

The main areas of application for access to science-based sustainability information listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Access reliable information and predict the effect on innovative practices associated with sustainability, thus reducing the risk to innovate and improve land management, optimize irrigation and implement regenerative practices.
Processing systems	Businesses can access data on sustainable sourcing and processing methods, reducing waste and promoting circularity.
Value chains and services	Stakeholders can track products, verify certifications and make informed purchasing decisions.
Energy and transportation	Information on renewable energy sources and efficient logistics can reduce the environmental impact of agriculture.
Food waste	Scientifically collected data on food waste can inform targeted interventions and raise consumer awareness.
Governance and trade	Policymakers can make evidence-based decisions, promote transparency and incentivize sustainable practices.
New materials, new proteins and circular economy	Information on sustainable materials and bio-based alternatives can drive innovation and reduce resource depletion while decreasing innovation risks.
One health and nutrition	Farmers and consumers can access information on healthy and sustainable food choices.
Blue economy	Stakeholders can access data on sustainable fishing practices and ocean health.
Inclusion of the most vulnerable	Providing accessible information empowers marginalized groups, promotes gender equality and supports indigenous knowledge systems.

Internet of Food

The Internet of Food (IoF) refers to the interconnected network of devices, sensors and data-driven technologies and innovations employed throughout the food supply chain.

Summary

The Internet of Food (IoF) integrates sensors, blockchain and AI to create a connected agrifood system, enhancing efficiency, traceability and sustainability. By providing real-time data on everything from production to consumption, IoF enables better resource management, reduces food waste and improves food safety. It also fosters transparency across the supply chain, empowering consumers and producers alike to make informed decisions.

Challenges include cybersecurity risks, data privacy concerns and the high energy demand required to maintain the network. Additionally, the complexity of IoF technologies and innovations can hinder adoption, particularly for small-scale farmers and marginalized communities. Ensuring equitable access to these technologies and innovations and addressing regulatory challenges will be critical to preventing the widening of the digital divide.

While some regions already see benefits, global implementation will depend on infrastructure development, policy support and capacity development. IoF holds the potential to reshape agrifood systems by improving transparency and driving sustainability, but it must be made accessible and secure for all.

Examples: blockchain-based traceability systems for food products, AI-powered analysis of real-time data from IoT sensors in food storage facilities to optimize temperature and humidity, smart packaging with embedded sensors to monitor food freshness and safety.

Comparators (examples of contemporary solutions): manual tracking and record-keeping in food supply chains, reliance on visual inspections for food quality and safety, traditional packaging with limited information

Main hopes: efficiency, transparency, sustainability across the supply chain, optimized resource use, reduced waste, improved food safety, traceability, fair labour practices, improved health and well-being.

Some concerns: cybersecurity, data privacy, fraud, energy demands, complexity hindering adoption, equitable access and regulatory frameworks needed.

The Internet of Food (IoF) offers transformative potential for the food industry, promising enhanced efficiency, transparency and sustainability across the supply chain. IoF enables real-time monitoring and data-driven decision-making in food production, distribution and consumption by integrating smart devices, sensors and data-driven technologies and innovations. This can lead to optimized resource utilisation, reduced food waste, improved food safety and enhanced traceability. For instance, farmers can use IoF to monitor crop health and soil conditions, allowing for precise irrigation and fertilisation. At the same time, consumers can access detailed information about the origin and quality of their food. Moreover, IoF can promote fair labour practices and equitable income distribution by providing transparency into supply chain operations and empowering producers and workers. This interconnected network can facilitate knowledge sharing and collaboration among stakeholders, fostering innovation and sustainable practices throughout the food ecosystem.

However, the reliance on a vast network of interconnected devices raises concerns about cybersecurity and data privacy, particularly regarding protecting sensitive food-related data. The energy demands of powering and maintaining this extensive network can be significant, potentially offsetting some environmental benefits. Additionally, the complexity of IoF technologies and innovations may pose barriers to adoption, particularly for those with limited technological literacy or resources. Ensuring equitable access to the benefits of IoF for all stakeholders, including small-scale farmers and marginalized communities, is crucial. Regulatory frameworks and international standards need to be developed to address these challenges and ensure the responsible and sustainable development of IoF. Furthermore, the potential for automation and data-driven decision-making to displace jobs in the food industry must be carefully considered and managed through appropriate policies and support mechanisms.

Results of the 2024 survey yielded positive evaluations, with average conduciveness scores of 1.19 for inclusivity, 1.46 for sustainability, and 1.44 for resilience. These scores, along with relatively low or very low standard deviations, suggest a general consensus among participants about the positive contribution of this technology/innovation, especially to sustainability (second best) and resilience (third best).

The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact before 2035.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: both the 2023 report and the 2024 survey acknowledge the transformative potential of the Internet of Food in improving efficiency, transparency and sustainability throughout the food supply chain. The report focuses on the role of IoF in real-time monitoring, data-driven decision-making and promoting fair labour practices. At the same time, the survey results reflect some support for its contribution to sustainability and resilience, a bit less so to inclusivity. The FSN Forum participants were more cautious also here, however, some considered this PETIAS as important for inclusion and resilience.
- Concerns and challenges: the 2023 report emphasizes cybersecurity, data privacy, complexity and equitable access. These concerns are less highlighted in the 2024 survey results, which suggest a focus on the benefits and possibly a perception of improved solutions to these issues.
- Impact timeline: many participants of the 2024 survey expect results before 2035. This is somewhat earlier than the report's maturity estimate for 2041.

Main areas of application

The main areas of application for the Internet of Food listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Processing systems	Ensures authenticity and manages inventory.
Value chains and services	Tracks food from farm to table, ensures authenticity, manages inventory and engages consumers with information.
Energy and transportation	Monitors cold chains and optimizes logistics for sustainability.
Food waste	Tracks food waste, monitors freshness and connects surplus food with needy organizations.
Governance and trade	Track products to verify ethical sourcing and fair compensation for farmers.
New materials, new proteins and circular economy	Monitor resource use and waste generation to identify opportunities for circularity.
Inclusion of the most vulnerable	Ensures provenance from smallholder farmers, women and youth.

Frugal innovation

Frugal innovation in agriculture entails the development of cost-effective, resource-efficient and contextually appropriate solutions to address agricultural challenges, particularly in resource-constrained settings.

Summary

Frugal innovation is a game-changer for agrifood systems, particularly in resource-constrained and marginalized regions. By focusing on cost-effective, resource-efficient and locally adaptable solutions, frugal innovation empowers communities to develop sustainable agricultural practices with limited resources. It fosters resilience, enabling smallholder farmers to access affordable technologies and innovations such as low-cost irrigation systems, mobile crop disease diagnosis and 3D-printed farm tools.

The value of frugal innovation lies in its ability to democratize access to technologies and innovations, driving social inclusion and capacity development. It supports local economies, reduces environmental impact and promotes sustainable practices, making it a critical driver of agricultural development in regions with limited access to capital or infrastructure.

While challenges include ensuring scalability and durability, frugal innovation remains essential for creating more equitable, sustainable agrifood systems. Its capacity to bring impactful, affordable solutions to those who need them most is expected to become reality by 2035.

Examples: low-cost solar-powered irrigation systems for smallholder farmers, mobile apps for crop disease diagnosis using AI and smartphone cameras, 3D-printed farm tools and equipment using recycled materials.

Comparators (examples of contemporary solutions): expensive and complex imported technologies and innovations, reliance on external expertise.

Main hopes: dustainability, accessibility, affordability, empowerment, local adaptation, social inclusion, knowledge sharing and capacity development.

Some concerns: potential for suboptimal solutions, effectiveness, durability, upfront investment needs, scalability limitations, regulatory barriers and IP issues.

Frugal innovation in agriculture presents a promising pathway towards sustainable development, particularly for resource-constrained regions and marginalized communities. By emphasising resource efficiency, affordability and local adaptation, frugal innovation not only makes the innovations more affordable and accessible to smallholders and marginalized communities but can also empower farmers to overcome challenges and improve their livelihoods. This approach fosters creativity and problem-solving, leading to the development of contextually relevant solutions that address specific needs. Moreover, frugal innovation can promote social inclusion by involving local communities in designing and implementing agricultural solutions, enhancing their ownership and agency. This participatory approach can also contribute to community knowledge sharing and capacity development. Furthermore, frugal innovation aligns with sustainability goals by minimising resource use, reducing waste and promoting environmentally friendly practices.

While frugal innovation's emphasis on affordability and accessibility can enhance food security in resource-limited regions, this focus may also lead to adopting suboptimal solutions prioritizing immediate benefits over long-term sustainability and scalability. Additionally, while frugal innovation can empower local communities, it may also require significant upfront investments in research, development and capacity development. Ensuring equitable access to funding and support for this innovation initiative is essential. Moreover, the focus on local adaptation might limit the scalability and transferability of frugal innovations to other contexts. Developing knowledge-sharing mechanisms and scaling up successful frugal innovations is crucial for maximising their impact.

Frugal innovation garnered extremely positive evaluations in the survey, with average conduciveness scores of 1.81 for inclusivity, 1.83 for sustainability, and 1.75 for resilience. These scores are however coupled with relatively high standard deviations. Nonetheless, no other PETIAS was assessed as favourably as frugal innovation, especially due to its high inclusivity. Generally, frugal innovation was the best of the set across all the conduciveness metrics. The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact before 2035.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: both the 2023 report and the 2024 survey recognize the high role of frugal innovation in promoting sustainable agricultural practices, particularly in resource-constrained settings. The report emphasizes its role in enhancing sustainability, accessibility and social inclusion. At the same time, the survey results reflect extremely positive views on its potential to improve inclusion, sustainability and resilience in the agrifood systems. The FSN Forum participants also considered this PETIAS as important, but with some reservations.
- Concerns and challenges: the 2023 report highlights the potential for suboptimal solutions, the need for upfront investment and regulatory barriers. These challenges are not featured in the 2024 survey results, suggesting either a shift in focus toward the benefits or a belief that these challenges are manageable.
- Impact timeline: the 2024 survey aligns with the 2023 report, with many participants expecting results before 2035, similar to the original 2034 ETM.

Main areas of application

The main areas of application for frugal innovation listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Processing systems	Low-cost sensors for precision agriculture, mobile apps for farm management, DIY hydroponics and soil restoration techniques.
Value chains and services	Energy-efficient tools, local resources and traditional knowledge for small-scale processing operations.
Food waste	Simple storage solutions and community-based food sharing.
Governance and trade	Accessible platforms/ social media for information and policy dialogue on sustainable solutions in the agrifood systems.
New materials, new proteins and circular economy	New sources of protein from traditional practices: driftwood, plants, algae, etc.
One health and nutrition	Affordable, locally sourced supplements promoting traditional diets.
Blue economy	Sustainable fishing and aquaculture techniques.

Digital twins

In agriculture, digital twins can be applied to various aspects such as crops, livestock and farms.

Summary

Digital twins offer a powerful tool for agrifood systems by creating virtual models that mirror physical assets and processes. This allows farmers, processors and supply chain managers to simulate scenarios, optimize resource use and make real-time informed decisions. Digital twins can improve efficiency in precision agriculture, monitoring equipment performance and forecasting environmental impacts.

However, implementing digital twins faces significant challenges, including high costs, data management complexities and the need for advanced technical skills. Access to reliable infrastructure and data-sharing protocols must also be addressed to prevent unequal adoption, particularly in less developed regions.

Digital twins are expected to have a significant impact by 2035.

Examples: digital twins of livestock to monitor individual animal health and behaviour, virtual models of food processing plants to optimize production flows and energy efficiency and digital replicas of entire farms to simulate and predict the impact of different management practices.

Comparators (examples of contemporary solutions): physical prototyping and testing, reliance on historical data and experience for decision-making, limited ability to simulate and predict complex scenarios.

Main hopes: optimization, real-time monitoring, analysis, prediction, improved resource management, decision-making, productivity and sustainability.

Some concerns: complexity hindering adoption, equitable access, cost, expertise/infrastructure/energy needs, overreliance on models, bias, inaccurate predictions and data privacy.

Digital twin technology in agriculture offers a powerful tool for optimising complex systems and processes. By creating virtual replicas of physical assets and systems, digital twins enable real-time monitoring, analysis and prediction of outcomes. This can lead to improved resource management, enhanced decision-making and increased productivity across various agricultural domains. For instance, digital twins of crop fields can simulate growth patterns under different environmental conditions, allowing farmers to optimize planting schedules, irrigation and fertilisation strategies. This can result in higher crop yields, reduced resource inputs and minimized environmental impact. Additionally, digital twins can aid in the early detection and prevention of diseases and pests, improving crop health and reducing the need for chemical interventions.

However, implementing digital twin technologies and innovations in agriculture also poses some challenges. Integrating such complex technologies and innovations into agricultural practices may create barriers to adoption among farmers with limited technological literacy or resource constraints. Ensuring equitable access and adequate training and support are crucial for widespread adoption, particularly among marginalized communities. Additionally, developing and maintaining digital twins require specialized expertise and infrastructure, which may be costly and limit accessibility for smaller agricultural operations. Another concern is the potential for overreliance on models and simulations, neglecting the importance of on-the-ground knowledge and experience. Data privacy and ownership concerns arise, especially when sensitive agricultural data is collected and analysed. Robust data governance frameworks and security measures are necessary to protect farmers' interests and prevent misuse of information. Furthermore, the environmental impact of these technologies and innovations, including energy consumption and electronic waste generation, should be considered when pursuing sustainable agricultural practices.

Digital twins also received moderate evaluations, with average conduciveness scores of 0.75 for inclusivity, 1.22 for sustainability, and 1.23 for resilience. These scores, along with relatively low standard deviations, suggest a general consensus among participants about the mildly positive contribution of this technology/innovation to the future global agri-food system. Similar to several previous technologies/innovations, it appears that its perceived low inclusiveness affects its rating negatively.

The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact around 2035.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

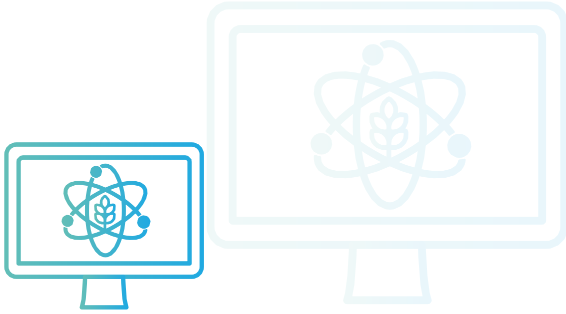
- Alignment on potential: the 2023 report acknowledges the transformative potential of digital twins in agriculture for optimizing resource management, enhancing decision-making and promoting sustainability. The report emphasizes their real-time monitoring and prediction role, while the survey results reflect cautious views on their contribution. To the contrary, the 2024 survey results are more moderate, while the FSN Forum participants did not consider this PETIAS as positively impactful on these three dimensions.

- Concerns and challenges: the 2023 report highlights concerns about the complexity of adoption, high costs, the need for technical expertise and potential overreliance on models. These challenges are somewhat reflected in the survey's inclusivity ratings and variability, indicating some participant reservations.
- Impact timeline: the 2024 survey indicates a slightly more optimistic timeline than the 2023 report's estimated maturity date of 2045, with many participants expecting a significant impact before 2035. However, this optimism is tempered in some regions.

Main areas of application

The main areas of application for the digital twins listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Optimize irrigation, fertilizer use and pest control for more than one weather scenario.
Processing systems	Optimize processes and equipment maintenance schedules for improved efficiency and reduced downtime, ensuring continuous improvement.
Value chains and services	Optimize logistics to ensure food safety.
Energy and transportation	Model energy use across the agrifood systems and optimize transportation.
Food waste	Identify waste reduction.
Governance and trade	Policymakers can make evidence-based decisions, promote transparency and incentivize sustainable practices.
One health and nutrition	Model disease spread, optimize animal and plant health and personalize nutrition.
Blue economy	Accelerate bio-based materials and protein alternatives.
Inclusion of the most vulnerable	Simulate ocean conditions and ecosystems.



Quantum internet and computing applied to agrifood systems

Quantum internet and computing, harnessing the principles of quantum mechanics, offer the potential to revolutionize agrifood systems through enhanced computational power and secure communication networks.

Summary

Quantum internet and computing hold the potential to revolutionize agrifood systems by offering unprecedented computational power and secure data transmission. These technologies and innovations could enable more accurate simulations, optimize complex supply chains and improve decision-making processes, especially for large-scale agricultural operations. Quantum computing's ability to process vast datasets could lead to breakthroughs in crop modelling, climate impact predictions and resource management.

However, these technologies and innovations remain in the early stages of development and face challenges in practical application within the agrifood systems: high costs, specialized infrastructure and the need for advanced technical expertise limit current feasibility. Widespread adoption in agriculture may not occur until after 2040, with progress dependent on further technological advances and reduced barriers to entry.

While quantum computing promises to transform agrifood systems in the long term, its impact is still distant, requiring significant advancements before it can be applied effectively in the field.

Examples: quantum algorithms for optimising complex breeding programmes to develop crops with desired traits, quantum sensors for real-time monitoring of soil nutrient levels at unprecedented precision and quantum-secure communication networks for protecting sensitive agricultural data.

Comparators (examples of contemporary solutions): classical computing for data analysis and modelling, traditional communication networks, limitations in computational power and data security.

Main hopes: revolutionising efficiency, productivity, sustainability, precision agriculture, optimized resource use, faster R&D, improved supply chains and reduced environmental impact.

Some concerns: high costs, market disruption, expertise needs, widening inequalities, energy use, data security, regulations, workforce impact and neglecting traditional knowledge.

The integration of quantum computing into the agrifood systems has the potential to initiate a revolutionary shift towards unprecedented levels of efficiency, productivity and sustainability. Its superior processing power could enable highly accurate and rapid data analysis, leading to improved decision-making across the entire food value chain and agrifood system. In precision agriculture, quantum computing could facilitate real-time monitoring and analysis of vast datasets related to soil conditions, weather patterns and crop health, allowing for optimized resource allocation, pest and disease management and yield prediction. This could significantly enhance food production efficiency and reduce environmental impact by minimising the use of fertilizers, pesticides and water. Additionally, quantum computing's computational power could accelerate research and development in crop and animal science, leading to more resilient and nutritious varieties bolstering global food security. The potential for advancements in supply chain optimisation and logistics management could also streamline food distribution, reducing waste and ensuring food reaches consumers in a timely and efficient manner.

However, the high costs and specialized expertise required for quantum computing infrastructure present a significant barrier to entry, potentially widening the gap between large-scale agricultural enterprises and smallholder farmers. This could exacerbate existing inequalities and create a technological divide within the agrifood systems. Furthermore, the immense processing capabilities of quantum computers raise concerns about energy use and data security and privacy, necessitating robust encryption and data protection mechanisms to safeguard sensitive agricultural information. Regulatory frameworks must evolve to address the unique challenges of quantum computing technologies and innovations, ensuring responsible and ethical use. The potential impact on the workforce, with automation and data-driven decision-making potentially displacing traditional agricultural jobs, necessitates proactive measures to facilitate upskilling and retraining programmes. Moreover, over-reliance on quantum computing could lead to a neglect of traditional agricultural knowledge and practices, potentially undermining the resilience and adaptability of the agrifood system.

As far as the results of the 2024 survey go, the feedback was lower than average, with conduciveness scores of 0.53 for inclusivity, 1.06 for sustainability, and 1.06 for resilience. These scores, along with relatively high standard deviations, suggest that the positive contribution of this technology/innovation is controversial. Low results in three metrics point to important risks along the way of potential implementation of quantum into agriculture. The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact before 2040.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: the 2023 report acknowledges the revolutionary potential of quantum internet and computing in transforming agrifood systems through enhanced data processing, secure communication and real-time analysis. The report highlights its ability to revolutionize efficiency and decision-making, while the survey results indicate a positive perception of its contribution to sustainability. Also here, the 2024 survey and FSN Forum results are much more cautious, with none or very few of the participants considering this PETIAS as positively impactful on inclusion, sustainability and resilience.

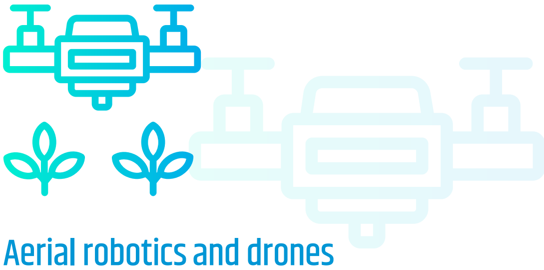
- Concerns and challenges: the 2023 report emphasizes significant problems, including high costs, the need for specialized expertise, the potential for widening inequalities and regulatory challenges. These concerns are reflected in the survey's low ratings, for all the three dimensions, indicating participants' awareness of potential barriers to widespread adoption.

- Impact timeline: the 2024 survey suggests a more optimistic timeline for the impact of quantum technologies and innovations, with many participants expecting significant developments before 2040, which is slightly earlier than the 2023 report's estimated maturity date of 2047.

Main areas of application

The main areas of application for Quantum internet and computing applied to agrifood systems listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Optimizes resource allocation, crop yields and environmental impact in precision, vertical and regenerative farming beyond the present level of complexity.
Processing systems	Processing systems Designing efficient algorithms for sorting, grading and processing of food products.
Value chains and services	Enhance supply chains, logistics and financial risk modelling.
Energy and transportation	Optimize biofuel production and transportation routes.
Food waste	Predict spoilage and develop preservation techniques.
Governance and trade	Tailoring dietary and food safety recommendations based on individual genetic and metabolic profiles while assessing food safety risks and proposing mitigation strategies.
One health and nutrition	Model disease spread, optimize animal and plant health and personalize nutrition.
New materials, new proteins and a circular economy	Accelerate the design of sustainable materials and proteins.
Blue economy	Improve fisheries management and environmental monitoring.



Aerial robotics and drones

Aerial robotics and drones leverage unmanned aerial vehicles (UAVs) equipped with sensors, robotics and AI capabilities to perform various tasks in agriculture.

Summary

Aerial robotics and drones are increasingly crucial in agrifood systems to enhance precision agriculture. By providing real-time data on crop health, irrigation needs and pest infestations, drones enable farmers to make more informed decisions, reduce input costs and improve yields. These technologies and innovations also offer valuable applications in monitoring large-scale agricultural operations and delivering inputs to remote or hard-to-reach areas.

However, challenges remain regarding high upfront costs, regulatory hurdles and the need for skilled operators. Additionally, data privacy concerns and infrastructure requirements may limit the adoption of drones, particularly for smallholder farmers in developing regions. Overcoming these barriers will be crucial for ensuring equitable access to drone technologies and innovations in agriculture.

While the potential of aerial robotics is clear, widespread adoption depends on addressing these challenges and ensuring that the benefits reach diverse agricultural contexts. With continued advancements, drones can play a significant role in driving efficiency and sustainability in agrifood systems.

Examples: swarms of autonomous drones for precision pollination or targeted pesticide application, drones equipped with hyperspectral cameras for early crop stress detection and drone-based delivery systems for agricultural inputs in remote areas.

Comparators (examples of contemporary solutions): manual aerial surveys and crop scouting, ground-based application of pesticides and fertilizers, limited access to remote or difficult-to-reach areas.

Main hopes: efficiency, precision, sustainability, real-time data, optimized interventions, wildlife conservation and monitoring, labour safety, biodiversity management and food security.

Some concerns: privacy, safety risks, scalability favouring larger entities, environmental impact (materials used in construction, electronic waste), technological barriers, noise/pesticide drift.

Aerial robotics and drones have the potential to significantly enhance efficiency, precision and sustainability across a wide range of agricultural applications. These technologies and innovations, equipped with advanced robotics, sensor technologies, artificial intelligence and communication systems, can autonomously navigate and execute tasks in crop fields and orchards. This autonomy facilitates the collection of real-time data on crop health, soil conditions and pest infestations, enabling farmers to make data-driven decisions and optimize resource allocation. Additionally, aerial robotics can perform precise interventions, such as targeted spraying of pesticides and fertilizers, reducing chemical use and minimising environmental impact. These technologies and innovations can also improve labour safety by automating hazardous tasks and reducing human exposure to chemicals. Their potential extends to managing biodiversity and food security, offering innovative solutions for monitoring ecosystems, tracking wildlife populations and assessing crop yields in remote areas (Tanaka *et al.,* 2022).

However, adopting aerial robotics and drones in agriculture also presents several trade-offs and risks. Privacy concerns arise from the collection of data through aerial surveillance, potentially impacting the privacy of individuals and communities, particularly in marginalized regions with limited technological literacy. Safety risks are associated with the operation of drones in shared airspace, necessitating robust regulations and air traffic management systems to prevent accidents and ensure public safety. Furthermore, the scalability and affordability of aerial robotics may favour larger agricultural enterprises, potentially sidelining small-scale farmers and exacerbating existing inequalities. The environmental impact of manufacturing and disposing of these technologies must be carefully considered to ensure sustainable life cycle management. Technological barriers, including battery life and payload capacity limitations, must be overcome to expand the range of applications, ensuring the availability of replacement parts and maintenance services in remote communities. Potential impacts on lateral fields, such as noise pollution and unintended pesticide drift, must be assessed and mitigated.

Aerial robotics and drones received mixed to positive evaluations in survey, with average conduciveness scores of 0.69 for inclusivity, 1.11 for sustainability, and 1.08 for resilience. These scores, along with relatively low standard deviations, suggest a general consensus among participants about the moderate contribution of this technology/innovation to sustainability of agrisfood systems. Similar to several previous technologies/innovations, it appears to be perceived with caution in terms of its potential to enhance inclusivity.

The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact before 2035.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: the 2023 report acknowledges the transformative potential of aerial robotics and drones in enhancing agricultural efficiency, precision and sustainability. The report emphasizes their role in providing real-time data and improving labour safety, while the survey results reflect positive views on their contributions to inclusivity, sustainability and resilience. The FSN survey results were more negative. The FSN Forum participants were also cautious, with only a few mentioning it as impactful on these three dimensions.
- Concerns and challenges: the 2023 report highlights concerns about privacy, safety, environmental impact and accessibility. These concerns appear to be somewhat reflected in the survey's ratings, particularly in the low score for inclusivity, indicating some reservations about these technologies and innovations' broad adoption and impact.
- Impact timeline: the 2024 survey suggests a slightly less optimistic timeline for significant impact than the 2023 report's estimated maturity date 2035.

Main areas of application

The main areas of application for aerial robotics and drones listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Monitoring and optimizing operations in food processing plants.
Processing systems	Tracking shipments, delivering products and providing crop insurance services.
Value chains and services	Inspecting infrastructure, delivering goods and monitoring transportation routes.
Energy and transportation	Optimize biofuel production and transportation routes.
Governance and trade	Monitoring illegal activities, enforcing regulations and facilitating fair trade.
One health and nutrition	Monitoring animal health, delivering medical supplies and mapping disease outbreaks.
Blue economy	Monitoring ocean health, tracking marine life and managing fisheries.

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New methods for controlling gene expression

Pre-emerging and emerging technologies and innovations for controlling gene expression, such as CRISPR-Cas9 gene editing and RNA interference, enable precise manipulation of gene activity. While gene editing is not new, its applications in agriculture are rapidly evolving and expanding, representing an area of significant innovation.

Summary

New methods for controlling gene expression offer promising tools for improving crop traits such as yield, disease resistance and environmental resilience. They allow for targeted interventions in crop development and livestock breeding. These innovations could reduce the need for chemical inputs and enhance food security by creating crops better suited to changing climates.

However, concerns about the ecological impact of gene-editing technologies and innovations, regulatory oversight and public acceptance pose significant challenges. Ethical questions about manipulating genetic material and potential unintended consequences in ecosystems must be addressed through thorough risk assessments and transparent governance.

Though early breakthroughs are promising, broader adoption will depend on overcoming regulatory barriers and gaining societal trust. The full potential of these technologies and innovations in agrifood systems may not be realized before 2040, but they represent a key frontier in sustainable agriculture.

Examples: CRISPR-Cas9 gene editing for developing crops with enhanced drought resistance or improved nutritional content, RNA interference (RNAi) for targeted pest control without harming beneficial insects and epigenetic modifications for fine-tuning gene expression in response to environmental changes.

Comparators (examples of contemporary solutions): traditional breeding techniques, random mutagenesis, limited ability to precisely target and modify genes.

Main hopes: enhanced crops (nutrition, disease resistance, stress tolerance), food security, sustainable farming and economic growth.

Some concerns: long-term consequences, unintended modifications, ecological disruptions, reduced or neglected biodiversity, regulations, public acceptance, corporate control and equitable access.

Advanced gene expression control techniques, including gene editing, promise significant advancements across various fields, including agriculture. The precision afforded by these methods enables targeted modification of genes, offering the potential to develop crops with enhanced nutritional value, disease resistance and tolerance to environmental stressors. This can bolster food security, especially in regions facing challenges due to climate change or resource limitations. In agriculture, precise gene editing could reduce the reliance on chemical inputs, promoting sustainable farming practices and minimising environmental impact. These innovations could stimulate economic growth by creating new industries and high-skill jobs.

However, applying new methods for controlling gene expression also raises ethical, social and environmental concerns. The long-term consequences of altering genetic information are not fully understood and potential risks, such as unintended genetic modifications or ecological disruptions, must be carefully assessed. Establishing clear regulatory frameworks and ethical guidelines is crucial to navigating complexities and ensuring the responsible use of these powerful tools. Moreover, public acceptance and understanding of these technologies and innovations remain critical for their widespread adoption. Effective science communication and public engagement are needed to foster informed discussions and address concerns surrounding gene editing.

Additionally, the concentration of these powerful technologies and innovations in the hands of a few corporations or institutions raises concerns about equitable access and potential socioeconomic disparities. Striking a balance between innovation, regulation and public engagement is crucial for harnessing the benefits of new methods for controlling gene expression while minimising potential risks and ensuring their responsible and equitable use.

New methods for controlling gene expression did not get a positive review in the survey, with average conduciveness scores of just 0.47 for inclusivity, 1.00 for sustainability, and 1.03 for resilience. These scores, along with relatively high standard deviations (1.73-1.78), suggest controversy among participants about the positive contribution of this technology/innovation to all three dimensions of sustainable agrifood systems. Similar to synthetic biology, it appears that trust in the benefits this PETIAS is still low.

The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact before 2040.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: the 2023 report recognizes the transformative potential of new methods for controlling gene expression in enhancing crop traits, contributing to food security and promoting sustainable farming practices. The report focuses on their ability to improve nutritional value, disease resistance and tolerance to environmental stressors. At the same time, the survey results reflect negative views on their contribution to inclusion, sustainability and resilience. Only a few among the FSN Forum participants mentioned this PETIAS as potentially positively impactful on resilience.

- Concerns and challenges: the 2023 report emphasizes significant problems, including potential unintended genetic modifications, ecological disruptions, ethical considerations and regulatory challenges. These concerns are mirrored in the survey's low rating among all the three mterics, indicating some reservations or uncertainties about the broad adoption and potential long-term impacts of these technologies and innovations.

- Impact timeline: in the 2024 survey many participants expect significant developments before 2040. This is earlier than the 2023 report's estimated maturity date of 2046.

Main areas of application

The main areas of application for new methods for controlling gene expression listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Enhance precision agriculture, optimize vertical farming and support regenerative practices.
Food waste	Reduce waste through enzyme and microbial engineering. Extend crop shelf life.
New materials, new proteins and circular economy	Design new biomaterials with improved properties, proteins and recycling processes.
One health and nutrition	Develop probiotics, vaccines and biosensors for disease detection.
Blue economy	Improve aquaculture species and seafood production.

Global logistics network

The global logistics network refers to the complex, interconnected and standardized system facilitating the movement of goods and services across international borders. Pre-emerging and emerging technologies and innovations, such as blockchain, AI and quantum computing, can enhance efficiency, transparency and sustainability within this network.

Summary

A global logistics network, driven by advancements in connectivity and automation, has the potential to revolutionize agrifood systems by optimizing the transportation and distribution of food products. This network can enhance efficiency, reduce food waste and improve traceability across supply chains, ensuring that food reaches markets more quickly and with fewer losses. It also offers opportunities for better integration of smallholder farmers into global markets, increasing their access to new opportunities.

However, significant challenges remain, including high infrastructure costs, data management complexities and the need for international collaboration on regulatory frameworks. Ensuring that marginalized communities benefit from these improvements is essential to avoid widening inequalities in access to markets and resources.

While the technologies and innovations, as well as infrastructure required for a global logistics network, are still developing, their impact is expected to materialize by 2035. Overcoming regulatory, logistical and cost barriers will be critical to unlocking its full potential in transforming agrifood systems.

Examples: AI-powered optimization of shipping routes and schedules to reduce food waste during transportation, blockchain-based platforms for transparent and secure documentation of food product journeys and autonomous cargo ships and trucks for more efficient and sustainable food distribution.ssion in response to environmental changes.

Comparators (examples of contemporary solutions): IT systems with limited integration and data sharing capabilities, reliance on centralized decision-making, challenges in real-time tracking.

Main hopes: efficiency, cost reduction, faster delivery, improved access, fair trade, ethical sourcing, economic growth and international cooperation.

Some concerns: increased emissions, equitable access, data privacy/security, job displacement, infrastructure investment favouring the wealthy, regulatory barriers and disruption vulnerability.

Implementing a global logistics network, facilitated by pre-emerging and emerging technologies and innovations like blockchain, AI and quantum computing, promises significant advantages. This interconnected system could streamline transportation, distribution and supply chains, leading to heightened efficiency, cost reduction and swifter delivery times. Such enhancements could improve access to goods and services, benefiting remote and marginalized communities and fostering social equity. The transparency inherent in blockchain technologies and innovations could further promote fair trade, mitigate corruption and ensure ethical product sourcing, positively impacting workers' rights, environmental sustainability and consumer trust. Additionally, this network could stimulate international trade and cooperation, driving economic growth and cross-border knowledge exchange, thereby contributing to several Sustainable Development Goals.

However, the establishment of a global logistics network also presents notable challenges. Increased transportation could elevate carbon emissions, harm biodiversity and hinder climate change efforts. Ensuring equitable access to the network's benefits for all stakeholders, especially small-scale farmers and marginalized communities, is crucial to prevent widening existing disparities. The network's reliance on complex technologies and innovations introduces concerns around data privacy, security and potential job displacement due to automation. Moreover, the system's development demands substantial investment in infrastructure and resources, potentially favouring wealthier nations and regions. Promoting local and territorial agrifood systems and value chains could also be hindered. Regulatory barriers and the need for international cooperation pose additional hurdles. The network's intricate nature also makes it susceptible to disruptions from conflicts, natural disasters or cyberattacks, potentially causing widespread shortages and economic instability.

Global logistics network did only get a moderate review in the survey, with average conduciveness scores of just 0.83 for inclusivity, 1.36 for sustainability, and 1.31 for resilience. These scores, along with relatively high standard deviations in resilience and inclusivity place it in the medium part of the PETIAS' set.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: the 2023 report recognizes the potential of a global logistics network to enhance efficiency, transparency and sustainability in food supply chains. The report emphasizes its role in optimizing transportation and distribution while addressing challenges like emissions and data privacy. The survey and the FSN Forum reflect a more cautious view, with moderate ratings for its potential impact on inclusivity, sustainability and resilience.
- Concerns and challenges: the 2023 report highlights concerns, including increased emissions, equitable access and the need for regulatory frameworks, which align with the survey's quite low ratings and variability in responses. This suggests ongoing concerns about the environmental and socioeconomic implications of developing a global logistics network.
- Impact timeline: the 2024 survey suggests a more optimistic timeline for significant impact than the 2023 report's estimated maturity date 2042, with many participants expecting developments before 2035.

Main areas of application

The main areas of application for the global logistics network listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Energy and transportation	Efficiently transports biofuel feedstocks and distributes finished products. Preserve perishable goods during transportation, reducing food waste.
Food waste	Connects surplus food with those in need and optimizes logistics to reduce spoilage.
Governance and trade	Streamlines international trade and ensures food safety compliance.
One health and nutrition	Distributes vaccines and improves access to nutritious food.
Blue economy	Enables global seafood distribution and supports aquaculture.
Inclusion of the most vulnerable	Improves distribution for smallholder farmers and promotes rural development.

Territorial or landscape value chain and food-to-consumer economy policies

Territorial or landscape value chains represent an emerging food production and distribution approach prioritizing localized supply chains and sustainable resource management within specific geographical areas. Food-to-consumer economy policies are increasingly gaining traction.

Summary

Territorial or landscape value chain policies focus on strengthening local agrifood systems by promoting regional integration and sustainability. These policies aim to enhance the linkages between producers, processors and consumers within specific geographic areas, supporting localized economies. By shortening supply chains and emphasizing local products, such policies can improve food security, reduce environmental impact and foster community resilience.

However, implementing these policies faces challenges, including aligning diverse stakeholders, addressing regional inequalities and ensuring consistent policy support. Successful adoption requires investment in local infrastructure, capacity development and equitable distribution of resources to ensure that smallholders and marginalized communities benefit from these changes.

With growing interest in sustainable and localized agrifood systems, the impact of these policies could be felt as early as 2035. However, their success will depend on creating inclusive frameworks that balance economic, environmental and social goals.

Examples: online platforms for direct sales of agricultural products from local farmers to consumers, community-supported agriculture (CSA) programmes and policies incentivising using locally sourced ingredients in food processing.

Comparators (examples of contemporary solutions): globalized agrifood systems, long and complex supply chains and the dominance of large-scale retailers and food processors.

Main hopes: sustainability, resilience, equity, local economies, jobs, social cohesion, traceability, transparency, reduced emissions, sustainable land management and empowerment.

Some concerns: balancing local/global trade, scalability/efficiency, infrastructure investment in underserved areas, regulations, workforce adaptation and existing supply chain disruption.

The adoption of territorial or landscape value chain and food-to-consumer economy innovations offers a promising pathway toward a more sustainable, resilient and equitable agrifood systems. These innovations can stimulate regional economies, create jobs and foster social cohesion by emphasizing local resources and production potential (Reynolds *et al.,* 2021). Shortening supply chains through direct sales to consumers can enhance food traceability and transparency, allowing consumers to make more informed choices and supporting local producers. This model can also reduce food miles and associated carbon emissions, contributing to climate change mitigation and promoting environmental sustainability. Moreover, by valuing local ecosystems and biodiversity, these innovations can incentivize sustainable land management practices, protect natural resources and enhance food security in the long term. Particularly in marginalized and remote communities, territorial value chains can empower local producers, preserve traditional knowledge and foster economic self-sufficiency. By promoting a greater connection between producers and consumers, these policies can also enhance food appreciation and encourage healthier dietary choices.

However, balancing local self-sufficiency with global trade dynamics can be complex, potentially impacting international market access and economic competitiveness. Ensuring the scalability and efficiency of regional production systems to meet growing food demands is crucial. Additionally, these innovations may require significant infrastructure, logistics and marketing investments to support local value chains. Regulatory frameworks and standards must be adapted to facilitate direct producer-consumer interactions while ensuring food safety and quality. The workforce in the agricultural sector may also face challenges as they adjust to new production and distribution models. Moreover, the transition towards localized agrifood systems may disrupt existing supply chains and impact the livelihoods of those involved in long-distance trade. Careful planning and stakeholder engagement are essential to manage these transitions and ensure equitable outcomes for all actors in the agrifood system.

In the 2024 survey, it received highly positive evaluations, with average conduciveness scores of 1.42 for inclusivity, 1.67 for sustainability, and 1.64 for resilience (third best for inclusivity and sustainability). These scores, along with some of the highest standard deviations, indicate a greater degree of consensus and positive opinions among participants compared to some of the previous technologies (top third PETIAS across all three dimensions). The estimated timeframe for significant impact also reflects this uncertainty, with a broader range of responses compared to some of the earlier technologies and innovations.

A significant proportion predicts a timeframe before 2035. This suggests that these technologies and innovations' adoption and impact might be subject to more complex and uncertain factors, including technological advancements, market dynamics and social acceptance. While promoting sustainability and local economies, these innovations face challenges in balancing local and global trade dynamics. Ensuring the scalability and efficiency of localized agrifood systems to meet growing demands can be complex. Additionally, the transition towards these models may disrupt existing supply chains and impact livelihoods tied to long-distance trade, highlighting the need for careful planning and equitable transition strategies.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: both the 2023 report and the 2024 survey acknowledge the significant role of these innovations in fostering local economies, food security, inclusivity and sustainability. The report emphasizes preserving cultural heritage and community involvement, while the survey highlights their ability to enhance sustainability, resilience and inclusiveness. According to the FSN Forum participants, this PETIAS is the most impactful on inclusion, while several mentioned also its potential importance for resilience.

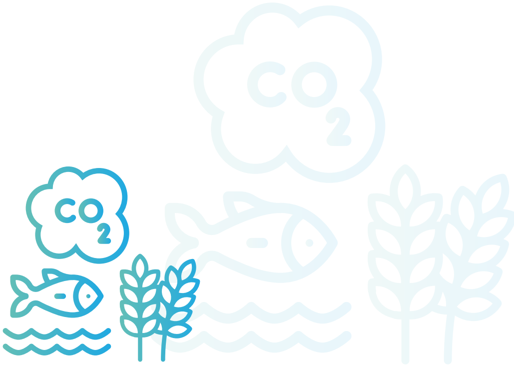
- Challenges and concerns: the report identifies potential challenges, including scalability, market access and the potential for protectionism, which are less visible in the survey's positive inclusivity and sustainability ratings. This suggests a shared understanding of the benefits in ensuring effective integration and beneficial outcomes of these innovations.

- Impact timeline: the survey indicates a slightly later expected impact compared to the report's estimated maturity date 2034, with many anticipating developments before 2035. This divergence may reflect regional variations in the adoption of these innovations or advancements in local agrifood systems initiatives.

Main areas of application

The main areas of application for territorial or landscape value-chain and food-to-consumer economy innovations listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Supports sustainable land management, connects urban farmers to local consumers and fosters regenerative practices.
Processing systems	Promotes local, smaller-scale processing and value-added products.
Value chains and services	Shortens supply chains, increases transparency and supports fair prices for farmers.
Energy and transportation	Reduces emissions by minimizing transportation distances and promoting local energy sources.
Food waste	Improves coordination between producers and consumers, reducing waste and facilitating local use of surplus food.
Governance and trade	Strengthens local agrifood systems and promotes fair trade policies.
New materials, new proteins and circular economy	Encourages local circularity.
One health and nutrition	Improves access to fresh, nutritious food and supports healthy diets.
Blue economy	Connects coastal communities with local seafood producers and promotes sustainable practices.
Inclusion of the most vulnerable	Empowers smallholder farmers, women, youth, elderly and Indigenous peoples by giving them direct access to markets and increasing control over their livelihoods.



Carbon credits in agriculture and aquaculture

Carbon credits in agriculture and aquaculture represent tradable units, signifying reducing or removing greenhouse gas emissions. Emerging carbon credit frameworks leverage innovative technologies and innovations, such as blockchain and remote sensing, to enhance transparency, accuracy and efficiency in carbon accounting and verification.

Summary

Carbon credits in agriculture and aquaculture provide a market-based approach to incentivize sustainable practices that reduce greenhouse gas emissions. By allowing farmers and aquaculture operators to earn credits for carbon sequestration or emission reductions, these systems can drive investments in regenerative agriculture, agroforestry and sustainable aquaculture. This mechanism helps align economic incentives with climate goals, offering a pathway to scale environmentally friendly practices.

However, challenges include accurately measuring and verifying carbon sequestration, ensuring fair participation for smallholders and creating equitable access to carbon markets. The regulatory frameworks governing carbon credits are still evolving and the risk of market exclusion for marginalized communities remains a concern.

While carbon credit systems are already gaining traction, their full potential in agriculture and aquaculture is expected to be realized by 2040. Ensuring transparency, equitable access and robust verification systems will be vital to maximizing their impact on sustainability.

Examples: bockchain-based platforms for transparent and traceable carbon credit accounting, remote sensing technologies and innovations for accurate measurement of carbon sequestration in soils and forests and carbon credit programmes that reward farmers for adopting regenerative agriculture practices.

Comparators (examples of contemporary solutions): traditional carbon credit systems with manual data collection and verification, limited transparency and traceability, voluntary adoption of sustainable practices without financial incentives

Main hopes: sustainable practices, emission reductions, incentivization, accuracy with future technologies and innovations, a valuable asset with growing demand.

Some concerns: inequitable distribution, measurement/verification debates, long-term effectiveness, a potential distraction from systemic change, negative impacts on local populations, agricultural land conversion, neglect of more systemic emission reduction measures and corruption.

The implementation of carbon credit in agriculture and aquaculture faces several challenges. One primary concern is the potential for inequitable distribution of credits, where larger, well-resourced entities might benefit disproportionately compared to small-scale ones and vulnerable populations. This could lead to a situation where the credits primarily reward those already capable of implementing sustainable practices, potentially exacerbating existing inequalities. Furthermore, ongoing debates exist about the methodology used to quantify and verify carbon reductions in agrifood and aquaculture systems. Accurate measurement and verification are crucial to ensure the integrity of the carbon credit system and prevent issues like double-counting or overestimation of emission reductions. The inability to ensure that actual emission reductions will equal (or surpass) projected reductions can not only lead to the idea of carbon credits being invalid – it can render the entire system counterproductive.

In addition, the long-term effectiveness of carbon credits in driving genuine emission reductions in agriculture and aquaculture remains a subject of discussion. Critics argue that the focus on offsetting emissions through credit purchases might distract from the need for fundamental systemic changes to reduce emissions at their source.

Despite these challenges, carbon credits in agriculture and aquaculture still hold significant promise to promote sustainable practices and incentivize emission reductions. Future breakthroughs in remote sensing, blockchain technologies and innovations and improved measurement methodologies could enhance carbon credit systems' transparency, accuracy and effectiveness. Moreover, as the global demand for sustainable products grows, carbon credits could become an increasingly valuable asset for agricultural and aquaculture producers, further driving the adoption of environmentally friendly practices. Regardless of potential future advancements, carbon credits must be implemented carefully and monitored closely regarding their expected and actual effectiveness. In addition, it should be ensured that the use of carbon credits does not negatively and unfairly affect local populations, as several cases have been documented concerning their displacement, conversion of agricultural land into forests and limitations for forest use for local communities. The implementation should also ensure that they don't discourage efforts to, first and foremost, drive genuine emission reductions.

In our 2024 survey, average conduciveness scores were 0.31 for inclusivity, 0.91 for sustainability, and 0.78 for resilience. These scores, along with lower than average standard deviations, suggest a general consensus among participants about the very limited positive contribution of this technology/innovation to inclusion and sustainability (second worse in both cases). It scored particularly low on resilience, with the lowest score among all the PETIAS.

The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact before 2040.

While incentivizing sustainable practices, carbon credits face challenges in ensuring equitable distribution and addressing concerns about potential negative impacts on local populations and land use. The focus on offsetting emissions through credit purchases might also detract from the urgency of systemic change to reduce emissions at their source.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

- Alignment on potential: the 2023 report and the FSN Forum acknowledge the potential of carbon credits to incentivize sustainable practices in agriculture and aquaculture. The report highlights their role in reducing emissions and enhancing soil health, while the survey reflects a rather negative view of their contribution to sustainability and resilience. However, the 2024 survey ranks this PETIAS very low.
- Concerns and challenges: the report emphasizes measurement accuracy, greenwashing potential and market inclusivity. These concerns align with the survey's very low ratings and the variability in participant opinions, suggesting a shared recognition of the complexities involved in implementing carbon credit systems effectively.
- Impact timeline: the survey suggests an optimistic but varied timeline for impact, with some participants expecting significant developments before 2040, while others foresee a more extended timeframe.

Main areas of application

The main areas of application for carbon credits in agriculture and aquaculture listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Rewards reduced emissions and carbon sequestration in soil through practices like sustainable land management, vertical farming and reforestation.
Processing systems	Promotes energy-efficient technologies and innovations, sustainable sourcing and transparent labelling.
Value chains and services	Promotes energy-efficient technologies and innovations, sustainable sourcing. and transparent labelling.
Energy and transportation	Encourages biofuels, electric vehicles and renewable energy use.
Food waste	Incentivizes reduction through better storage and distribution practices.
Governance and trade	Creates a market for rewarding sustainability and promotes transparency.
New materials, new proteins and circular economy	Supports the development of low-carbon bio-based materials.
Blue economy	Promotes sustainable aquaculture practices like seaweed farming.
Inclusion of the most vulnerable	Provides income for marginalized groups adopting sustainable methods.

Nanomaterials for water technologies

Nanomaterials for water technologies and innovations involve applying nanoscale materials with unique properties to address water-related challenges.

Summary

Nanomaterials offer significant potential for water technologies and innovations in agriculture by improving filtration, desalination and water purification processes. Due to their unique properties at the nanoscale, these materials can enhance water efficiency, reduce contaminants and make irrigation more sustainable. They are particularly valuable in addressing water scarcity and quality issues in regions heavily reliant on agriculture.

However, the deployment of nanomaterials faces challenges, including high production costs, potential environmental risks and regulatory concerns over their long-term impacts on ecosystems and human health. Ensuring that nanotechnology remains accessible to smallholder farmers and marginalized communities is essential for widespread adoption.

While still in the early stages of development, nanomaterials for water technologies and innovations are expected to see a significant impact by 2040, especially in areas facing acute water challenges. Continued research, risk assessment and cost reduction will be key to unlocking their potential in sustainable water management.

Examples: nanofiltration membranes for removing micropollutants and pathogens from agricultural wastewater, nano-enabled sensors for real-time water quality monitoring irrigation systems and nanomaterials for slow-release fertilizers to reduce nutrient runoff.

Comparators (examples of contemporary solutions): conventional water treatment technologies and innovations (e.g., filtration, chlorination), reliance on chemical fertilizers, limited ability to monitor water quality in real time.

Main hopes: addressing water quality, scarcity, sustainability, efficient treatment, safe drinking water, improved agricultural efficiency, public health and economic development.

Some concerns: environmental release impacts, food safety, regulatory frameworks, high cost/complexity, public perception and unintended consequences.

Integrating nanomaterials into water technologies and innovations offers a promising avenue for addressing critical global water quality, scarcity and sustainability challenges. The unique properties of nanomaterials, such as their high surface-to-volume ratio and reactivity, enable the development of more efficient and effective water treatment processes. For instance, nanofiltration membranes can remove contaminants at a molecular level, providing safe drinking water even from heavily polluted sources (Jakšić, Z. and Jakšić, O., 2020). This is particularly important in regions with limited clean water or sanitation infrastructure access. These materials can improve water use efficiency in agriculture, a crucial factor in regions where water resources are limited. Nanomaterials can contribute significantly to public health, agricultural productivity and overall socioeconomic development in developing countries by enhancing water quality and availability.

However, releasing nanomaterials into the environment during manufacturing, use and disposal could have unintended consequences for ecosystems and human health. For instance, releasing nanomaterials into the environment could contaminate soil and water used for irrigation or aquaculture, affecting crop growth and food safety. The accumulation of nanomaterials in plants or animals could also affect food quality and human health. Ensuring the responsible and sustainable use of nanomaterials in water treatment applications requires the establishment of comprehensive safety assessments and stringent regulatory frameworks.

Furthermore, the high cost and intricate nature of nanomaterial-based technologies and innovations pose challenges to accessibility and affordability, especially in developing nations. Public perception and acceptance of nanomaterials in water treatment also pose a challenge, as concerns about their safety and potential long-term effects can lead to mistrust and resistance. Effective communication and transparency about the benefits and risks of nanomaterials are essential to build public trust and support for their scaling up in water technologies and innovations.

When we asked the survey participants in 2024 about nanomaterials, average conduciveness scores was of 0.72 for inclusivity, 1.14 for sustainability, and 1.11 for resilience. These scores, along with relatively moderate standard deviations, suggest a general consensus among participants about a rather limited positive contribution of this technology/innovation to these three dimensions. The estimated timeframe for significant impact shows a generally optimistic outlook, with most respondents in most regions anticipating an impact before 2040.

While these technologies and innovations offer promising solutions for food preservation, water purification and resource efficiency, their impact on inclusivity and potential long-term environmental consequences raise concerns. The high costs and complexity associated with nanomaterial production and integration could limit their accessibility, particularly for small-scale producers and developing regions. Additionally, the potential release of nanomaterials into the environment and food chains necessitates careful assessment and management to ensure the safety and sustainability of these applications.

Main points from the comparison between our 2023 synthesis report, the FSN Forum and the new survey results

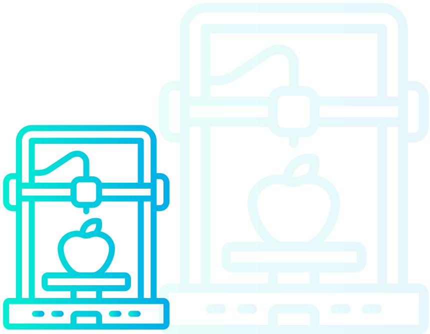
- Alignment on potential: the 2023 report recognizes the transformative potential of nanomaterials in improving water quality and management. The report focuses on the ability of these technologies and innovations to provide clean water and enhance irrigation efficiency. At the same time, the survey reflects a less positive view of their impact on sustainability and resilience. In contradiction to these results, none of the participants of the FSN Forum voted this PETIAS as impactful on inclusion, sustainability and resilience.
- Concerns and challenges: the report highlights concerns about nanomaterials' environmental and health risks, regulatory challenges and the need for long-term impact assessments. These concerns align with the survey's moderate ratings, indicating some uncertainty or caution among participants about their widespread application.
- Impact timeline: the survey suggests a slightly more optimistic impact timeline than the 2023 report's estimated maturity date of 2041, with many expecting significant developments before 2040.

Main areas of application

The main areas of application for nanomaterials for water technologies and innovations listed below follow a logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages and the overarching goals of sustainability, democratization and efficiency.

Production systems	Nanofiltration membranes purify and recycle water, offering energy-efficient desalination solutions, providing fresh water for agriculture in arid regions and reducing consumption and waste.
New materials, new proteins and circular economy	Bio-based nanomaterials replace traditional plastics.
One health and nutrition	Nanomaterials remove harmful microorganisms and toxins from drinking water, improving public and animal health.
Blue economy	I mprove water quality in aquaculture and monitor marine ecosystems.
Inclusion of the most vulnerable	Nanomaterials enable decentralized and cost-effective water treatment and purification technologies and innovations, accessible to vulnerable communities.

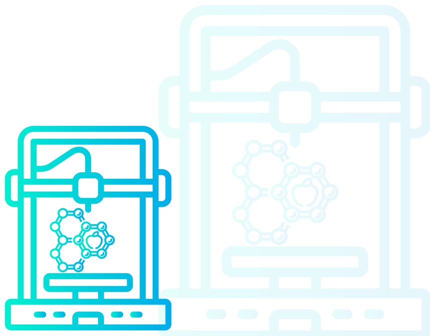
3.2.2 Other promising PETIAS with longer timeline of emergence and potentially medium to high trade-offs



3D printing of food and liquids

While 3D food and liquid printing present innovative opportunities, it also carries potential trade-offs and risks. A primary concern is food safety. The complexity of printing edible materials raises questions about contamination and necessitates stringent quality control. Additionally, affordability could be a barrier, potentially limiting access for economically vulnerable populations and exacerbating disparities in access to nutritious and varied diets. Moreover, these technologies and innovations can disrupt traditional food production systems and regional value chains, impacting livelihoods and cultural practices tied to food. Concerns have been raised about the technologies and innovations' potential negative impacts on traditional diets and regional value chains, highlighting the need to carefully consider how 3D food and liquid printing might inadvertently contribute to the erosion of culinary traditions and the displacement of local food producers. The technologies and innovations' impact on employment and labour dynamics within the food industry also warrants careful consideration. If not carefully managed, 3D food and liquid printing could disproportionately benefit large-scale producers, further concentrating power and control within the food system. Additionally, it is essential to consider the environmental implications of these technologies and innovations, including their energy consumption and potential impact on natural resources. Life cycle assessments and environmental impact studies should be conducted to guide sustainable design and minimize the ecological footprint of 3D-printed food and liquids.

However, 3D food and liquids printing technologies and innovations offer various advantages with potential impacts on individuals and the global community. It allows the creation of customized food products tailored to individual nutritional needs. This could be particularly beneficial for individuals with specific dietary requirements or those seeking to optimize their nutrient intake. It could also represent an option for ensuring food supply in food insecure communities or during drought, etc. (although the cost of implementing it could be high. Additionally, 3D printing could enable the incorporation of novel ingredients, such as alternative proteins or micronutrients, into food products, further enhancing their nutritional value. Moreover, 3D food and liquid printing can contribute to sustainability by reducing food waste. The ability to create food products in exact quantities and shapes and on-demand production minimizes the likelihood of overproduction and spoilage.

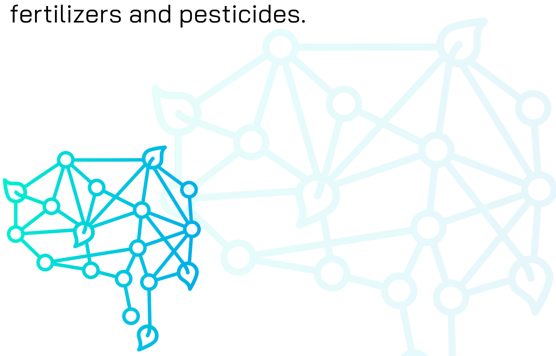


4D nanoscale printing

A primary concern around 4D nanoscale printing revolves around the environmental and health implications of nanomaterials used in the printing process. The potential release of nanoparticles into ecosystems and food chains could pose unforeseen ecological consequences and health risks for consumers. Additionally, the scalability and cost-effectiveness of these technologies and innovations for food production remain uncertain, potentially limiting its accessibility and favouring larger, well-resourced entities. Furthermore, the intricate and time-dependent nature of 4D printed structures might complicate food safety regulations and quality control, necessitating the development of novel assessment and monitoring frameworks.

Additionally, consumers may be hesitant to adopt 4D-printed food due to concerns about safety, novelty and potential ethical implications. Building consumer trust and addressing these concerns will be crucial for widely scaling up technologies and innovations. Further research is needed to explore its full potential in agrifood systems, develop new applications and address existing limitations.

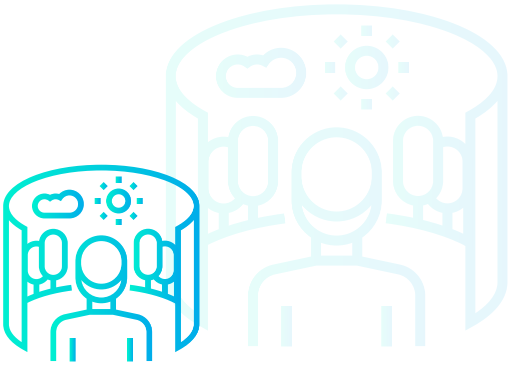
Despite these challenges, 4D nanoscale printing offers a range of potential benefits for agrifood systems. The technologies and innovations' ability to create dynamic, self-transforming structures could revolutionize food packaging, enabling the development of intelligent materials that respond to environmental conditions to extend shelf life, enhance food safety and reduce waste. In food production, 4D printing could improve the nutritional value of food products by encapsulating nutrients within printed structures, protecting them from degradation and ensuring their bioavailability. It also enables the incorporating of novel ingredients like bioactive compounds or nutraceuticals, offering additional health benefits. The technologies and innovations also potentially improve the sensory experience of food. By manipulating texture, controlling flavour release and creating visually appealing designs, 4D printing can lead to the development of food products with enhanced sensory appeal. Moreover, the technologies and innovations could open new avenues for sustainable agriculture, such as creating responsive crop protection materials or targeted delivery systems for fertilizers and pesticides.



Artificial neurons

The implementation of artificial neurons within agrifood systems holds immense promise for their sustainable transformation. These computational models can optimize resource allocation and decision-making by processing vast amounts of data, significantly improving productivity and efficiency. Artificial neurons have the potential to enhance crop yield predictions, fine-tune irrigation and fertilizer application and facilitate early detection of pests and diseases. This precision agriculture approach reduces the environmental footprint by minimising resource waste and the overuse of agrochemicals, thus promoting biodiversity conservation and reducing pollution risks. Furthermore, such technological advancements could enable farmers to adopt more sustainable practices, leading to healthier soils and improved ecosystem resilience. Additionally, the ability of artificial neurons to model complex biological processes could enhance our understanding of plant physiology and ecosystem dynamics, fostering innovation in sustainable agricultural practices and contributing to long-term food security.

Incorporating artificial neurons into agricultural practices requires meticulous planning and attention to various factors. A primary concern lies in the reliance on vast amounts of data and connectivity, potentially excluding remote communities with limited access to technologies and innovations and infrastructure. The technologies and innovations' inherent complexity might also create barriers to adoption among small-scale farmers with limited resources or technical expertise. The cybersecurity risks associated with large-scale data collection and processing demand robust security measures to protect sensitive information and prevent malicious attacks. Additionally, overreliance on models and algorithms could undermine the value of traditional agricultural knowledge and experience. Integrating artificial neurons into agricultural systems may also lead to workforce displacement as automation and data-driven decision-making become prevalent. The development and implementation of artificial neurons should be guided by comprehensive regulatory frameworks that address data privacy, security and ethical considerations.

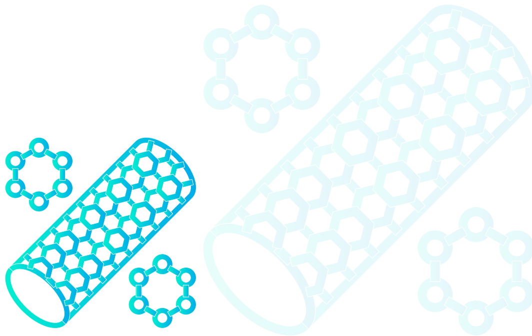


Metaverse, VR and AR

Integrating metaverse, virtual reality (VR) and augmented reality (AR) technologies and innovations in agriculture offer a range of potential benefits. These interactive platforms can provide farmers with powerful data visualisation, simulation and decision-making tools (Almessabi and Al-kfairy, 2024). Farmers can test and optimize various agricultural techniques by creating virtual replicas of farming environments, improving crop yields, resource efficiency and sustainability. Moreover, these technologies and innovations can facilitate remote training and knowledge sharing, benefiting farmers in marginalized communities with limited resource access. VR and AR can also enhance agricultural education and outreach, fostering a new generation of tech-savvy farmers. Additionally, the immersive experiences offered by these technologies and innovations can promote agricultural tourism and public engagement with farming practices.

On the other hand, the high cost of equipment and infrastructure may limit accessibility for small-scale farmers and exacerbate existing disparities (Almessabi and Al-kfairy, 2024). Ensuring equitable access to these technologies and innovations is crucial for avoiding further marginalization of vulnerable populations. Additionally, the reliance on digital platforms raises concerns about technology dependency and the potential for alienation from traditional farming practices. Striking a balance between technological innovation and preserving agricultural heritage is essential for sustainable transformation. Furthermore, developing and spreading these technologies and innovations require significant energy and resources and generating electronic waste, potentially undermining some ecological benefits. Careful consideration of the environmental footprint of metaverse, VR and AR is necessary to ensure their sustainable integration into agricultural systems.

Lastly, regulatory barriers and data privacy concerns must be addressed to ensure the responsible and ethical use of these technologies and innovations in the agrifood systems.

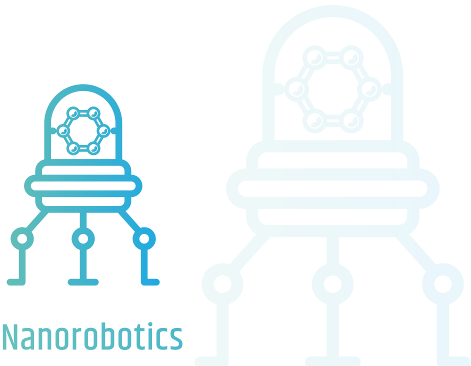


Nanomaterials for food packaging

Nanomaterials for food packaging offer several potential benefits for the agrifood systems. They can enhance the barrier properties of packaging materials, improving food preservation, extending shelf life and reducing food waste. This can contribute significantly to food security, particularly in regions with limited infrastructure or harsh environmental conditions. Additionally, nanomaterials can enable the development of intelligent packaging systems with real-time monitoring capabilities, enhancing food safety and traceability throughout the supply chain. These advancements can benefit consumers by providing greater assurance about the quality and origin of their food. Moreover, nanomaterials can potentially reduce the environmental impact of food packaging by enabling the use of lighter, thinner and more sustainable materials (Mohammad and Ahmad, 2024).

While the application of nanomaterials in food packaging presents numerous advantages, several crucial concerns warrant careful consideration. The potential migration of nanoparticles from packaging into food raises concerns about food safety and human health. Rigorous safety assessments and regulatory frameworks are essential to address these concerns and ensure consumer safety. Regulatory barriers, including labelling requirements and safety standards, may hinder the widespread adoption of nanomaterials in food packaging. The production and disposal of nanomaterials can also have environmental implications, requiring careful consideration of their life cycle impacts. The long-term impact of nanomaterials on ecosystems and biodiversity also requires further research and monitoring. Additionally, the complexity and cost of incorporating nanomaterials into packaging may pose barriers to adoption, particularly for small-scale producers in marginalized communities.

Furthermore, nanomaterials in food packaging could disrupt existing packaging industries and supply chains, potentially impacting jobs and livelihoods. Careful planning and transition strategies are needed to mitigate these effects. The long-term effects on the agricultural workforce, including potential job displacement and the need for new skill sets, must also be carefully evaluated and managed.



Nanorobotics

Nanorobotics offer a transformative potential for agriculture and food systems, promising enhanced precision, efficiency and sustainability. Their ability to perform precise tasks at the nanoscale can revolutionize various processes, from targeted delivery of nutrients and pesticides to real-time monitoring of crop health and soil conditions. This precision agriculture approach can optimize resource utilisation, reduce environmental impact and improve crop yields (Yadav *et al.,* 2023). Additionally, their ability to detect pathogens, microorganisms, allergens and contaminants in food can significantly improve food safety and quality. Nanorobots can also be used for targeted delivery of nutrients or therapeutics to plants, enhancing crop health and productivity. These capabilities can contribute to sustainable agriculture by optimising resource use, reducing chemical inputs and improving yields. By automating labour-intensive tasks and optimising resource allocation, nanorobotics has the potential to alleviate workforce burdens and promote a more sustainable and resilient agricultural sector.

The implementation of nanorobotics in agrifood systems presents some challenges as well. Nanomaterials' long-term environmental and health impacts remain uncertain, requiring rigorous and prolonged safety assessments to ensure their responsible use. Questions related to unintended consequences, potential misuse, electronic waste and impact on biodiversity necessitate ongoing ethical review and public engagement. Public perception and acceptance of nanotechnology in agriculture also pose a challenge, requiring transparent communication and engagement to build trust and address concerns.

The high cost and complexity of nanorobotic systems may limit their accessibility and affordability, particularly for small-scale farmers and in developing regions. Furthermore, introducing nanorobotics into the workforce raises concerns about job displacement and the need for upskilling to adapt to new technologies and innovations. A proactive approach to workforce development and retraining is crucial to ensure a just transition and equitable distribution of benefits.

Novel biomass energy

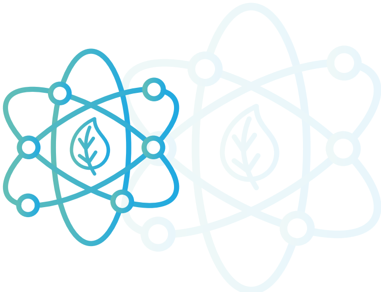
Novel biomass energy technologies and innovations, harnessing renewable organic materials like algae and microorganisms, offer a promising pathway towards sustainable energy production. These innovative methods can significantly reduce greenhouse gas emissions compared to fossil fuels, contributing to climate change mitigation and improved air quality. By harnessing diverse biomass sources, including waste-derived materials, these technologies and innovations can contribute to a circular economy, reducing waste and promoting resource efficiency. Increased energy production from biomass can enhance energy security and independence, particularly for remote and marginalized communities with limited access to traditional energy grids. This decentralized approach to energy generation can stimulate local economies and create jobs. Moreover, cultivating biomass feedstocks, such as algae, can have positive environmental impacts, including carbon capture, water purification and soil remediation (Javaid *et al.,* 2023).

While novel biomass energy technologies and innovations hold significant promise, their implementation requires careful consideration of potential trade-offs and risks. The large-scale cultivation of biomass feedstocks can compete with food production for land and water resources, potentially impacting food security. To mitigate competition for land use, it is vital to prioritize the utilisation of waste-derived biomass and promote less energy-intensive agricultural practices. Additionally, innovative cultivation techniques such as vertical farming and marine algae production should be explored to reduce the pressure on land resources. Technological barriers, such as the need for efficient biomass conversion processes and cost-effective energy storage solutions, must be overcome to ensure these technologies and innovations' scalability and economic viability and innovations. Regulatory frameworks and incentive mechanisms may also need to be adapted to support developing and deploying these technologies and innovations. Public acceptance and understanding are crucial for successfully integrating novel biomass energy technologies and innovations into the energy mix. Therefore, transparent communication and stakeholder engagement are essential to address concerns and build public trust.

Novel pesticides, fertilizers, antibiotics including nanotechnology substances

Incorporating nanotechnology into pesticides, fertilizers and antibiotics is a promising avenue for enhancing agricultural productivity and sustainability. The precise and controlled release mechanisms facilitated by nanomaterials can optimize the delivery and efficacy of these inputs, leading to reduced application rates, minimized environmental impact and improved resource efficiency. This targeted approach can help decrease the risks associated with chemical runoff and contamination of soil and water sources, safeguard biodiversity and promote a healthier ecosystem. In addition, nanotechnology-enabled formulations could address challenges like pesticide resistance and nutrient deficiencies, enhancing crop yields and food security. This could benefit marginalized communities and regions facing resource constraints or harsh environmental conditions. Furthermore, integrating nanotechnology into agricultural inputs could stimulate innovation in related fields, such as precision agriculture and smart farming, fostering a sustainable agrifood systems' transformation (Prasad *et al.,* 2017).

However, the adoption these technologies and innovations also raises concerns that must be addressed. Nanomaterials' long-term environmental and health impacts remain an area of active research. Developing clear regulatory frameworks and standards is essential to ensure these novel substances' responsible and safe use. Furthermore, the possibility of these technologies distracting from sustainable farming practices such as crop rotation, use of local varieties and integrated pest management highlights the significance of a comprehensive strategy for agricultural sustainability. There could also be a risk of developing antibiotic resistance. The high cost and technological complexity associated with nanotechnology-based inputs can pose a barrier to adoption, particularly for small-scale farmers in developing regions. Ensuring equitable access and affordability is crucial to avoid exacerbating existing inequalities in the agricultural sector. Lastly, overcoming technological barriers to creating, producing and delivering these novel inputs requires ongoing research and investment.



Nuclear fusion

The prospect of harnessing nuclear fusion as a clean and abundant energy source presents transformative opportunities for agrifood systems, particularly in achieving sustainability and bolstering food security (Dunlap, 2021). Nuclear fusion can power advanced agricultural technologies and innovations, such as vertical farming, precision irrigation and controlled environment agriculture. These applications can significantly enhance crop yields, reduce reliance on fossil fuels and minimize greenhouse gas emissions. Additionally, nuclear techniques can be employed for pest and disease control, reducing the need for chemical pesticides and promoting sustainable farming practices. Using isotopes in agricultural research can also lead to developing more resilient and resource-efficient crop varieties, contributing to food security and climate change adaptation.

However, adopting nuclear fusion in agriculture also raises significant concerns and challenges. Public perception and acceptance of these technologies and innovations remain a vital barrier, often driven by fears of accidents, radiation exposure and waste disposal. Stringent safety regulations and robust oversight mechanisms are essential to address these concerns and ensure nuclear fusion's safe and responsible use in agriculture. The management and disposal of radioactive waste pose long-term environmental and public health risks that require careful planning and technological solutions. Additionally, the high costs and technological complexities associated with nuclear fusion development and deployment can limit accessibility and affordability, particularly for developing countries and small-scale farmers. International cooperation and knowledge sharing are crucial to address these challenges and ensure equitable access to the benefits of nuclear fusion technologies and innovations in agrifood systems.

Personalized nutrition

AI-driven personalized nutrition has the potential to revolutionize dietary practices and health outcomes. By leveraging machine learning algorithms and vast data sets, these solutions can offer tailored nutritional guidance based on individual needs, preferences and health conditions. This personalized approach can improve adherence to dietary recommendations, leading to better management of chronic diseases like diabetes, heart disease and obesity and potentially also therapies for stunting and wasting (although high implementation costs could be involved) (Theodore Armand *et al.*, 2024). Personalized nutrition can promote sustainable dietary patterns by optimising nutrient intake and reducing food waste. By leveraging AI algorithms and data analytics, these technologies and innovations can identify trends and patterns in nutritional habits, enabling the development of targeted interventions and public health policies. Furthermore, personalized nutrition can foster a more consumer-centric approach to food production and marketing, driving innovation in the food industry.

However, the widespread adoption of personalized nutrition also presents several challenges. Data privacy and security concerns are paramount, as the collection and analysis of sensitive personal information raise ethical questions and require robust data governance frameworks. Additionally, the affordability and accessibility of these solutions could create disparities, limiting their reach to those with financial resources and technological literacy. Addressing cost barriers and ensuring equitable access is essential to maximize the social benefits of personalized nutrition. The reliance on AI algorithms also raises concerns about potential biases and inaccuracies in recommendations, particularly for underrepresented populations with limited data representation. Likewise, the algorithms should not only focus on a few main food products but also consider local, often underutilized and neglected varieties that are locally available and frequently hold great nutritional potential. Rigorous validation and continuous improvement of these algorithms are necessary to ensure their accuracy and fairness. Furthermore, the widespread adoption of personalized nutrition could inadvertently lead to the proliferation of misguided nutritional advice and unregulated health claims. Establishing clear regulatory guidelines and promoting evidence-based recommendations to protect consumers is important. The potential impact on the food industry and the workforce must also be addressed, as shifts in consumer demand and production practices may disrupt traditional food systems and require workforce adaptation.

RNA interference

RNA interference (RNAi) offers a powerful and precise tool for manipulating gene expression, potentially revolutionizing various aspects of agrifood systems. In agriculture, RNAi can be harnessed to develop crops with enhanced traits such as improved nutritional value, increased yield, resistance to pests and diseases and tolerance to environmental stressors. This can significantly contribute to food security, especially in regions facing challenges due to climate change or limited resources. RNAi-based approaches can promote sustainable farming practices and minimize environmental impact by reducing the need for chemical pesticides and fertilizers. In animal health, RNAi can be employed to develop novel vaccines and therapeutics, combating infectious diseases and improving animal welfare. This can increase livestock productivity and reduce the reliance on antibiotics, further contributing to environmental sustainability and public health.

The release of genetically modified organisms utilising RNAi technologies and innovations raises concerns, i.e. about unintended ecological consequences, such as potential harm to non-target species, reduced biodiversity or disruptions to ecosystem dynamics. Rigorous risk assessments and monitoring are essential to safeguard biodiversity and prevent unforeseen environmental impacts. Public perception and acceptance of RNAi-based products remain challenging as concerns persist regarding the safety and long-term effects of consuming genetically modified foods. Transparent communication, public engagement and evidence-based risk assessment are crucial to address these concerns and foster informed decision-making. Additionally, developing and deploying RNAi-based solutions can be costly and complex, potentially limiting access for small-scale farmers and marginalized communities. Ensuring equitable access to these technologies and innovations and fostering capacity development are vital for achieving a just and sustainable transformation of agrifood systems. Regulatory barriers and intellectual property considerations can impede the adoption of RNAi technologies and innovations. Streamlining regulatory processes and promoting open science initiatives can facilitate innovation and ensure the benefits of RNAi reach those who need it most. Finally, the workforce implications of RNAi-based advancements, particularly regarding skills development and potential job displacement, necessitate proactive measures to support workers and ensure a smooth transition (Christiaens *et al.,* 2022).

Teleportation of complex molecules

The theoretical concept of teleporting complex molecules within agrifood systems presents a radical shift in our agricultural production and food systems approach. The ability to instantaneously transmit intricate molecular components across vast distances could revolutionize agricultural practices, offering unprecedented precision and efficiency in delivering essential nutrients, pesticides and other bioactive molecules directly to target sites. This could significantly enhance crop yields, reduce reliance on chemical inputs, ensure supplies to remote or crisis-affected areas and minimize environmental impact. Moreover, the targeted delivery of molecules could improve the nutritional content of food products and facilitate the development of novel therapeutics and bio-based products. The potential for teleportation to reduce transportation-related emissions and energy consumption could further contribute to sustainability goals. Furthermore, these technologies and innovations could enable the creation of novel food production and processing systems, such as on-demand nutrient delivery and personalized food production, leading to a more sustainable and efficient food system.

However, the realisation of complex molecule teleportation in agriculture faces formidable technological and scientific challenges, as the fundamental principles underlying this concept remain primarily theoretical. The energy requirements and potential environmental impacts of such technologies and innovations are currently unknown, necessitating thorough research and assessment. Ethical considerations surrounding manipulating matter at the molecular level also warrant scrutiny. The potential societal implications, including workforce displacement and the need for new regulatory frameworks, must be proactively addressed. The feasibility and scalability of these technologies and innovations for widespread agricultural use remain uncertain, requiring substantial investments in research and development. Finally, as with many other technologies and innovations, it is also far from obvious how to ensure that these technologies and innovations are accessible and benefit small entities rather than just increasing the advantage of the large.

3.3 PRE-EMERGING AND EMERGING TECHNOLOGIES AND INNOVATIONS FOR INCLUSION, SUSTAINABILITY AND RESILIENCE

While the Delphi survey conducted in 2023 analyzed the potential impact of the PETIAS on the agrifood systems challenges, the initiatives in 2024 - the survey and the FSN Forum submissions - addressed their potential impact on the inclusion, sustainability and resilience of the future agrifood systems.

The new analytical perspective is necessary to determine which PETIAS, while effectively addressing existing challenges, can boost the transformative outcomes, minimize trade-offs in terms of these three dimensions and promote broader system-wide benefits.

The results are largely aligned, though some differences in views between the survey and FSN Forum can be attributed to different respondent groups. This section provides an overview of the results, focusing on the most highly voted PETIAS.

Policy and organizational, and market innovations are the most PETIAS to bring a positive impact on all three dimensions, emphasizing the need of a systemic change at low trade-off level for achieving impact. The highest ranked technological innovations (6th place and below) are in support to 6-10G connectivity infrastructure and logistics (see Figure 2, Figure 3, Figure 4).

To address the inclusion, territorial or landscape value-chain and food-to-consumer economy innovations, access to science-based sustainability information, agricultural innovation policy labs have been ranked both by the survey and the FSN Forum participants as the most impactful on inclusion. Results differ between the sources regarding frugal innovations (ranked the highest in the survey while not mentioned by the FSN Forum participants), social impact bonds (5th according to the survey, while not voted in the FSN Forum), and nature-based and ecosystems innovations, scored relatively high in the FSN Forum, while much lower in the survey results.

Regarding sustainability, the survey and FSN Forum results are more varied, although both acknowledge the importance of non-technological innovations. The survey highlights frugal innovation, territorial or landscape value-chain and food-to-consumer economy innovations, and access to science-based sustainability information, while also ranking high some technological solutions like IoT and aerial robotics. In contrast, the FSN Forum emphasizes nature-based and ecosystem innovation, carbon credits, and frugal innovation, with a focus on energy-related technologies.

For resilience, the survey and FSN Forum results show some misalignment. The survey again scores frugal innovation highest, followed by access to science-based sustainability information, emphasizing social, policy, and low-tech innovations. The FSN Forum, however, votes highest for technologies like energy storage and real-time satellite imagery. For non-technological innovations, the FSN Forum results show more trust in nature-based and ecosystem innovations and territorial or landscape value-chain and food-to-consumer economy innovations, which received lower scores in the survey.

Figure 2. The impact of pre-emerging and emerging technologies and innovations on achieving an inclusive agrifood systems globally. The scale range used is from - 3 (very negative) to +3 (very positive) answers by the respondents.

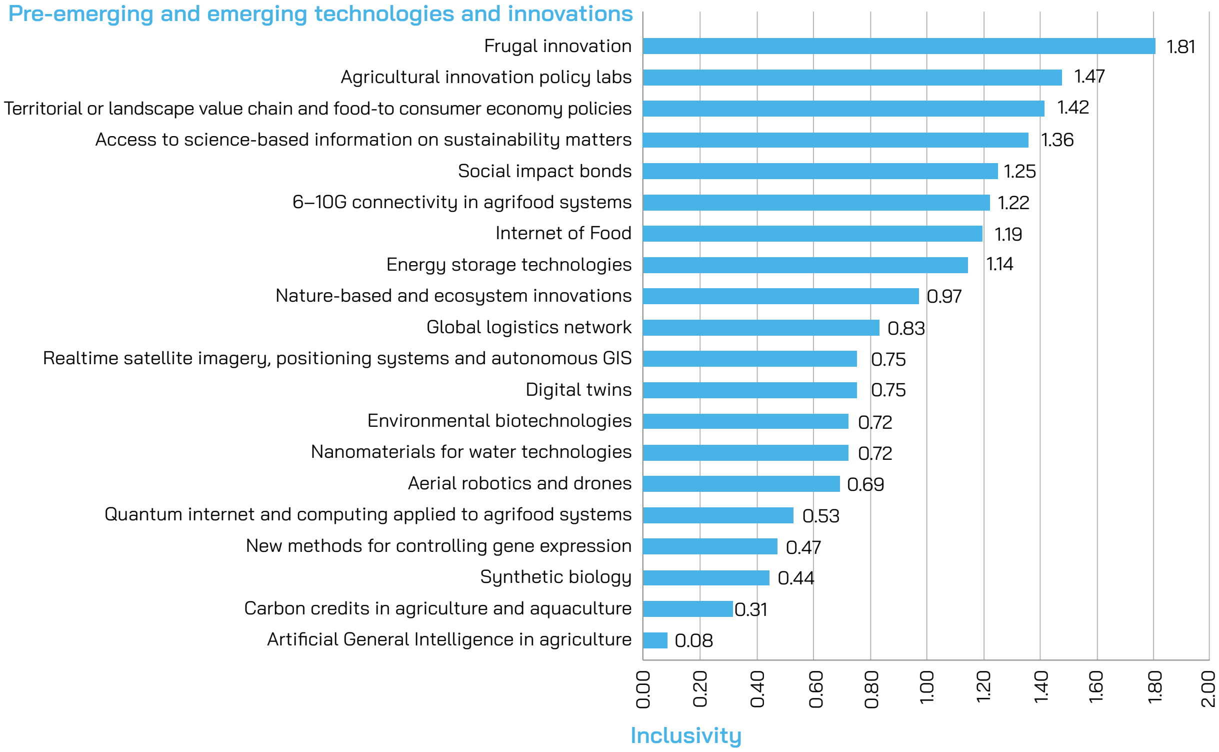


Figure 3. The impact of pre-emerging and emerging technologies and innovations on achieving a sustainable agrifood systems globally. The scale range used is from - 3 (very negative) to +3 (very positive) answers by the respondents.

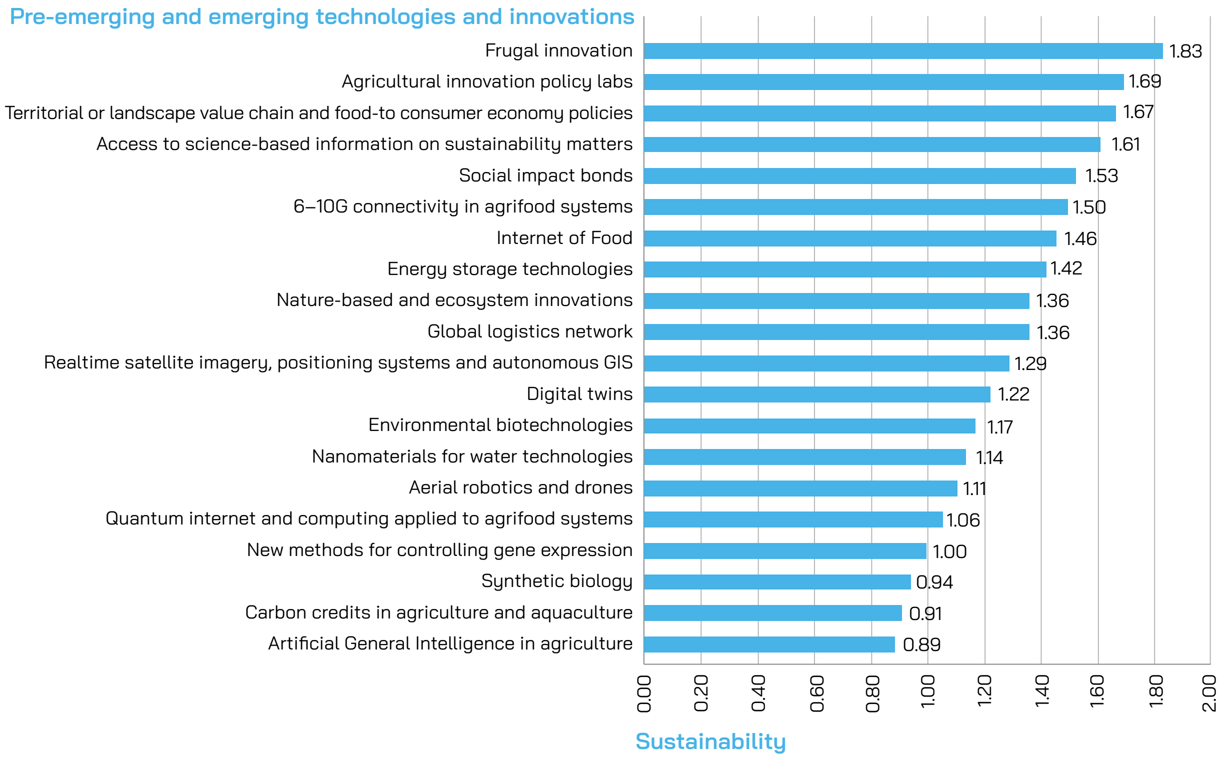
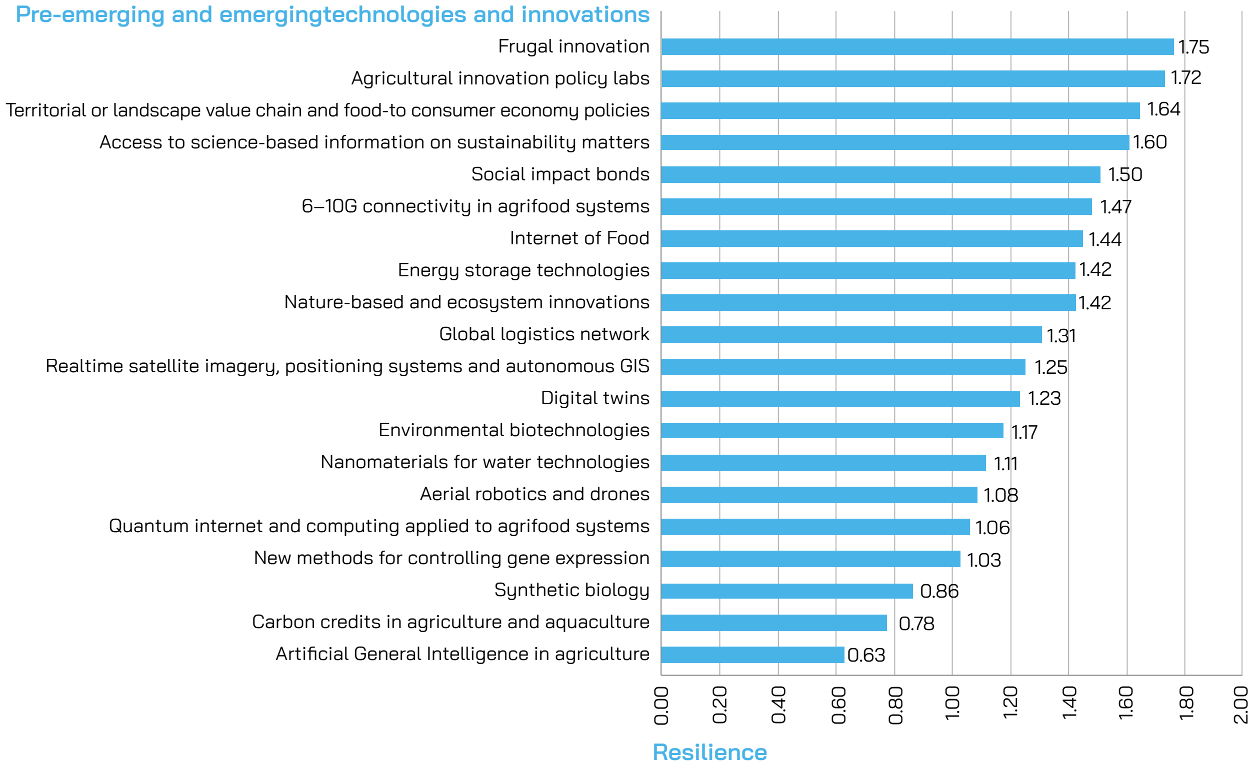


Figure 4. The impact of pre-emerging and emerging technologies and innovations on achieving a resilient agrifood systems globally. The scale range used is from - 3 (very negative) to +3 (very positive) answers by the respondents.



The survey also provides insights into the expected timeframe for achieving impact on inclusion sustainability, and resilience at global (Figure 5, Figure 6, Figure 7), and regional levels. While regional insights will be presented in a separate chapter, this section provides a global overview. Several PETIAS leading in both the survey and FSN Forum results are expected to achieve impact before 2035, including territorial or landscape value-chain and food-to-consumer economy innovations, access to science-based sustainability information, and technological solutions like aerial robotics and drones and real-time satellite imagery. The combination of perceived impact and time for impact emphasizes the importance of these PETIAS in accelerating inclusive, sustainable, and resilient transformation of agrifood systems.

Interestingly, some non-technological innovations, such as agricultural innovation policy labs and nature-based and ecosystem innovations with low trade-offs and generally available now, are not expected to achieve the impact before 2035, showing a potential gap between their implementation and the effects. Due to their nature and that they often lack policy support, they may end up unscaled. Similarly, also some technologies like those related to energy, are not expected to achieve impact before 2040.

Despite their potential – high relative advantage in addressing challenges - AGI and carbon credits were perceived as having the lowest potential to advance resilience, inclusivity, and sustainability. This perception may stem from concerns about the ethical implications of AI, its potential to exacerbate inequalities, and the complexity of implementing effective carbon credit systems. Additionally, there may be skepticism regarding the long-term effectiveness of carbon credits in mitigating climate change and promoting sustainable development.

To conclude, the results emphasize the importance of policy, financial and market innovations, as well as those with low tradeoffs to address broad systemic issues, related to the three dimensions of the agrifood systems. Improving policy and governance frameworks to address concerns related to AI and accelerate the upscaling of frugal and nature-based innovations calls to action.

Figure 5. Assessment of pre-emerging and emerging technologies and innovations on the global agrifood systems regarding inclusivity and the estimate time frame to achieve their significant impact.
The scale range uses is from -3 (very negative) to +3 (very positive) answers by the respondents.

PETIAS	ID
Nature-based and ecosystem innovations	1
Artificial General Intelligence in agriculture	2
Agricultural innovation policy labs	3
Energy storage technologies	4
Social impact bonds	5
Realtime satellite imagery, positioning systems and autonomous GIS	6
6–10G connectivity in agrifood systems	7
Environmental biotechnologies	8
Synthetic biology	9
Access to science-based information on sustainability matters	10
Internet of Food	11
Frugal innovation	12
Digital twins	13
Quantum internet and computing applied to agrifood systems	14
Aerial robotics and drones	15
New methods for controlling gene expression	16
Global logistics network	17
Territorial or landscape value chain and food-to consumer economy policies	18
Carbon credits in agriculture and aquaculture	19
Nanomaterials for water technologies	20

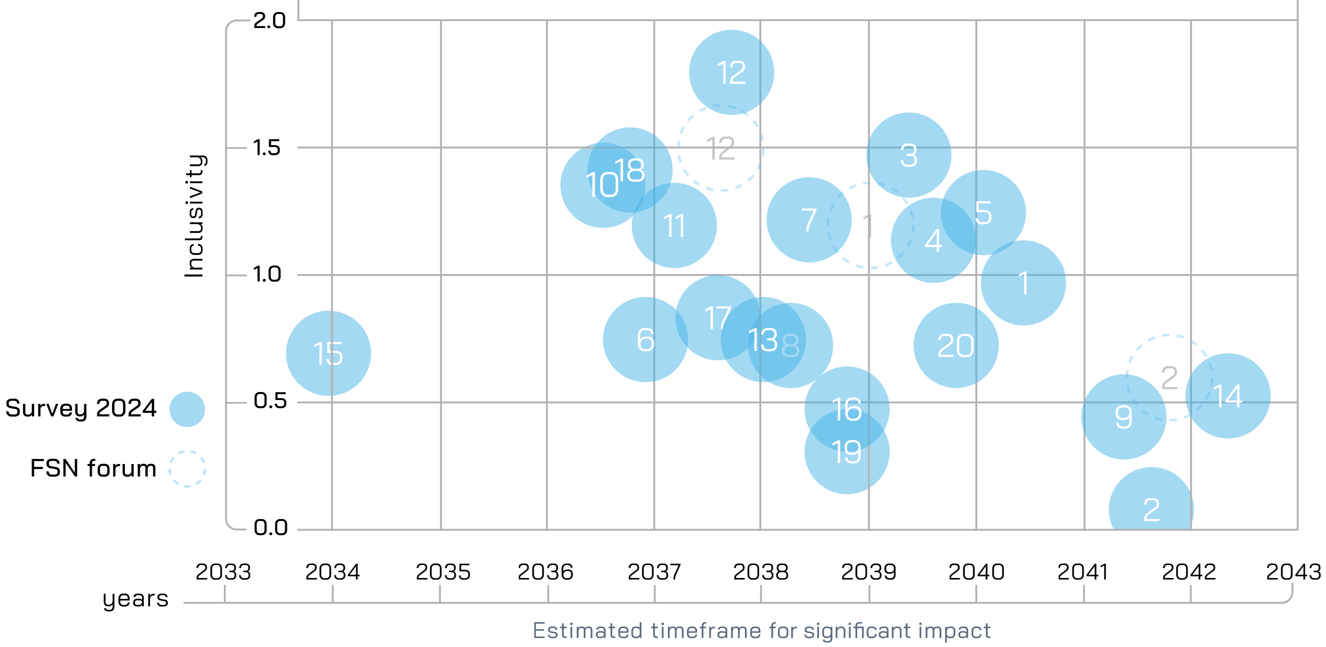


Figure 6. Assessment of pre-emerging and emerging technologies and innovations on the global agrifood systems regarding resilience and the estimate time frame to achieve their significant impact.
The scale range uses is from -3 (very negative) to +3 (very positive) answers by the respondents.

PETIAS	ID
Nature-based and ecosystem innovations	1
Artificial General Intelligence in agriculture	2
Agricultural innovation policy labs	3
Energy storage technologies	4
Social impact bonds	5
Realtime satellite imagery, positioning systems and autonomous GIS	6
6–10G connectivity in agrifood systems	7
Environmental biotechnologies	8
Synthetic biology	9
Access to science-based information on sustainability matters	10
Internet of Food	11
Frugal innovation	12
Digital twins	13
Quantum internet and computing applied to agrifood systems	14
Aerial robotics and drones	15
New methods for controlling gene expression	16
Global logistics network	17
Territorial or landscape value chain and food-to consumer economy policies	18
Carbon credits in agriculture and aquaculture	19
Nanomaterials for water technologies	20

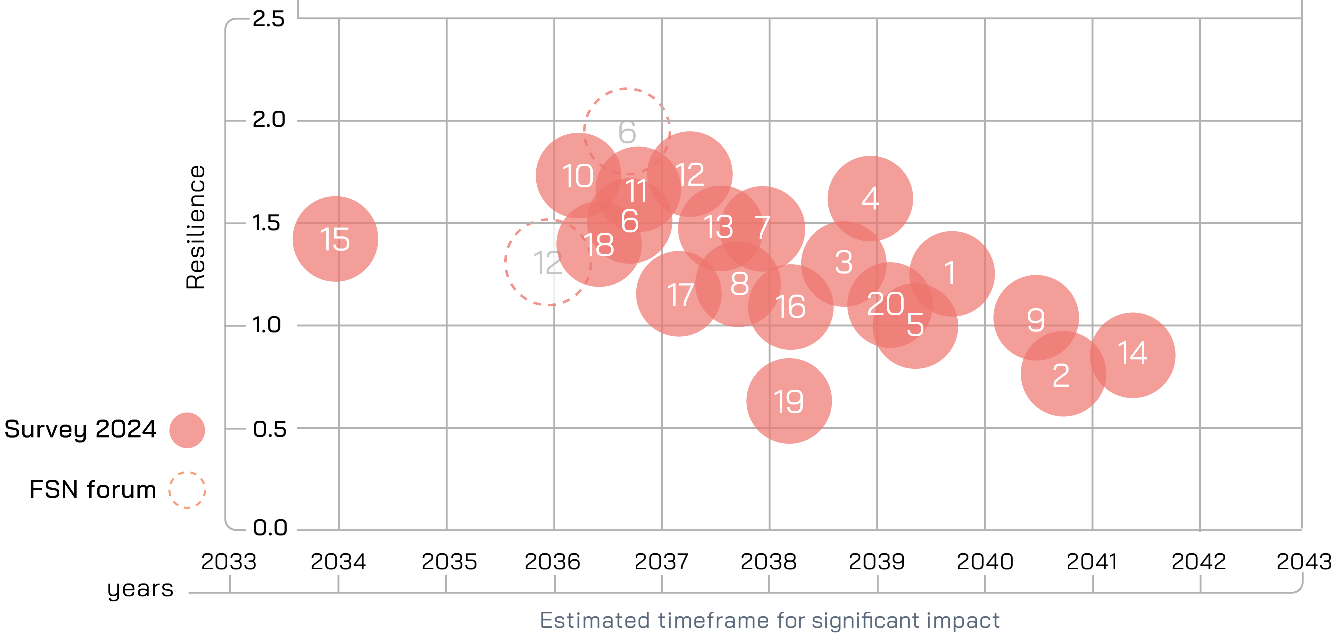
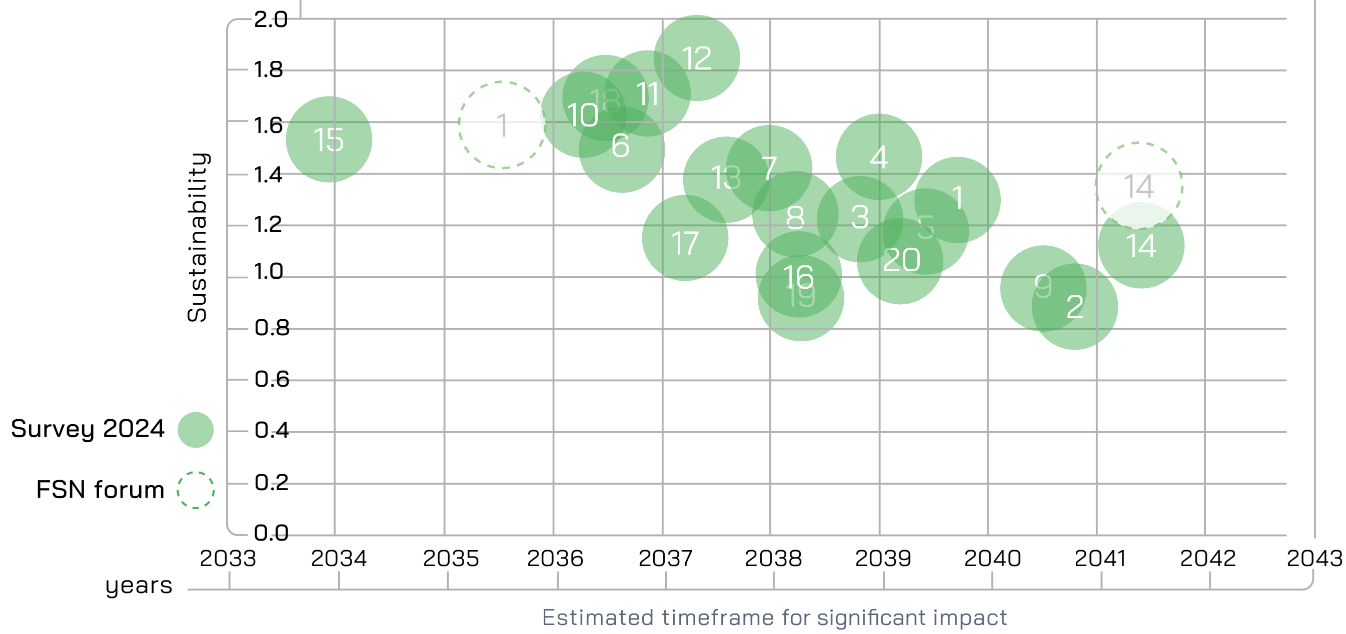


Figure 7. Assessment of pre-emerging and emerging technologies and innovations on the global agrifood systems regarding sustainability and the estimate time frame to achieve their significant impact.
The scale range uses is from -3 (very negative) to +3 (very positive) answers by the respondents.

PETIAS	ID
Nature-based and ecosystem innovations	1
Artificial General Intelligence in agriculture	2
Agricultural innovation policy labs	3
Energy storage technologies	4
Social impact bonds	5
Realtime satellite imagery, positioning systems and autonomous GIS	6
6–10G connectivity in agrifood systems	7
Environmental biotechnologies	8
Synthetic biology	9
Access to science-based information on sustainability matters	10
Internet of Food	11
Frugal innovation	12
Digital twins	13
Quantum internet and computing applied to agrifood systems	14
Aerial robotics and drones	15
New methods for controlling gene expression	16
Global logistics network	17
Territorial or landscape value chain and food-to consumer economy policies	18
Carbon credits in agriculture and aquaculture	19
Nanomaterials for water technologies	20



3.4 LOOKING BACK: EVOLVING PERCEPTIONS

The comparison between the 2023 synthesis report and the 2024 survey results for the 20 PETIAS highlights a shared recognition of their transformative potential in advancing agrifood systems sustainability, efficiency, and resilience. All sources acknowledge the promise of these technologies in addressing key challenges like climate change, food security, resource management, and environmental sustainability. Innovations such as nature-based ecosystem solutions, digital twins, and synthetic biology are seen as having the capacity to revolutionize agrifood systems through enhanced precision, holistic solutions with respect to the ecosystems and environment, real-time monitoring, and improved crop traits.

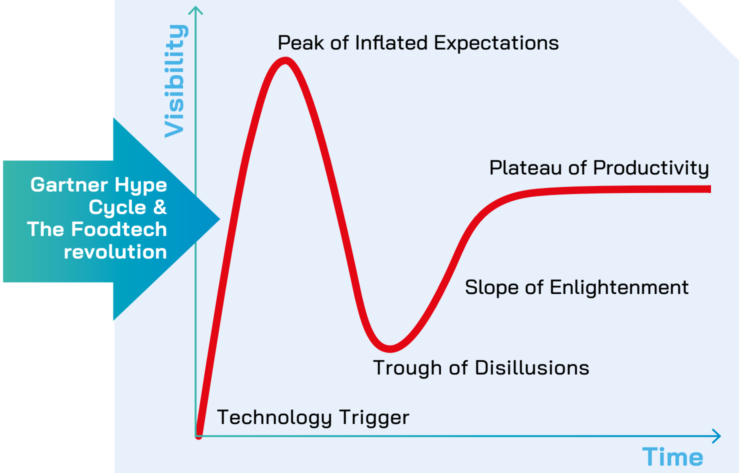
However, these sources reflect concerns and challenges associated with the adoption and integration of these PETIAS. Ethical considerations, regulatory hurdles, public acceptance, data privacy, and equitable access are recurrent themes. For instance, synthetic biology and new methods for controlling gene expression raise questions about unintended ecological consequences in some contexts and public perception. Similarly, carbon credits in agriculture and aquaculture, as well as global logistics networks, face challenges related to market stability, measurement accuracy, and inclusivity for smaller producers. These concerns underscore the complexity of implementing these innovations on a global scale.

Reflecting on the results from both years, the sign of skepticism can also be partly attributed to the recent boom in generative artificial intelligence (AI) and the associated sense of technological acceleration. While change generative artificial intelligence to Artificial Generative Intelligence (AGI) has demonstrated its transformative capabilities in recent years, there remains a degree of skepticism about its long-term benefits and the potential for it to revolutionize other sectors, including agrifood systems. The rapid advancements in AI have undoubtedly influenced perceptions of how quickly other technologies might emerge and be implemented, but there is a growing awareness of the limitations and challenges associated with AI adoption in the social sphere, including the possible societal consequences from applying universal basic income (UBI) to mitigate job displacement and economic inequality.

The AI boom has particularly impacted fields, such as precision agrifood systems, where technologies like digital twins, real-time satellite imagery, and autonomous systems can be enhanced through advanced AI models. The 2024 survey respondents' more optimistic timelines for these technologies might reflect the influence of AI's swift progress, which has set a precedent for rapid innovation and deployment. This perception is reinforced by the immediate and visible impact of AI in other industries, leading to an expectation that similar breakthroughs can be achieved in agrifood systems, thereby shortening the timeframes for significant technological impact.

However, this feeling of acceleration is accompanied by a degree of hype (see Figure 8), which can create an overly optimistic view, or contrastingly, disillusioning of how quickly complex technologies can be integrated into existing systems. While AI has shown remarkable progress, the adoption of many PETIAS still faces significant challenges, including ethical considerations, regulatory barriers, and the need for robust infrastructure and capacity development. The 2024 survey's more cautious timelines, often projecting maturity around 2040 or later, highlight these complexities and suggest that despite the excitement generated by AI, the road to full implementation of these technologies may

Figure 8. The (adapted) Gartner Hype Cycle provides insights on hypes and disillusionments related to PETIAS (Stamford, 2024).



This cycle shows very well how an initial research and investment enthusiasm can transform in the disillusionment (e.g. new research priorities, practical or regulatory obstacles with technology development or implementation, lack of public acceptance etc.). As the red line in the graph illustrates, this phase can be partially overcome (e.g. with new financing, new related discoveries etc.) but the initial peak is unlikely to happen again, leading rather to a ''plateau'' of productivity. This does not imply that the given technology is necessarily abandoned, but the research and investment priorities, as well societal interest and trust are not so high anymore. Clearly, this innovation process graph may be telling just a part of the story: new discoveries, new areas of applications, improved access etc. may continue shifting the red line up and down. However, this innovation dynamic explains well the differing perceptions about readiness, potential for impact and sustainability of AI (and other PETIAS) that we encountered through different consultations at different points of time.

require careful, deliberate efforts.

In summary, the recent surge in AI advancements has undoubtedly contributed to a sense of acceleration and related skepticism reflected in the 2024 survey's shorter timelines for the impact of PETIAS. However, while AI has sparked a wave of innovation and set high expectations, the varied and multifaceted challenges of integrating these pre-emerging and emerging technologies into the agrifood systems suggest that a balanced approach, acknowledging both potential and limitations, is necessary for achieving sustainable and resilient agrifood systems. A more analytical rating of PETIAS, which explicitly takes into account the potential for democratization and which we undertook in the 2024 survey, suggests that it is the narrower, more familiar aspects of AI that inspire hope in agrifood innovations, rather than a vision of a major revolution prompted by AGI and quantum computing.

4

Clusters and emerging innovation fields

4.1 CLUSTERS

The clusters in our typology are groups of related technologies and innovations of a similar nature. From the perspective of the pre-emerging and emerging technologies and innovations, we have identified the following clusters: advanced biotechnologies, advanced digital technologies and innovations, advanced geospatial technologies and innovations, new renewable energy and transportation, micro- and nanotechnology and nanobiotech, market and financial innovations and policy and organisational innovation. The latter category includes a seemingly mixed group of innovations, from nature-based and frugal to consumer-to-food economy and innovation policy labs; however, from the point of view of emergence and impact, they all have a common ground: to be able to make a significant impact these sometimes not new practices and forms of organisation need to be scaled up through policies and new forms of organisation.

Figure 9. Pre-emerging and emerging technologies and innovations clusters

According to the 2024 survey, among the pre-emerging and emerging agrifood technologies and innovations, the cluster with the most significant impact on achieving inclusive agrifood systems is policy and organizational innovations (1.41), while the most negligible impact is attributed to advanced biotechnologies (0.55).

Regarding achieving sustainable agrifood systems, experts rated technologies and innovations from the policy innovation (1.52) and advanced geospatial technologies (1.50) clusters the highest. In contrast, micro-nanotechnology, nanobiotechnology (1.06) and market and financial innovation (1.04) received the lowest scores.

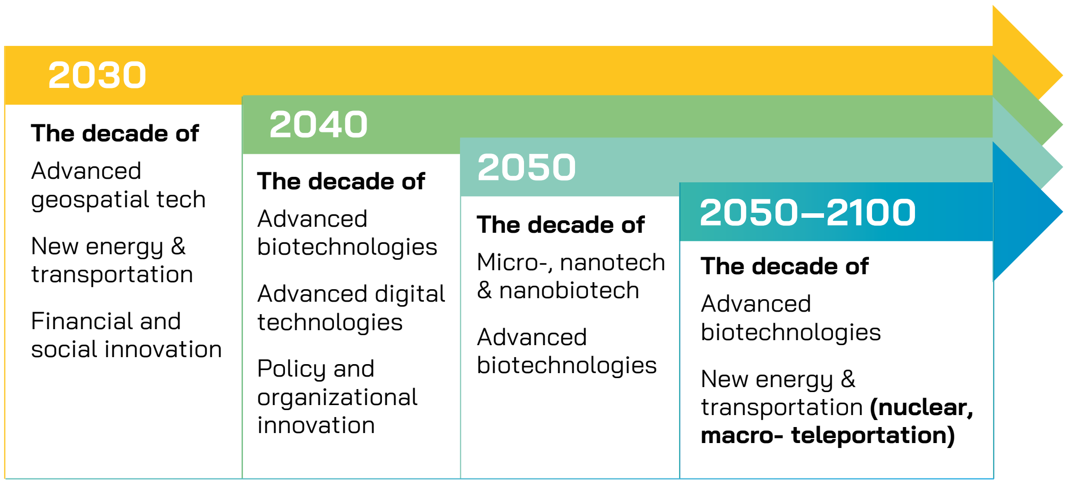
Similar results were observed when assessing the impact of technologies and innovations on resilient agrifood systems. According to respondents, advanced geospatial technologies (1.50) and policy innovation (1.48) may have the most significant impact, while market and financial innovation (0.84) may have a marginal impact.

Based on expert assessments, policy and organizational innovations and advanced geospatial technologies appear to be critical to the development of global agrifood systems. The table below presents the complete treatment of average values per cluster.

Table 2. Clusters' impact on achieving a inclusive/sustainable/resilient agrifood systems
the scale uses ranges from - 3 (very negative) to +3 (very positive)
perceived impact by the respondents

		Average		
	Emerging agrifood technologies and innovations clusters	inclusive	sustainable	resilient
1	Advanced biotechnologies	0.55	1.10	1.12
2	Advanced digital technologies	0.75	1.33	1.27
3	Advanced geospatial technologies	0.75	1.50	1.50
4	Policy and organizational innovation	1.41	1.52	1.48
5	New renewable energy and transportation	0.99	1.30	1.39
6	Market and financial innovation	0.78	1.04	0.84
7	Micro-nanotechnology and nanobiotech	0.72	1.06	1.11

Figure 10. Horizon of the emergence of clusters of technologies and innovations



4.2 EMERGING INNOVATION FIELDS

Emerging innovation fields refer to rapidly evolving areas of technology and innovation that have the potential to significantly impact various aspects of society, the economy and culture, including agrifood systems. These fields often involve interdisciplinary approaches, groundbreaking concepts, novel applications and cutting-edge research, or they may consist of a growing number of incremental changes that can eventually lead to a major shift.

Emerging innovation fields emphasize the interdisciplinary nature of the PETIAS that comprise them. These PETIAS, which vary in their stages of emergence and maturity, interact with one other and their broader innovation ecosystems, driving the rapid development and transformative potential of these fields.

Moreover, the pace of emergence may differ across regions (Alexandrova-Stefanova N., *et al.*, 2023), and their potential to influence agrifood systems and research and innovation paradigm shifts (RIPS) will not be uniform (see Chapter 7). The purpose of presenting them in this chapter is to raise awareness, stimulate reflection on the available options and encourage informed decision-making and community engagement to drive transformational change in agrifood systems.

It is important to note that these fields are often interconnected and can overlap. For instance, Web3.0 and molecular computers may be integrated with circular and nature-positive agriculture practices to create a more efficient, democratic and sustainable agrifood nexus.

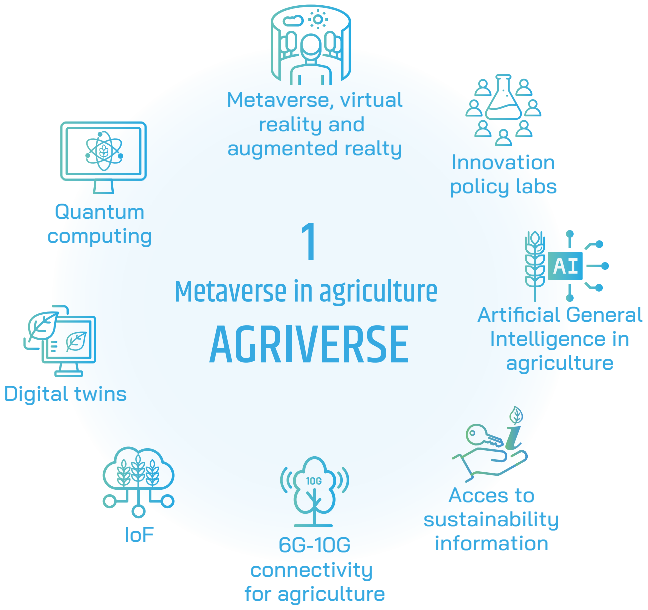
We believe that identifying emerging innovation fields in agrifood systems – beyond individual PETIAS and clusters – is essential due to their rapid development and potential for significant interdisciplinary impact. Interdisciplinarity plays a crucial role in driving innovation, as it promotes the interaction of diverse ecosystems, creating synergies that accelerate progress (WIPO, 2024a).

When experts from various fields collaborate, they bring unique perspectives, skills and resources towards a common goal, resulting in more comprehensive, rapid and effective solutions.

In contrast to traditional multidisciplinary approaches, which often remain within the boundaries of existing disciplines, interdisciplinary emerging fields facilitate deeper integration by analysing, synthesizing and harmonizing connections between disciplines into a coherent whole (Choi and Pak, 2006). However, the pace of development in these emerging fields is often constrained by the slowest-advancing component, referred to as the "most lagging behind" factor. By integrating knowledge and aligning policies and investments across multiple disciplines, we can accelerate the development of these lagging areas, enhancing the overall impact and speed of innovation. This holistic approach ensures that advancements are interconnected rather than isolated, amplifying their potential to address complex challenges and create meaningful change.

Based on this framework, ten emerging innovation fields were selected from 44 identified through literature reviews, critical analysis and input from FSN Forum submissions and FAO Foresight workshop participants. While we focused on these ten specific emerging innovation fields in our analysis, it is important to remain vigilant about other promising areas that were not included in the initial selection. These include space-based food production innovations, food-sensing technologies for monitoring food quality and safety, ecosystem engineering for efficiency and resilience, food from waste, financial technologies and new financial models, circular feedstock production (from feed to fertilization) and unmanned aerial systems.

These fields should remain on our radar, as their development could accelerate and lead to significant change, contributing to grater innovation and uncertainty in the agrifood systems.



Related RIPS: Convergence, Biomimicry, Plant diseases, Geoengineering.

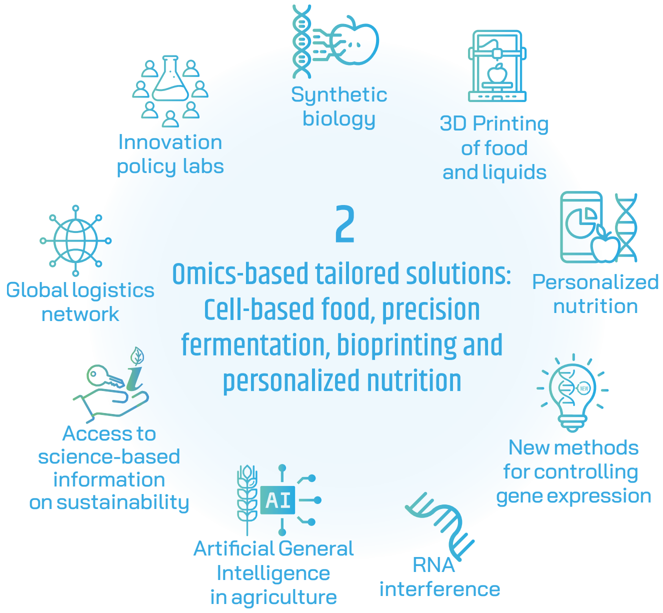
The metaverse is defined as an integrative ecosystem of virtual worlds offering immersive experiences to users (ITU, 2023). As our agrifood systems undergo profound transformations, the convergence of digital technologies is giving rise to an emerging field known as the agricultural metaverse (or agriverse). This immersive virtual space holds the potential to revolutionize farming practices, advance science, enhance market functions, improve decision-making and forecasting and anticipate systemic synergies. Ultimately, it offers a way to enhance sustainability, resilience and food security. By enabling anticipatory actions in complex scenarios while stimulating learning, the metaverse can help maximize benefits and minimize trade-offs in emerging fields like vertical farming, regenerative agriculture, cell-based food, precision fermentation and circular economy practices. The metaverse can also become essential in preparing for emergency situations and disaster management.

At the core of the agricultural metaverse are virtual reality (VR), augmented reality (AR), Internet of Things (IoT) and blockchain, often powered by digital twins and AI. VR and AR create realistic simulations of farms, allowing farmers to visualize and interact with their fields virtually. These technologies can be used for tasks such as remote crop monitoring, virtual site visits and training on new agricultural techniques. Blockchain, which is a decentralized ledger system, offers secure, transparent solutions for supply chain management, decision-making, traceability and land ownership records, enabling farmers to build trust with consumers, policymakers and financial institutions. Integrating blockchain with the metaverse can foster decentralized and more democratic agrifood systems.

The potential benefits of the agricultural metaverse are vast. By optimizing resource allocation, reducing waste and improving yields, farmers can enhance profitability, while decision-makers can increase the efficiency of agrifood systems in a democratic and sustainable manner. Precision agriculture within the metaverse can help minimize the environmental impact of farming by reducing pesticides and fertilizer use. The metaverse also fosters knowledge sharing and collaboration among farmers, researchers, agribusinesses, promoting co-innovation and empowering functional Agrifood Innovation Systems (AISs) to drive sustainable practices.

However, several challenges and risks accompany the adoption of the agricultural metaverse. The high cost of these technologies can be prohibitive for small-scale farmers. Ensuring data privacy and security is crucial to protect sensitive information. Robust internet connectivity, cyber security and digital literacy are also needed at all levels to fully harness the metaverse's potential for all. Innovative policies and regulations for data protection, as well as financial mechanisms to ensure access for smallholders, are vital for sustainable and equitable implementation. Technological and policy innovations are also necessary to secure the whole system against hacking or technological failures. Given the metaverse's potential for education, new learning and training modalities must go beyond simply adapting traditional extension content into virtual environments.

Despite these challenges, the agricultural metaverse is poised to play a key role in shaping the future of agrifood systems. By addressing the risks and capitalizing on its benefits, farmers, practitioners and decision-makers can leverage this emerging field for preparedness and to create more sustainable, efficient and resilient agrifood systems. As the metaverse evolves, fostering multistakeholder collaboration, investing in research and development and ensuring equitable access for all will be crucial to realizing its full potential.



Related RIPS: Convergence, Open innovation, Geoengineering, Citizen science.

FAO defines cell-based food production as the use of cells isolated from animals, plants or microorganisms to produce food products, ingredients or additives (FAO, 2022c). These products can often mimic existing animal products, such as meat, poultry, seafood, dairy and eggs, but are produced in controlled conditions. By bypassing traditional livestock farming, which is a controversial concept, cellular agriculture might offer a solution to address global challenges related to food security, sustainability and animal welfare.

A notable variant of cell-based food is cultivated seafood, which involves cultivating seafood cells in a laboratory environment, producing various seafood products without harming marine ecosystems (Chandimali *et al.,* 2024). Similarly, precision fermentation (FAO, 2022c) involves microorganisms like bacteria, yeast or fungi in controlled environments to produce target products such as proteins, enzymes, vitamins or other bioactive substances. Both cell-based food and precision fermentation are at the cutting edge of biotechnology and food science, poised to revolutionize how we produce food and understand agriculture.

Central to cell-based food are advanced technologies that facilitate the growth and differentiation of animal cells or microorganisms. Bioreactors, specialized vessels with nutrient-rich media and temperature controls, allow cell proliferation and precision fermentation. These bioreactors can cultivate muscle or fat cells, which are then assembled into products like meat or dairy. Precision fermentation can produce proteins and other compounds found in animal-derived foods, tailored for specific nutritional content and textures to meet consumer preferences. Tissue engineering techniques, combined with genetic engineering, allow scientists to produce specific tissues and products. Furthermore, advancements in bioinformatics and computational biology help optimize production methods.

Bioprinting enables the creation of complex three-dimensional structures of cultured meat, mimicking the natural texture and appearance of traditional meat (Kang *et al.,* 2021). It also allows for the incorporation of ingredients like plant-based proteins or fats, enhancing flavour and nutritional profiles. By combining new proteins with bioprinting, it is possible to develop realistic and appealing meat alternatives catering to diverse consumer preferences.

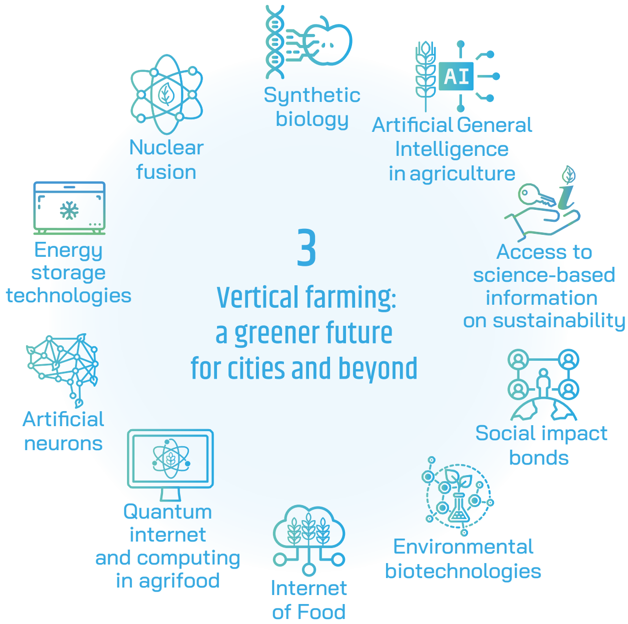
The potential benefits of this emerging field are immense. By reducing or even eliminating the environmental footprint associated with livestock farming – such as greenhouse gas emissions, deforestation and water pollution – this technology can significantly contribute to climate change mitigation. Cell-based food also offers a more humane and ethical approach to animal welfare by eliminating the need for animal slaughter. Additionally, it can provide a stable food supply in regions with limited agricultural resources or extreme weather conditions, as it is less vulnerable to disease outbreaks, extreme weather or geopolitical instability. Innovations in logistics and food distribution are also crucial to ensure food produced in one place reaches regions experiencing food deficits. Moreover, cell-based food offers the potential for products free from antibiotics, hormones and other contaminants commonly found in traditional animal agriculture.

Personalized nutrition, also known as precision nutrition or nutrigenomics, is an area of intersection for food, nutrition and medicine. It tailors dietary recommendations based on individual genetic, environmental and lifestyle factors. Supported by precision fermentation and cell-based food, this area seeks to optimize health outcomes and prevent chronic diseases. Bioprinting can also create customized protein products tailored to specific dietary needs or health conditions. By incorporating functional ingredients like omega-3 fatty acids, probiotics or plant-based proteins into bioprinted products, it is possible to develop foods that are not only nutritious but also have therapeutic benefits.

However, the adoption of cell-based food, precision fermentation and bioprinting presents several challenges and trade-offs. Production costs are currently higher than traditional livestock farming. Social sustainability poses a concern, particularly for pastoralist communities and livestock farmers who rely solely on livestock for their livelihoods. To prevent job losses, innovative policy measures must focus on requalification and job creation, while also preserving the traditional lifestyles of pastoralist communities. For example, combining science with traditional knowledge and creating market niches for sustainably produced meet could provide solutions.

Consumer acceptance is another hurdle, as many people may be hesitant to consume products grown in a laboratory. Establishing or adapting regulatory frameworks and safety standards is also necessary to ensure the safety and quality of cellularly produced foods.

Despite these challenges, omics-based tailored solutions hold immense promise as a sustainable and innovative approach to food production. As research advances, production costs will likely decrease, making these technologies more accessible to consumers. This may imply coexistence between the traditional and omics-based meat production in a manner in which the pastoralists, livestock growers and consumers should not loose from the innovation.



Related RIPS: Convergence, Diseases and On-farm food systems.

Vertical farming, a method of cultivating plants in stacked vertical layers, often without soil or natural light, in controlled environment (Freizer, 2017), is rapidly emerging as a sustainable and efficient alternative to traditional agriculture. By utilizing controlled environments, vertical farms can produce crops year-round, independent of weather conditions or geographic limitations. This innovative approach addresses global challenges such as food security, land scarcity and climate change, particularly in regions with harsh conditions.

At the core of vertical farming are advanced technologies that optimize plant growth and resource management. Hydroponics, aeroponics and aquaponics are commonly used, allowing plants to grow without soil, using nutrient-rich water or air. LED lighting systems provide tailored light spectra to enhance photosynthesis and maximize crop yields. Automated systems regulate temperature, humidity and CO2 levels, ensuring optimal conditions for plant growth. Furthermore, data analytics and artificial intelligence are increasingly employed to optimize operations, reduce waste and improve overall efficiency.

Applying efficient vertical farming minimize environmental impact by reducing the need for vast tracts of land, mitigating issues like deforestation, soil erosion and pesticide runoff. Urban vertical farms can be situated closer to consumers, shortening food transportation distances, reducing the carbon footprint and improving food distribution for food security. They also generate jobs for urban populations and contribute to building a more sustainable and resilient food system, less vulnerable to weather-related disasters and pests.

However, the adoption of vertical farming faces several challenges. The high capital cost for constructing and operating vertical farms, along with the complexity of the technology, can create barriers to entry. Energy consumption for lighting, climate control and nutrient systems can also be significant. Moreover, concerns persist about the long-term sustainability of vertical farming, particularly regarding water usage and reliance on synthetic nutrients.

Despite these challenges, vertical farming has the potential to shape the future of agrifood systems significantly. As technology advances and costs decrease, vertical farms are likely to become more widespread and accessible. To fully harness this potential, innovative measures such as financial incentives (e.g. social impact bonds) to support the introduction of vertical farming by smallholders, and tailored innovation support services, particularly in urban areas where agricultural advisory services are often limited.

Related RIPS: On-farm agrifood systems, Biomimicry, Open innovation.

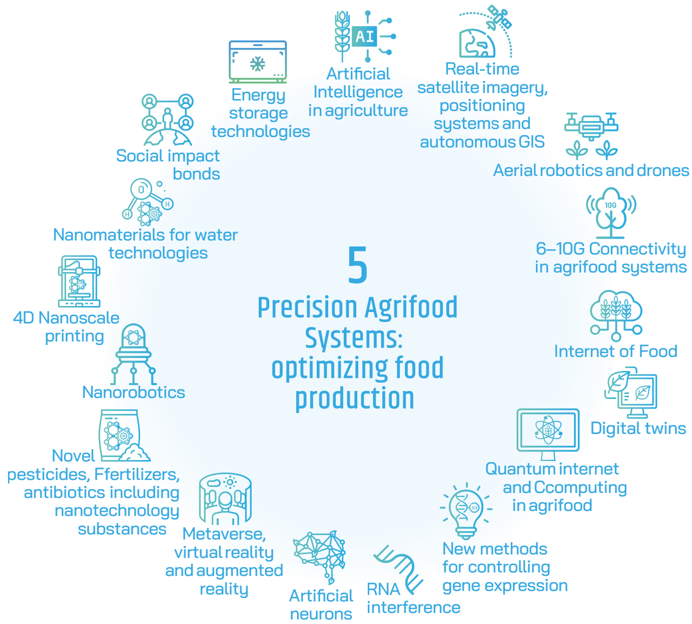
Circular agriculture aims to establish a closed-loop system where waste is repurposed as a resource, minimizing environmental impact and promoting sustainability by shifting away from linear production and consumption models. It seeks to create a more resilient and circular agrifood system (UNDESA, 2021).

At the core of circular agriculture are technologies that enhance resource efficiency and reduce waste. Composting systems convert organic waste into nutrient-rich fertilizers, decreasing reliance on synthetic inputs. Biogas digesters transform food scraps and manure into renewable energy, offering a sustainable power source for farming operations. Aquaponics integrates aquaculture with hydroponics, using fish waste to nourish plants, thus promoting efficient resource use. Precision agriculture, employing drones, sensors and data analytics, enables farmers to optimize resource utilization, minimize waste and increase yields (ISPA, 2024).

The benefits of circular agriculture are extensive. By reducing waste, pollution and resource consumption, it contributes to environmental health. Circular agriculture can also improve food security by fostering sustainable, resilient agrifood systems that are less vulnerable to disruptions and generate system-wide gains.

However, adopting circular agriculture comes with challenges. The upfront costs for technology and infrastructure can be prohibitive, particularly for small-scale farmers. There may be technical and logistical difficulties, especially in regions with limited resources or infrastructure. Fortunately, many nature-based, traditional and grassroots innovations exist that smallholders can implement at lower costs, but innovation support services, as well as incentivizing policies and financial mechanisms (e.g., social impact bonds or crowdfunding), are essential. Additionally, consumer acceptance and market demand for circularly produced goods will play a role in determining the success of these practices. It is thus crucial to simultaneously promote market innovations that raise awareness and create niches for circularly produced foods, such as participatory guarantee systems.

Despite these challenges, circular agriculture presents a promising path towards a more sustainable future. As technology advances and the awareness of its benefits increases, a gradual shift towards circular agricultural practices may be expected. Embracing this innovative paradigm can help create a more resilient, sustainable and equitable food system for generations to come.



Related RIPS: Convergence, Geoengineering.

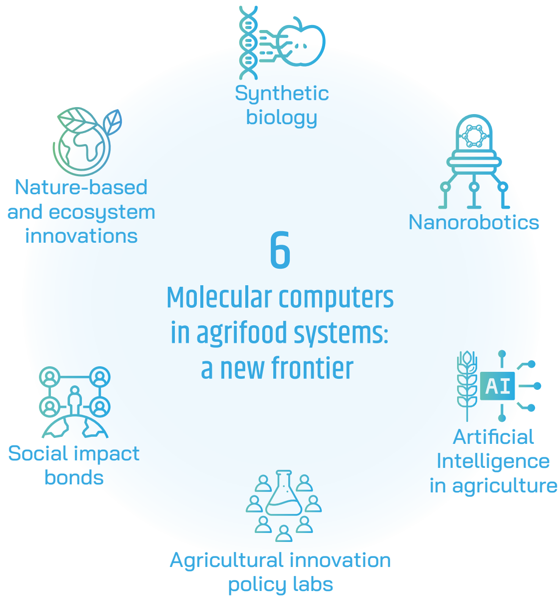
Precision agrifood systems, which merge cutting-edge technology with agricultural practices, aim to optimize food production by improving efficiency, minimizing waste and promoting sustainability. This emerging field encompasses a wide range of technologies and approaches, from digital tools for precise land, water and fertilizer management to innovative techniques in breeding and machine learning.

At the core of precision agrifood systems are advanced technologies like remote sensing, drones, sensors and data analytics, which help farmers collect and analyse extensive data on crops, soil and environmental conditions. These insights inform smarter decision-making. Precision breeding techniques, such as gene editing and modern breeding methods, enable the development of crop varieties with improved traits, like higher yields, disease resistance and better nutritional content. Precision learning, powered by artificial intelligence, uses machine learning algorithms to analyse data and identify patterns, allowing farmers to fine-tune their practices in real-world conditions.

The benefits of precision agrifood systems are considerable. By optimizing resource use, reducing waste and improving yields, these systems can significantly boost agricultural productivity and profitability. They also contribute to environmental sustainability by reducing the need for pesticides and fertilizers, lowering water consumption and protecting biodiversity. Moreover, precision agrifood systems can enhance food security by ensuring a reliable and efficient food supply.

However, there are challenges to their adoption. The high costs of implementing these technologies can be prohibitive for small-scale farmers. Ensuring data privacy and security is essential to protect sensitive information. Additionally, the lack of robust internet connectivity and digital literacy in some areas may hinder the full potential of these systems. To make precision agrifood systems more accessible, particularly for smallholders, innovative financial mechanisms like social impact bonds or crowdfunding are needed, as well as tailored innovation support services with modern training approaches such as living labs. Combining precision agriculture with evidence-based traditional, grassroots and nature-based-solutions could further optimize resource use while promoting more equitable access.

Despite these challenges, precision agrifood systems are set to play a transformative role in the future of agriculture. As technology continues to advance and costs decrease, these systems are likely to become more widespread and accessible. By addressing the barriers and leveraging the benefits, we can build a more sustainable, efficient and resilient agrifood systems for generations to come.



Related RIPS: Biomimicry, Convergence of technologies, On-farm agrifood systems.

Molecular computers, or DNA computers, represent a groundbreaking field that harnesses biological molecules to perform computational tasks (Ezziane, 2005). These tiny devices hold vast potential for use in agrifood systems, leveraging the unique properties of DNA and other biomolecules to offer innovative solutions to complex challenges in agriculture and food production.

One of the most promising applications of molecular computers in agrifood systems is biosensing. DNA-based sensors can detect and monitor contaminants, pathogens and allergens in food products, ensuring food safety and quality. These computers can also diagnose plant and animal diseases quickly and accurately, enabling timely interventions to reduce crop and livestock losses. Additionally, molecular computers can help optimize agricultural practices by monitoring environmental factors such as soil quality, water availability and pest populations.

The benefits of molecular computers are substantial. They offer unparalleled sensitivity, specificity, and speed, making them ideal for rapid, accurate analysis. Their portability and ability to be integrated into point-of-care devices allows for on-site testing and monitoring. They are also often more energy-efficient and environmentally friendly than traditional electronic computers.

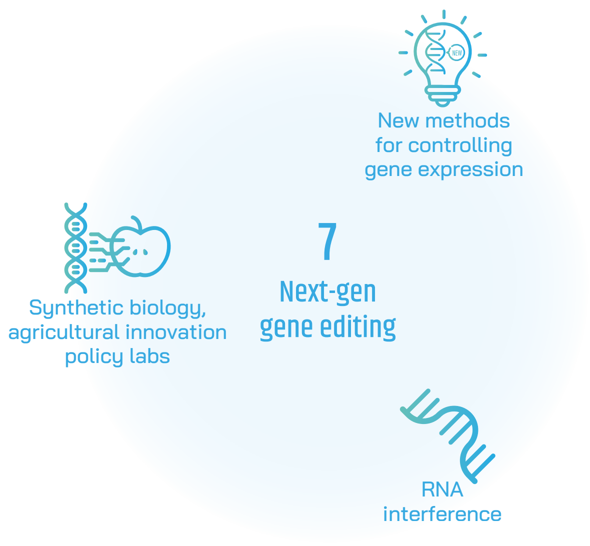
The potential widespread adoption of DNA computers could significantly impact agrifood systems by increasing demand for biomass and building blocks. This demand would create new biomass markets, raising the value agricultural produce and allowing farmers to diversify their operations. By producing biomass for DNA computer components, farmers could generate additional revenue and reduce reliance on traditional crops. Furthermore, biomass products used in DNA computer production could command premium prices due to their specialized applications.

Molecular computers also align with circular economy and no-waste food production principles, as biomass building blocks can be derived from agricultural waste or byproducts. This would reduce waste and enhance resource efficiency. Moreover, by converting waste into valuable resources for DNA computer production, farmers and food processors can recover value from otherwise discarded materials. However, this shift requires coherent policies, regulations to promote the sustainable application of molecular computers and tailored innovation support services for advanced skills, as well as financial mechanisms to make the technology accessible to smallholders. The integration of DNA computers into food production systems could enable a more efficient use of resources, reducing waste and further promoting a circular economy approach.

Despite their promise, the adoption of molecular computers in agrifood systems faces several challenges. Designing and constructing these devices is complex, and ensuring their reliability and reproducibility can be difficult. Food safety concerns and the potential for increased disease transmission must be addressed. Regulatory obstacles and ethical concerns related to the use of biological materials may also hinder widespread adoption.

Although increased biomass demand could compete with food production, the two sectors could complement each other if appropriate safeguards are implemented. For instance, agricultural residues and byproducts could be used for biomass production without compromising food supply. Moreover, new crop varieties and cultivation techniques, including traditional and nature-based solutions, could facilitate the simultaneous production of food and biomass (e.g., using underutilized or neglected crops).

Ultimately, the impact of DNA computers on agrifood systems will depend on several factors, including their specific applications, the availability and cost of biomass and building blocks and the development of sustainable production methods. However, the widespread adoption of molecular computers has the potential to drive significant innovation and create new opportunities in the agrifood systems.



Related RIPS: Convergence of technologies, Biomimicry, Geoengineering, Nature-positive innovations.

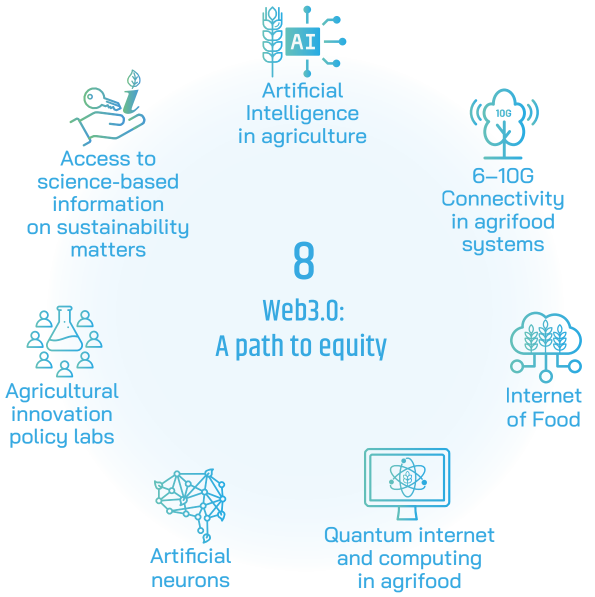
Next-gen gene editing technologies have emerged as a transformative force in agrifood systems since the early 21st century. These advancements hold the potential to address numerous challenges, from boosting crop yields and pest and disease resistance to improving nutritional value and creating more sustainable food sources (FAO, 2022d).

One of the most notable gene editing technologies is CRISPR-Cas9 (Barrangou *et al.,* 2016), a highly precise and efficient tool for modifying the genetic code of organisms, diagnosing diseases and studying the gene functions. CRISPR-Cas9 enables targeted DNA sequence alterations to introduce new traits, correct genetic defects or disable unwanted genes. Other methods, such as zinc-finger nucleases (ZFNs) (Urnov *et al.,* 2010) and transcription activator-like effector nucleases (TALENs) (Christian *et al.,* 2010), have also been applied in agriculture. After publishing FAO's Foresight Synthesis Report (Alexandrova-Stefanova N., *et al.*, 2023), which identified what we called "new methods for controlling gene expression", further advancements in gene editing emerged. These include multiplexed orthogonal base editors (MOBEs) with improved efficiency for installing multiple point mutations simultaneously (Zhang *et al.,* 2023), chimeric immune editing (CHIME) for gene knockouts without affecting immune cell function (LaFleur *et al.,* 2019) and Retron Library Recombineering (RLR), a more flexible gene editing tool that simultaneously creates mutations and tags mutated cells, addressing limitations of CRISPR (Schubert *et al.,* 2021). Additionally, CRISPR and RLR, Compact Fanzor systems, are RNA-targeting eukaryotic proteins that offer more precise editing of fungi, plants and animal genomes (Saito *et al.,* 2023).

The benefits of gene editing in agrifood systems are significant. By developing crops with enhanced traits, gene editing can increase yields, improve nutritional content and reduce the reliance on pesticides and herbicides. It also helps develop crops and breeds that are more resilient to pests, diseases and environmental stresses, contributing to climate adaptation. Moreover, gene editing can create innovative food products with unique characteristics, such as hypoallergenic grains or alternative protein sources.

However, the adoption of gene editing in agrifood systems presents challenges. Unintended consequences, such as unforeseen mutations or the introduction of invasive species, are key concerns. Animal welfare must also be carefully considered. Additionally, regulatory issues and public acceptance could pose barriers to the widespread adoption of gene editing technologies. To overcome these challenges, innovative policies, regulatory frameworks, monitoring systems and transparent communications channels – such as those provided by innovation policy labs and living labs – are essential.

Despite these hurdles, gene editing is one of the fastest developing emerging field. Continuous improvements in the technology address the drawbacks of earlier generations. Enhancing understanding of the benefits and potential hazards various contexts, alongside establishing appropriate regulatory and governance frameworks, will support the development of a more sustainable, efficient and resilient agrifood system for the future generations.



Related RIPS: Open innovation, On-farm agrifood systems, Citizen science convergence, Biomimicry, Geoengineering, Pests.

The early internet, or Web 1.0, mainly connected people to information. Web 2.0 introduced user-generated content and social media, enhancing interaction and community building but also raising privacy concerns. Now, Web3.0 (Liu *et al.,* 2022), the next generation of the internet, aims to revolutionize how services are delivered to farmers and consumers by sharing user-generated content and fostering innovation in food networks and urban and rural communities – without requiring personal data to be handed over to companies. In doing so, Web 3.0 can create an "internet of value", democratizing agrifood systems by incorporating decentralized technologies that promote transparency, traceability and sustainability. This emerging field integrates blockchain, decentralized applications (dApps) and tokenization to build a more interconnected and efficient agrifood systems.

One of the key benefits of Web3.0 in agrifood systems is enhanced transparency and traceability. Blockchain technology enables the creation of immutable records for food products, tracing them from farm to fork and ensuring consumers have access to accurate information about food origin, production methods and handling. It also facilitates transparent contacts arrangements and data management, building trust between producers and consumers, reducing food fraud and improve food safety.

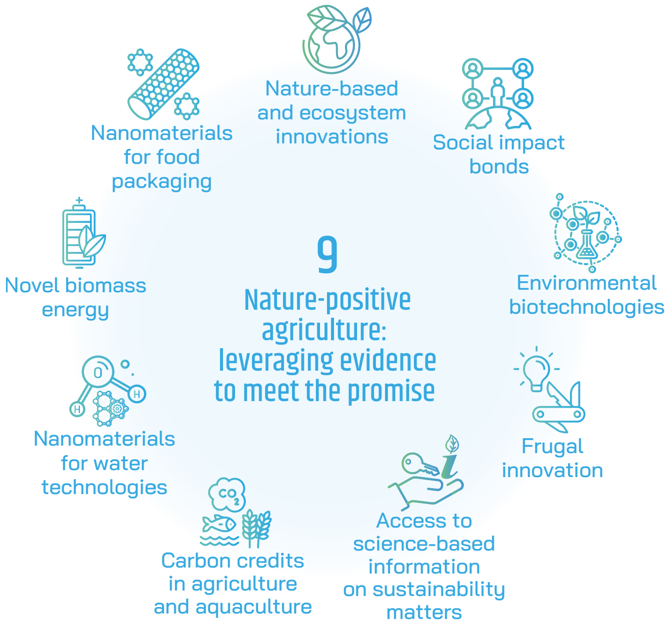
Decentralized applications (dApps) can be used to create platforms for farmers, offering a direct connection between famers and consumers, bypassing intermediaries and reducing transaction costs (Buterin, 2014). This empowers small-scale farmers and gives consumers access to fresher, more affordable food. Additionally, dApps can support peer-to-peer transactions, allowing farmers to sell their products directly to consumers without the need for traditional payment systems. This can be integrated with social innovations, such as participatory guarantee systems.

Tokenization, which involves representing assets as digital tokens on a blockchain, offers new economic models in the agrifood systems. For instance, farmers can tokenize their land or crops, enabling investors to purchase fractional ownership and share in the profits. This model provide farmers with access to capital, reducing their reliance on traditional financing methods (Tarhini *et al.,* 2021).

The combination of AI and blockchain can optimize 5G and 6G networks by improving configuration, routing and resource allocation. This enhances efficiency, transparency and provides a verifiable record of network activities.

Despite its potential, Web3.0 also faces challenges. The complexity of blockchain technology can hinder adoption by farmers and consumers. Issues of scalability and interoperability may also limit the widespread use of Web3.0 solutions. Moreover, regulatory uncertainties, alongside data privacy and security concerns, need to be addressed. Therefore, digital literacy programmes, innovation support services and modern data protection policies are critical to facilitate Web 3.0 adoption.

Finally, this section also highlights two longstanding approaches – grassroots innovation and nature-positive innovation. Although they have been part of human practice since the dawn of civilization, these fields are considered emerging due to their renewed attention and significant potential for sustainability and inclusivity in agrifood systems.



Related RIPS: Biomimicry, Citizen science open innovation.

Nature-positive agriculture, as defined by FAO, involves "actions to protect, sustainably manage and restore natural or modified ecosystems and that address societal challenges effectively and adaptively, simultaneously providing benefits for human well-being and biodiversity. In agriculture (including the crop, livestock, fisheries, apiculture, aquaculture and forest sectors), they mean natural processes relying on ecosystem functioning to ensure food and livelihood security, healthier diets and more inclusive rural economies.'' (FAO, 2018b).

Today, this broad approach includes various strategies, such as organic, regenerative and conservation agriculture, permaculture, agroforestry and agroecology. In this chapter, we focus specifically on those fields that best align with the definition of emerging innovation.

Regenerative agriculture is a holistic approach that aims to restore and enhance land health. By emphasizing soil health, biodiversity and ecosystem functions, regenerative practices seek to create more sustainable and resilient agricultural systems. Similarly, agroecology not only focuses on ecologically sound farming but also incorporates circularity, food culture, traditions and social benefits. This knowledge- and innovation-intensive field involves holistic, bottom-up, sustainable and territorial science and practices, optimizing interactions between plants, animals, humans and the environment. Agroecology is both a scientific approach and a socio-political paradigm that aims for socially equitable agrifood systems (FAO, 2018c).

Key practices of regenerative agriculture include, various practices that promote soil health and biodiversity cover cropping, crop rotation and no-till farming. Cover crops – planted between cash crops – help protect soil from erosion, improve soil structure and enhance nutrient cycling. Crop rotation, the practice of alternating different crops in a field over time, prevents soil depletion and reduces the risk of pest and disease outbreaks. No-till farming – a method that avoids disturbing the soil – preserves soil structure, reduces erosion and increases carbon sequestration. Regenerative agriculture also includes practices like agroforestry, where trees and shrubs are integrated into agricultural land, and livestock grazing management that mimics natural grazing patterns.

A notable example of nature-positive agriculture through agroforestry is "land maxing" in tropical zones (Leakey, 2024). This process involves planting nitrogen-fixing "fertiliser trees" to enhance soil fertility, domesticating elite trees for income generation and improved nutrition and processing fruits to extend their shelf life and marketability. This creates a highly adaptable generic model that can close the yield gaps in failing farming systems.

The benefits of regenerative agriculture are numerous. It improves soil health, increases crop yields, reduces the need for synthetic inputs and enhances water retention. Regenerative practices can also contribute to climate change mitigation by sequestering carbon in the soil and reducing greenhouse gas emissions, nutrient cycling, water retention, soil regeneration, carbon storage and nitrogen fixation. Furthermore, regenerative agriculture promotes biodiversity by creating habitats for beneficial insects and other organisms, including humans.

However, adopting nature-positive agriculture presents challenges. The transition to regenerative practices often requires significant changes in farming practices and may involve a steep learning curve for farmers, with ecosystem services taking time to develop. Initial financial and labour investments in regenerative practices and agroecology can be substantial, underscoring the need for innovative and equitable land tenure laws. Moreover, access to market for regenerative products, particularly in global contexts, can be difficult, making it challenging for farmers to find profitable outlets. Innovative marketing mechanisms such as ecotourism, fair trade and e-platforms that connect consumers directly with producers are needed to facilitate market access for naturally produced food products, including local, underutilized and neglected crops.

Lastly, nature-based innovations – especially agroecology – require a substantial paradigm shift. This shift values traditional and indigenous knowledge, counters industrial agriculture monopolies and prioritizes social and environmental practices.

Despite these challenges, nature-positive agriculture holds great promise path for a sustainable future. While they hold great potential, their economic, social and environmental sustainability should be rigorously evaluated, considering various contexts and dynamics over time. As evidence of its benefits grows and consumer awareness increases, agroecology research and regenerative practices continue to advance, leading to a gradual shift towards these practices. However, this transition will require significant changes in knowledge, innovation systems and policy support, promoting the democratization of information and agricultural practices.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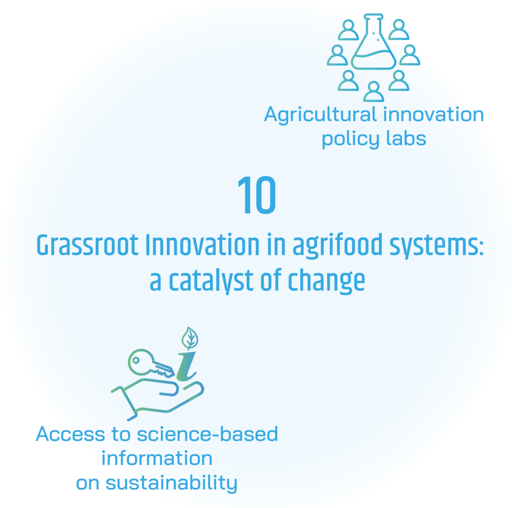


Related RIPS: Biomimicry, Citizen science open innovation.

Grassroots innovation, driven by local communities and individuals, has become a powerful force in agrifood systems. This bottom-up approach, characterized by trial-and-error experimentation and the blending of traditional knowledge with scientific insights, provides innovative solutions to agricultural challenges. There is no universally accepted definition of grassroots innovation, but for this report, we have adopted the definition that best fits our context: "Innovations created by individuals or collectives from indigenous or peasant communities or organizations, which generate new social or technological solutions based – at least partially – on local or traditional knowledge, to satisfy their social and environmental needs" (Orozco-Meléndez *et al.,* 2022). While grassroots innovations can be profit-driven, they are often primarily motivated by social needs, ideological principles and collective ownership. These innovations typically draw on social values, culture, volunteer labour and donations, and are developed in a social context rather than an economic one (Seyfang *et al.,* 2007; Seyfang *et al.,* 2013). Their aim is to address societal needs unmet by the state, empower marginalized communities and promote decolonial, political, social and cultural principles (Orozco-Meléndez *et al.,* 2022).

One of the key strengths of grassroots innovation is its ability to address specific local needs and constraints. By leveraging the unique knowledge and experiences of farmers and communities, grassroots innovators can create solutions tailored to their particular circumstances. This context-specific approach often results in highly effective and sustainable practices that top-down initiatives may struggle to replicate.

Grassroots innovation can also contribute to the development of new technologies, practices or social networks that have the potential to scale up and be more widely adopted. For instance, traditional farming techniques proven effective in certain regions may be adapted and combined with modern technologies to create more sustainable and resilient agricultural systems.

However, scaling grassroots innovations and gaining wider recognition is challenging. Because these innovations often stem from local or indigenous knowledge rather than traditional scientific institutions, they do not follow the conventional technology development model. In traditional models, innovation begins with a scientific discovery, followed by research to increase efficiency or reduce costs, then pilots and finally scaling through technology transfer. In contrast, grassroots innovations emerge through less linear processes, making it difficult to pinpoint their origins or anticipate when they will enter the mainstream. As a result, grassroots innovators, typically collectives, often lack the resources and institutional support needed to document and validate their work, limiting its visibility and potential for broader impact.

To overcome these challenges, supportive environments that nurture grassroots innovation must be established. This includes strengthening local agrifood innovation systems (AISs), fostering collaboration between grassroots innovators and researchers, including social scientists, and providing them with the necessary policies, institutions, capacities and financial resources. Supporting grassroots innovation will harness the creativity and ingenuity of local communities to address pressing challenges in agrifood systems. Additionally, finding a balance between open-source approaches and intellectual property rights must be found.

In conclusion, grassroots innovation represents a valuable and often underutilized source of creative solutions within agrifood systems. By leveraging the unique knowledge and experiences of local communities, grassroots innovators can develop sustainable and effective practices that address specific local needs. While scaling up these innovations can be difficult, creating supportive environments and encouraging collaboration will allow us to harness the power of grassroots innovation, leading to more resilient and sustainable communities.

Concluding remarks on emerging innovation fields

Identifying emerging innovation fields within agrifood systems is essential due to their rapid development and potential for significant interdisciplinary impact. Ten emerging innovation fields believed to shape agrifood systems have been studied and described.

Interdisciplinarity is a key driver of innovation. By fostering interactions across diverse ecosystems, interdisciplinary approaches create synergies that accelerate progress. When experts from various fields collaborate, they bring unique perspectives and skills, leveraging diverse resources towards common goals. This results in more comprehensive, rapid and effective solutions.

Beyond traditional multidisciplinary approaches, interdisciplinary fields play a crucial role in development by analysing, synthesizing and harmonizing links between disciplines into a coordinated and coherent whole. The pace of development in these fields is often limited by the slowest advancing component, the “most lagging behind” factor. By integrating knowledge and targeting policies and investments from multiple disciplines, we can accelerate progress in these lagging areas, enhancing the overall impact of innovation.

This holistic approach ensures that advancements are interconnected, amplifying their potential to address complex challenges and create meaningful change. Successful implementation of any technology requires conducive policies that ensure social, food safety and environmental safeguards. Balancing intellectual property rights with open-source innovation, providing support services and creating inclusive and transparent spaces for dialogue with society are all key elements. Recognizing diverse sources of knowledge, such as innovation policy labs and living labs, further strengthens this dynamic and inclusive innovation ecosystem.

5

Areas of application and challenges

5.1 KEY AREAS OF APPLICATION

An analysis of key areas of application impacted by pre-emerging and emerging agrifood technologies and innovations (PETIAS) is crucial for this report as it provides a comprehensive understanding of how technology and innovation can transform various segments of the agrifood systems. By examining the major breakthroughs expected per area and its time horizon, as well as specific ways in which PETIAS can enhance production systems, processing systems, value chains, energy and transportation, food waste management, and other critical areas, agrifood systems' stakeholders can identify targeted opportunities for innovation, efficiency, inclusion, sustainability and resilience. This analysis would help policy makers, industry and community leaders, and researchers prioritize investments, develop supportive policies, and foster collaborative efforts that drive positive impact of cutting-edge and silent traditional knowledge solutions. Ultimately, it provides yet another angle for the data we collected which may be helpful in drawing conclusions about immediate opportunities for investment or policy improvement. Detailed information can be found in the Annex 6.

The application areas categorisation has been inspired by the logical framework based on the stages of the agrifood systems, the cross-cutting themes that impact multiple stages, and the overarching goals of sustainability, democratization and efficiency. The reasoning behind the categorisation is presented below.

1. Production systems

Production systems encompass the methods and practices used to grow crops and trees, raise livestock, and cultivate fish. These systems are fundamental to food production and directly impact food availability and quality. By focusing on PETIAS for production systems, we address applications related to crop yields, soil health, water use efficiency, and sustainable agricultural practices. Innovations in this area can lead to increased productivity, reduced environmental impact, and improved food security (Charatsari *et al.*, 2022).

2. Processing systems

Processing systems involve transforming raw agricultural products into consumable goods. This step is critical for enhancing food safety, extending shelf life, and adding value to agricultural commodities. Innovations in processing systems can lead to reduced post-harvest losses, improved nutritional content, and diversified product offerings. Efficient processing contributes to economic growth and ensures safe and nutritious food for consumers.

3. Value chains and services

Value chains encompass the journey from after the food is produced to market, as well asservices playing a crucial role in supporting this journey. This area relates to post-harvest production and storage, marketing and access to markets, and includes storage, food safety, market, social, financial and policy innovations.

4. Energy and transportation

Energy and transportation are integral components of agrifood systems and their importance cuts across all phases of the agrifood systems, such as production, processing, distribution and disposal. Energy powers machinery, irrigation, and processing facilities, while efficient transportation ensures the smooth movement of agricultural products. Innovations in renewable energy sources (such as solar or wind) and sustainable transportation (including smart logistics and low-carbon transport) contribute to reducing carbon footprint of agrifood systems. Reliable energy and efficient transportation enhance overall efficiency, democratization and sustainability.

5. Food waste

Food waste occurs at various stages of the supply chain, from production to consumption. Addressing food waste is essential for resource conservation and reducing environmental impact and presents a global issue with increasing impact not only in the HMICs. Innovations in minimizing food waste can lead to better resource utilisation, reduced greenhouse gas emissions, and improved food securit, and affecting the overall sustainability and resilience of the agrifood systems. It includes waste-to-energy technologies, composting, and food recovery programs. Reducing food waste is essential for improving food security, conserving resources, and minimizing environmental impact (Charatsari *et al.,* 2022).

6. One Health and nutrition

One Health and nutrition play a central role in agrifood systems. They impact both producers and consumers, livestock, marine organisms, trees and crops affecting productivity, well-being, and food safety. Focusing on nutrition involves addressing food quality, micronutrient content, and dietary diversity. Innovations in promoting balanced diets, fortification, and sustainable food choices contribute to better health outcomes. PETIAS that address effectively this area of application contribute significantly to the agrifood systems' resilience, sustainability and inclusion.

7. Governance and trade

Effective governance and trade policies are essential for regulating agrifood systems, ensuring integrity, safety, fair practices, multistakeholder participation and promoting international cooperation, facilitating global food distribution, as well as just and equitable innovation for all. This involves both technological (such as blockchain-based) and non-technological innovations in policies, regulations, financing and trade that influence the agrifood systems.

8. New materials, new proteins and circular economy

This category cuts across several agrifood subsystems, placing emphasis on novel approaches to sustainability. It includes the development of innovative materials used in agriculture and food packaging, development of alternative protein sources such as plant-based proteins, cell-based food and insect proteins, as well as creating a closed-loop system where not only waste is minimized, but resources are reused. It includes processes such as recycling and upcycling of materials, and emerging innovation fields such as omics, nature-positive agriculture and grassroot innovations. It also encompasses biodegradable packaging, smart materials, and nanotechnology (Alexandrova-Stefanova N., *et al.*, 2023). New proteins address the growing demand for sustainable and ethical protein sources, reducing the reliance on traditional livestock farming and its associated environmental impact (WEF, 2024; Charatsari *et al.,* 2022).

9. Blue economy

The blue economy focuses on marine and aquatic resources. It includes technology and innovation in fisheries, aquaculture, and coastal ecosystem management. It cuts across the phases of the agrifood systems and strives to promote sustainable seafood production, protect marine ecosystems, and enhance livelihoods for coastal communities. Innovations in aquaculture and responsible fishing practices are crucial for long-term food security, global resilience and sustainability.

10. Inclusion of the most vulnerable

Ensuring food security and nutrition for all and empowering vulnerable populations (such as small-scale farmers, women, youth and marginalized communities) are a moral imperative. To promote equity, social justice, and human rights, we found it crucial to prioritize inclusion as a separate application area for various technologies and innovations, both technological and non-technological. Innovations that empower vulnerable groups lead to more resilient, sustainable and equitable agrifood systems.

Major breakthroughs per area of application

Time horizons

The Delphi survey in 2023 asked experts and stakeholders to project the biggest breakthroughs in specific application areas by 2030, 2040 and 2050 (Figure 11).

2030 Projections: By 2030, the most significant breakthroughs are anticipated in production systems, which include precision agriculture, farm and land management, and regenerative agriculture, with 16 indications. Energy and transportation also stand out with 7 mentions, suggesting a focus on sustainable energy and transport solutions. Other notable areas include governance and trade (4 indications), processing systems (4 indications), and new materials, new proteins, and circular economy (3 indications). These priorities reflect an emphasis on improving efficiency, sustainability, and innovation in food production, resource management, and infrastructure.

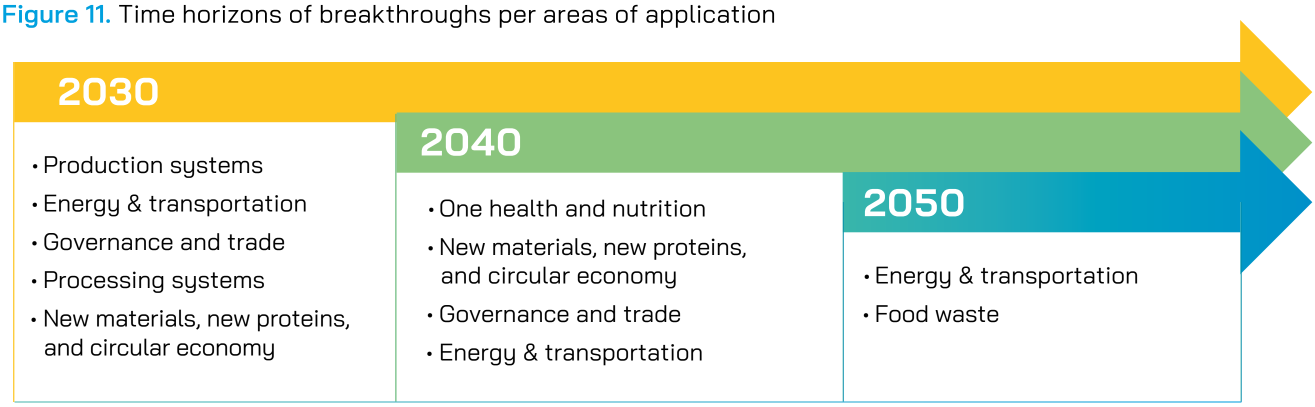
2040 Projections: By 2040, there is an expected shift towards further advancements in One Health and nutrition, receiving 6 indications. This reflects a growing focus on integrated approaches to health that consider the interconnection between people, animals, plants, and their shared environment. New materials, new proteins, and circular economy (5 indications) and governance and trade (5 indications) remain important, indicating ongoing efforts to develop sustainable materials and improve global collaboration and trade systems. Additionally, energy and transportation continue to be a priority with 5 mentions, signaling continued innovation in sustainable energy solutions.

2050 Projections: Looking forward to 2050, energy and transportation remains a significant focus area, with 5 indications suggesting a long-term commitment to revolutionizing these sectors for sustainability. Food waste also emerges as a notable area with 3 indications, emphasizing the importance of reducing waste in agrifood systems to enhance efficiency and sustainability. The continued emphasis on these areas suggests an enduring need for innovation in managing resources and infrastructure as the world moves towards a more sustainable future.

In addition, the contributors to the FSN Forum (2024) identified several key areas where significant breakthroughs are expected in the coming years. These areas include:

- **Value chains and services:** digital agriculture platforms, blockchain technology, and other innovations related to value chains and services are expected to play a crucial role in transforming the agrifood systems.

Figure 11. Time horizons of breakthroughs per areas of application



- **Production systems:** precision agriculture, sustainable farming practices, and digitalization are seen as key drivers of increased productivity and sustainability in agricultural production.
- **Governance and trade:** E-governance and trade facilitation are expected to improve the efficiency and effectiveness of governance and trade at international and national levels.
- **Energy and transportation:** renewable energy integration and electric transportation are seen as essential for reducing the environmental impact of agrifood systems and improving their sustainability.
- **Inclusion:** promoting inclusivity in the agrifood systems is a key priority, with a focus on women, youth, and marginalized communities.
- **New proteins:** developing new sources of protein, such as alternative proteins and plant-based foods, is seen as essential for sustainably meeting the growing demand for food.
- **One Health and nutrition:** integrated health approaches and biofortified crops are expected to improve the nutritional value of food and promote human health.
- **Circular economy:** adopting circular economy principles can help reduce waste and promote sustainability in the agrifood systems.
- **Novel agricultural inputs:** new materials for plant and soil health and nutrition can improve agricultural productivity and sustainability.

In addition to the key areas mentioned earlier, participants also highlighted several other areas where breakthroughs are expected:

- **Territorial agrifood systems and local participatory governance:** strengthening local agrifood systems and involving communities in decision-making can improve food security, inclusion and resilience.
- **Women and youth empowerment:** empowering women and youth in the agrifood systems can lead to increased innovation, productivity, and equitable access to resources.
- **Community-based innovations:** grassroots innovations can address local needs and promote sustainable and inclusive development.
- **Minor crops and farmers' seed systems:** diversifying crop production and preserving traditional seed varieties can enhance food security, farmers' autonomy and biodiversity.
- **New local and branded food production:** developing local food brands and promoting regional products can support rural economies and create new market opportunities.
- **New sustainable nearshore aquaculture governance:** improving the governance of nearshore aquaculture can ensure its sustainability, improved livelihoods of local communities and contribute to food security.
- **Unlocking the potential of data and data sharing in agriculture:** leveraging data and analytics can improve decision-making, resource management, and market access.

Some participants focused on specific regions and countries within their respective areas. For instance, major breakthroughs are anticipated in governance and trade, particularly in North Africa and the Near East, with a strong emphasis on Turkey due to its advancements in E-governance, blockchain, and global trade. In Latin America, breakthroughs are envisioned primarily in production systems, while in Mozambique, a broader range of areas including energy, transportation, value chains, and one health and nutrition were highlighted.

The most detailed regional perspective concerned Africa, where breakthroughs are anticipated in production systems, energy and transportation, value chains and services, one Health and nutrition, digital governance and trade, new materials, proteins, and circular economy. These breakthroughs are expected to contribute to improved food security, sustainability, and economic development in the region.

For detailed information regarding the application context, relavant clusters and PETIAS, please see the Annex 3.

5.2 ADDRESSING AGRIFOOD SYSTEMS CHALLENGES

Pre-emerging and emerging technologies and innovations (PETIAS) can revolutionize multiple aspects of the functioning of agrifood systems, offering solutions to pressing challenges and driving sustainable development. This chapter explores how the insights from our foresight and research on 32 PETIAS, the clusters and the emerging fields can help develop focused strategies in addressing the eight key challenges facing agrifood systems, (Alexandrova-Stefanova, N. *et al.*, 2023) (Annex 1). It's important to note that the following examples of how PETIAS can address challenges are not exhaustive and may not include many indirect impacts and synergies worth further research. Instead, they aim to provide a glimpse into the diverse applications of these technologies and how they intersect with complex agrifood system challenges to understand better how PETIAS are distributed across challenges and how multiple interconnected technologies and innovations can cover them. This holistic view is essential for developing comprehensive strategies that leverage the full potential of PETIAS.

In analysing the distribution of PETIAS across the eight agrifood challenges (average relative advantage vs. maximal relative advantage), it is evident that:

- **All of the 32 PETIAS contribute to addressing the challenges.** Upon reviewing the distribution of PETIAS, it appears all 32 PETIAS have been assigned to at least one challenge. This ensures comprehensive coverage of potential solutions across the identified agrifood challenges.
- **Some PETIAS have a more specific focus.** For example, 3D printing of food and liquids is primarily relevant to food and nutrition security. At the same time, nuclear fusion mainly applies to energy demand (with a more indirect impact on the other challenges).
- **The contribution of each technology or innovation varies significantly.** Some PETIAS, such as innovation policy labs, nature-based and ecosystem innovations, real-time geospatial technologies, frugal innovations and territorial value chains and consumer-to-food, have potential solid applications across multiple challenges (Figure 12).

Figure 12. Top 5 technologies and innovations perceived to have the highest impact on each challenge. The score in the figures represent the relative advantage (RA) for each PETIAS.

Perceived impactful response (relative advantage score) to multiple challenges in a short time frame

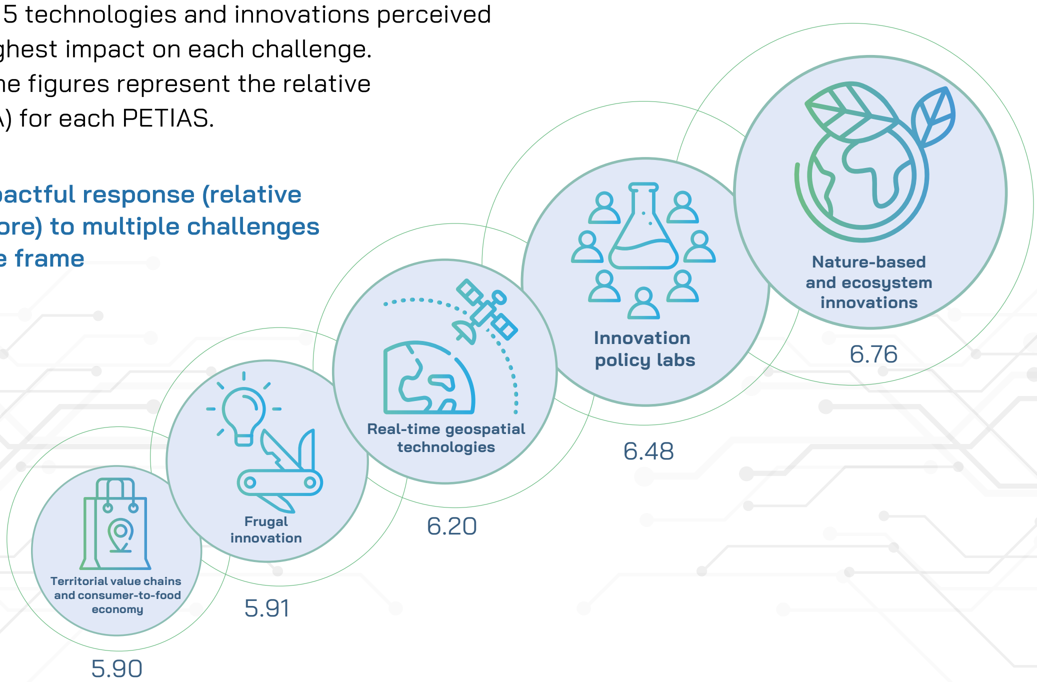
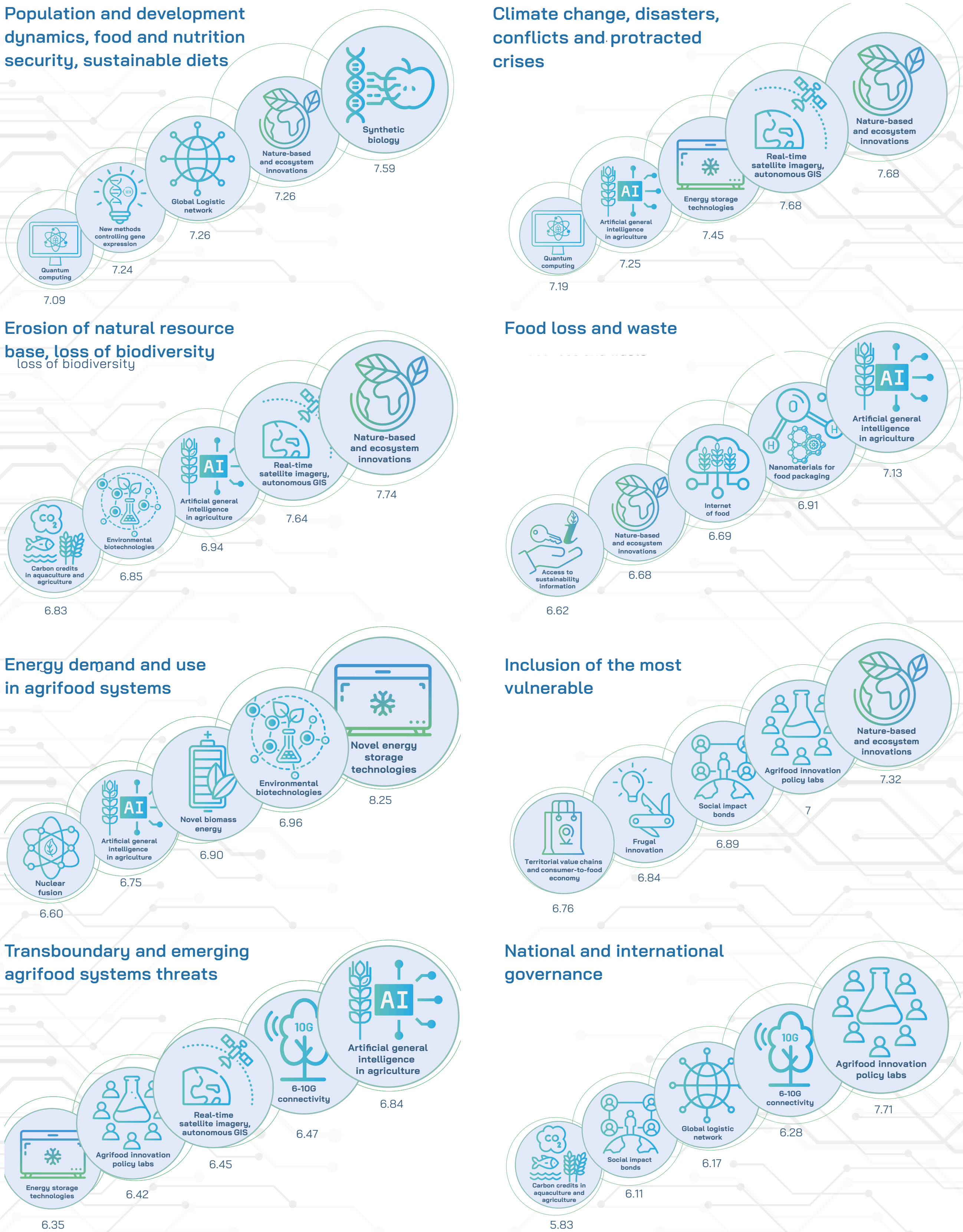


Figure 13. Top 5 technologies and innovations perceived to have the highest impact on each challenge. The score in the figures represent the relative advantage (RA) for each PETIAS.



- Some PETIAS are **believed to have outstanding performance and a very high level of effectiveness in addressing a particular challenge** (Alexandrova-Stefanova N., *et al.*, 2023), summarized again in Figure 13.

A closer look into the cluster and emerging field ecosystems further enriches insights.

- **The cluster's potential to address a given challenge varies across challenges.** Figure and tables (in the Annex 4) show how the clusters would address a challenge. The information about the clusters' strength, as well as the information about the single PETIAS, their ETM and ETSI, as well as the level of trade-offs, may guide the strategies for the challenge response, e.g. to create preparedness and invest in a longer-term technology or innovation that is particularly promising, or /and take action with PETIAS that have a low level of trade-offs and lower possible impact.

- When comparing clusters' ability to respond to a challenge, another cluster may be better positioned to address that challenge on average due to the cumulative strengths of its composing PETIAS. For example, **Population and development dynamics, food and nutrition security and sustainable diets** have two advanced biotechnologies in the top five and the cluster's strength is high. However, advanced geospatial technologies would be more promising as a cluster. Investing in a cluster with synergetic ecosystems and experience with their emerging fields could be a preferred strategy.

Figure 14a. Harnessing top PETIAS, clusters (the scores refer to their respective relative advantage per challenge), and emerging fields to address an agrifood systems challenge

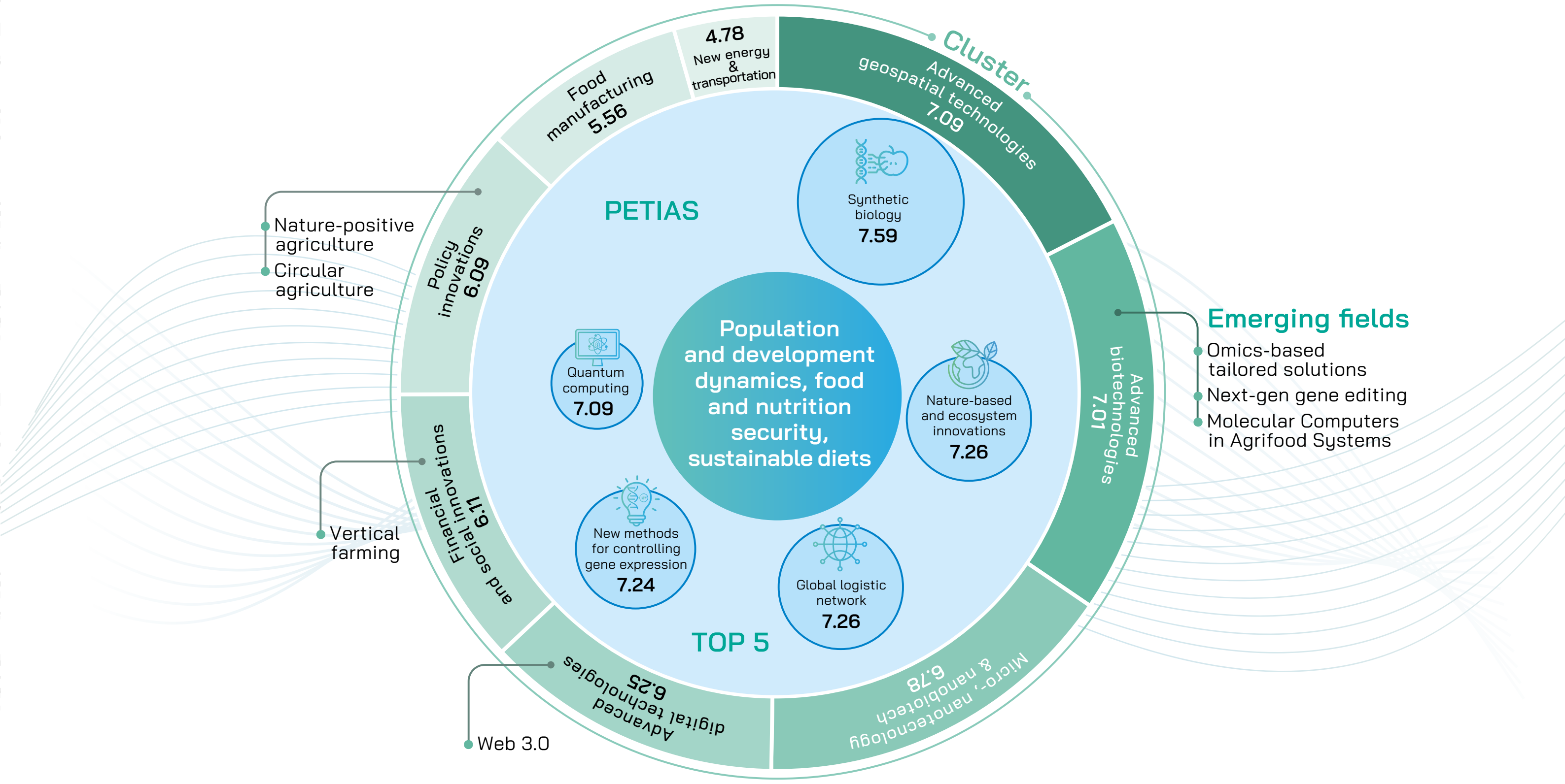
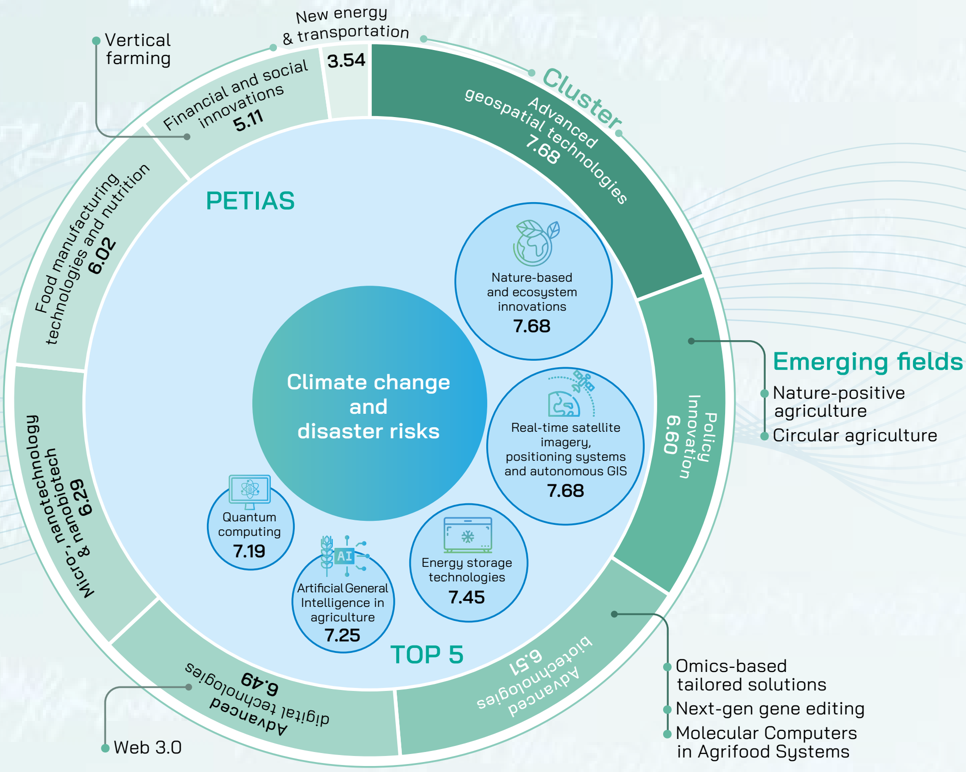


Figure 14b/c. Harnessing top PETIAS, clusters (the scores refer to their respective relative advantage per challenge), and emerging fields to address an agrifood systems challenge



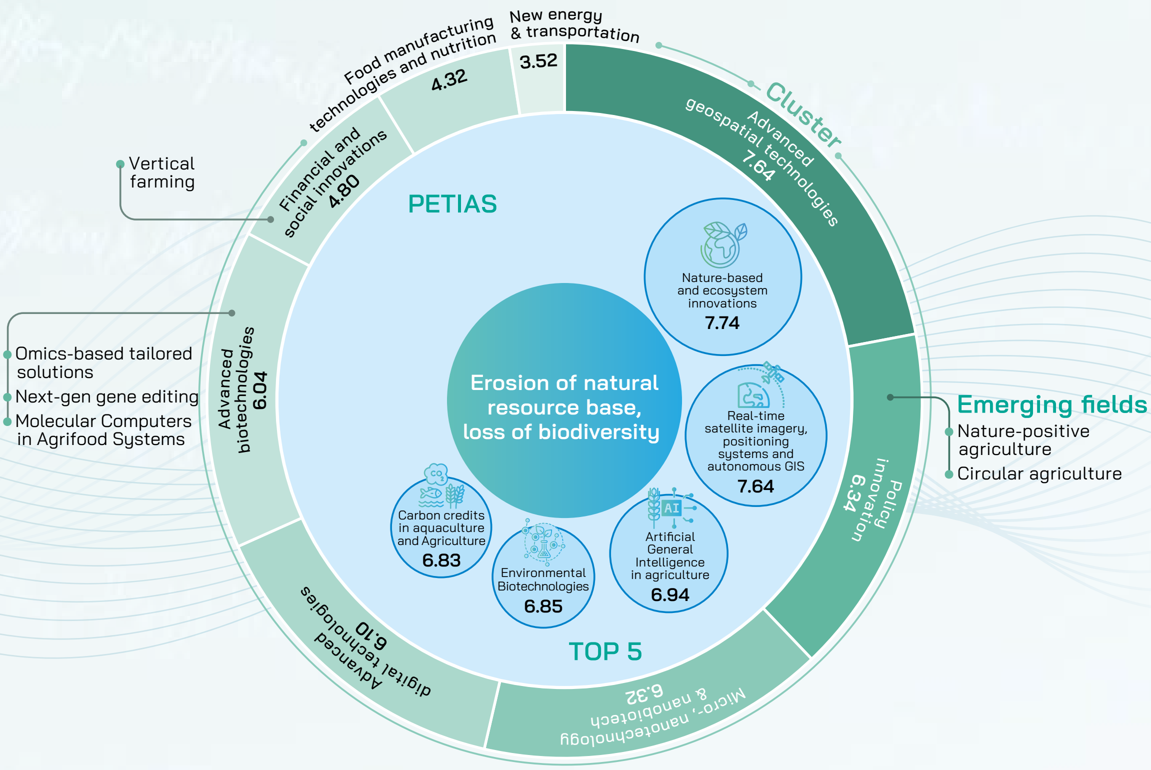
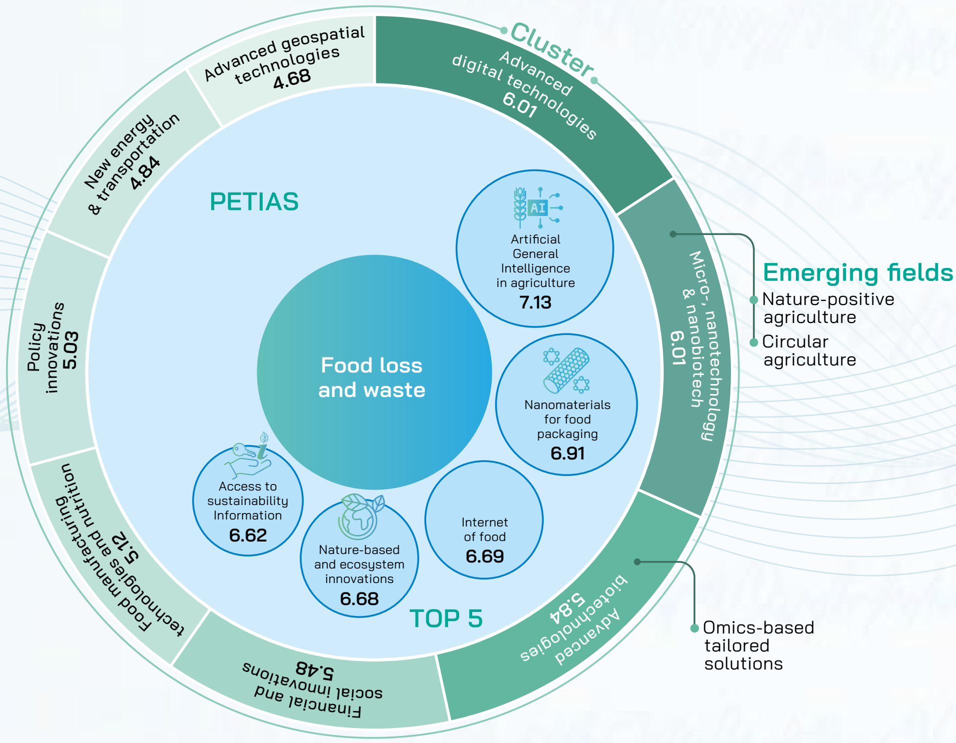


Figure 14d/e. Harnessing top PETIAS, clusters (the scores refer to their respective relative advantage per challenge), and emerging fields to address an agrifood systems challenge



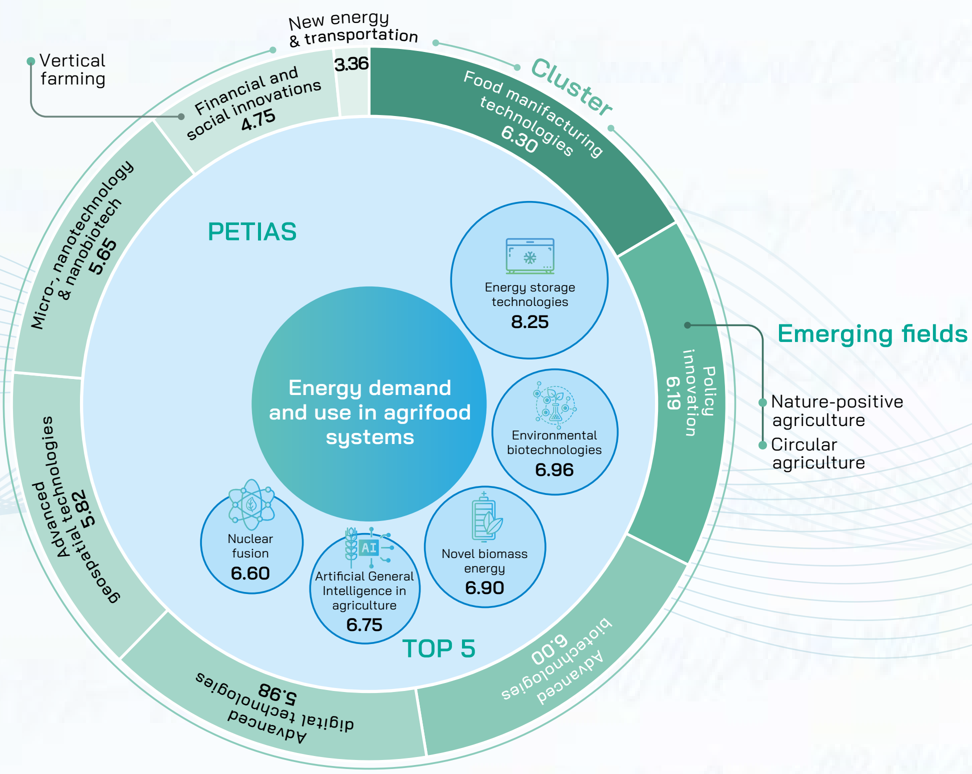
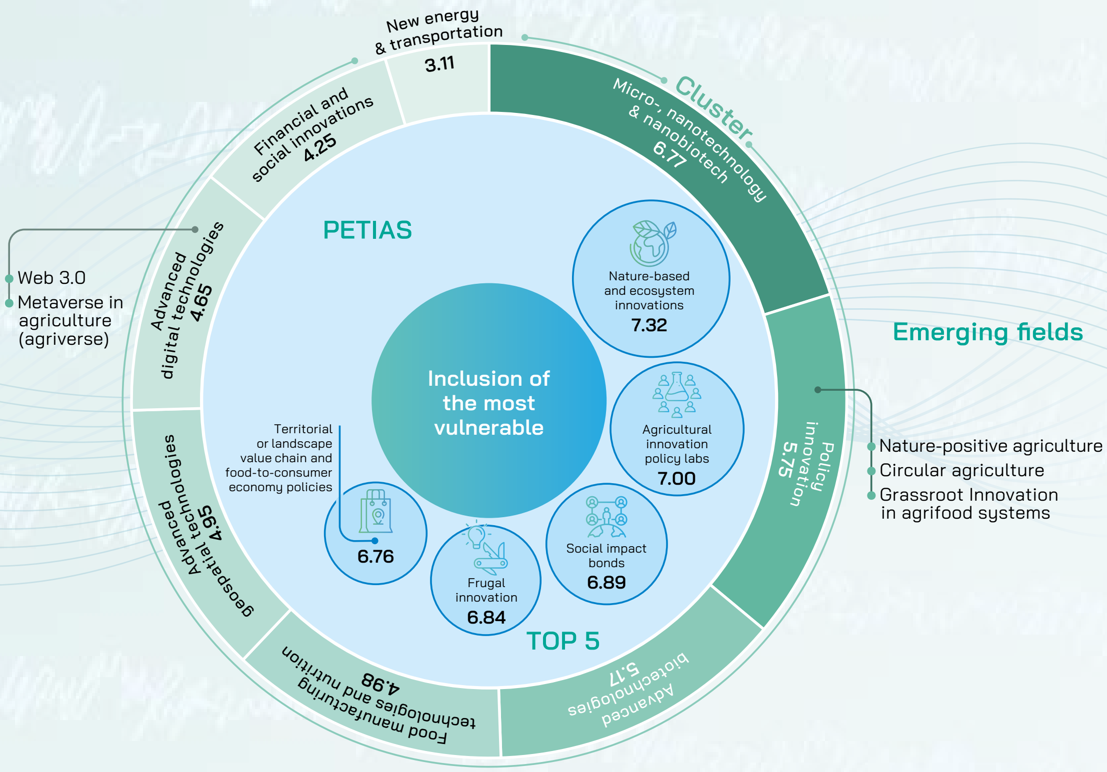


Figure 14f/g. Harnessing top PETIAS, clusters (the scores refer to their respective relative advantage per challenge), and emerging fields to address an agrifood systems challenge



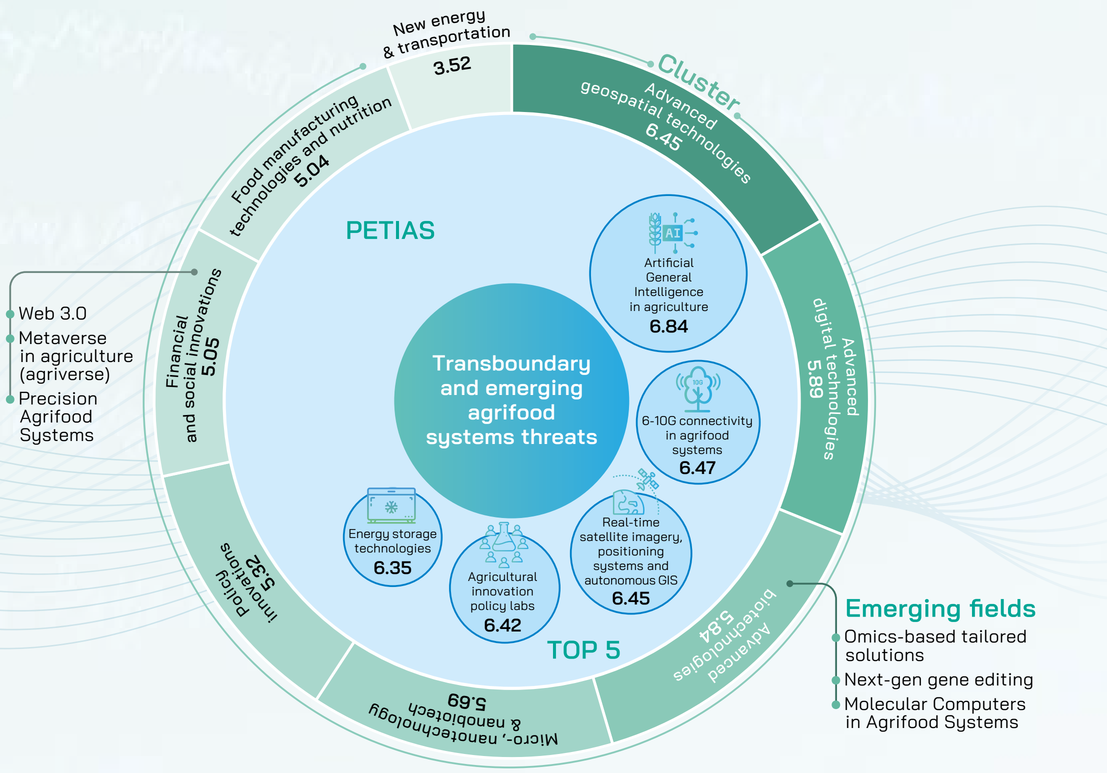
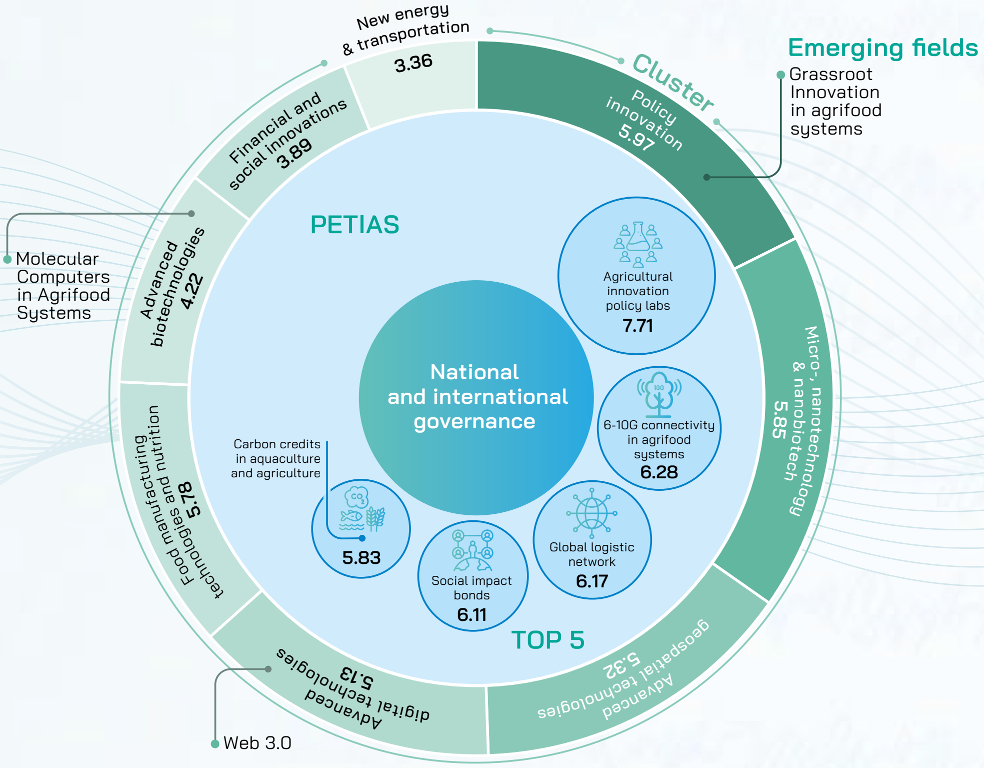
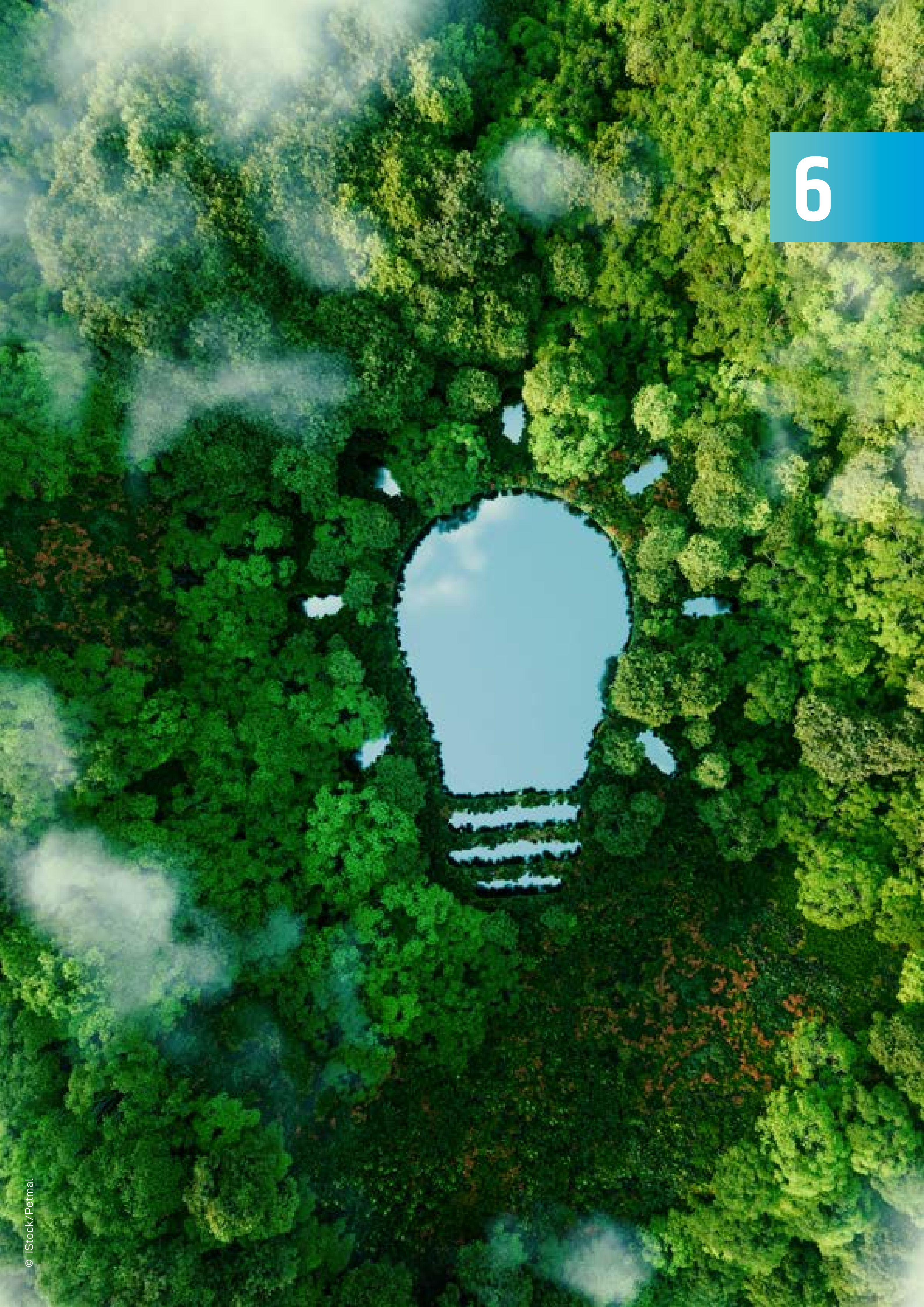


Figure 14h. Harnessing top PETIAS, clusters (the scores refer to their respective relative advantage per challenge), and emerging fields to address an agrifood systems challenge



In conclusion, the relations between agrifood systems challenges, the 32 PETIAS, clusters and emerging innovation fields presented in these chapters offer a diverse and promising toolkit for supporting efforts to address agrifood systems' complex challenges. Their potential impacts span multiple dimensions, from enhancing food security and nutrition to mitigating climate change and promoting sustainable resource management. However, realising the full potential of PETIAS requires a holistic approach and a combination of various solutions to address complex and intertwined challenges, as well as careful consideration of their possible implications – both positive and negative (see the Chapter 3).



6

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Shaping the global dynamics of innovation

6.1 DRIVERS

Drivers (developments causing change, affecting or shaping the future) not only influence the traditional aspects of agrifood systems but also play a determining role in shaping the direction of pre-emerging and emerging technologies and innovations. Table 3 presents the global ranking of agrifood systems drivers based on the FOFA (FAO, 2022a) and then assessed through a real-time Delphi question in which respondents were asked to select five key drivers for each of the six regions by order of their importance. Global and regional scores were normalized so that the drivers indicated as key most often have a value of 1 and the least frequently 0.

Table 3. Global rank of agrifood systems drivers

Global ranking	Driver
1	Climate change
2	Population dynamics and urbanization
3	Economic growth, structural transformation and the macroeconomic outlook
4	Public investment in agrifood systems
5	Food prices
6	Innovation and science
7	Scarcity and degradation of natural resources
8	Geopolitical instability and increasing conflicts
9	Inequalities are widespread and deep-rooted
10	Consumption and nutrition patterns
11	Big data generation, control, use and ownership
12	Rural and urban poverty
13	Capital and information intensity of production
14	Epidemics and degradation of ecosystems
15	Uncertainties
16	Cross-country interdependencies
17	Input and output market concentration
18	The "sustainable ocean economies"

6.2 TRENDS

Trends (a general tendency or direction of development or change over time) are important to technology and innovation but also shape the future of food and the livelihoods of those depending on food and agrifood systems. They have been further evaluated in the real-time Delphi. Each trend received a score indicating its impact on the emergence of agrifood technologies and innovations: -5 represents a highly negative effect, 0 is neutral and 5 signifies an extremely positive impact. In summary, the future of agrifood systems is poised to be shaped by a blend of efficiency, democratization and sustainability, with precision and integration acting as significant enablers. It represents a significant shift from current technological trends related to personalization and minimization, exemplified by the most popular current innovation: the smartphone.

- Increasing efficiency of resources: it remains a cornerstone for the future of agrifood systems. This trend underscores the need for innovations addressing wastage, optimizing farm operations and accelerating food production without compromising quality. Score: 2.79

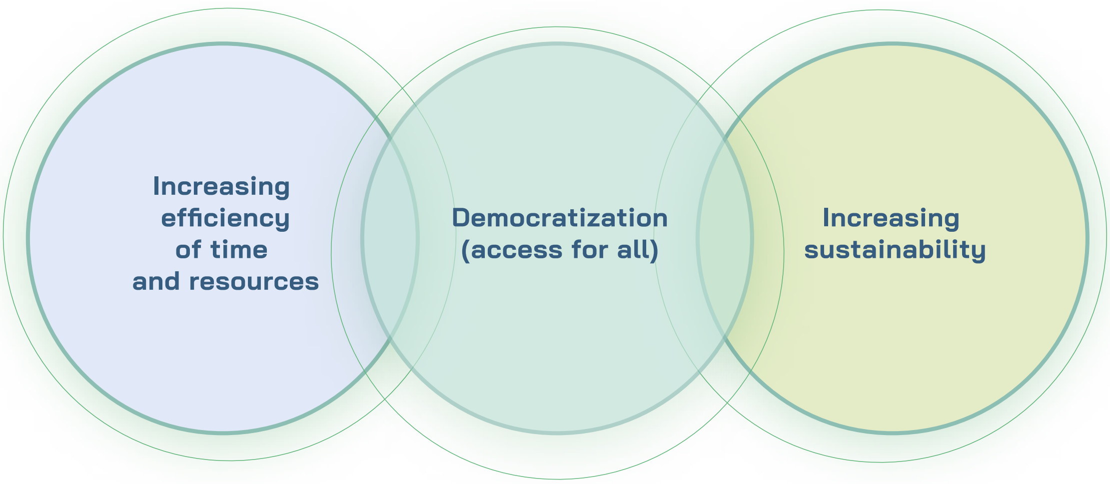
- democratization, allowing for accessibility for all. Score: 2.75

- Increasing sustainability of technologies and innovations through reduced carbon footprints, sustainable farming techniques or eco-friendly packaging. Score: 2.60

Other trends identified and assessed include: increasing precision (for more precise output); increasing the integration of technologies (fusion or combination of several types of technologies and innovations); increasing possibilities of real-time notification and interaction (allowing for observation during the actual time of occurrence); increasing universality (multipurpose, functionality valid for all); minimization, allowing for a reduction in size of particles or device; and personalization, allowing for specifications according to the individual needs.

In particular, democratization is a new trend gaining more and more relevance. Democratization is key to ensuring that technologies and innovations are conceived and implemented inclusively and are relevant, accessible and affordable for all. It also implies the participation of diverse stakeholders in the innovation process, from the conception through the implementation to monitoring and evaluation. From another angle, responsible and inclusive STIs could also have the potential to empower their users, including the most vulnerable ones and connect them to build stronger societal cohesion, as well as facilitate their participation in the policy process (e.g. through digital tools, improved livelihoods etc.), enabling thus broader democratization in the society. For this to happen, holistic and innovative approaches are needed at the system level to trigger a profound transformation and make PETIAS (social innovation, frugal innovation or high-tech solutions) more democratic while leveraging their potential to empower their users and democratize society.

Figure 15. Top three internal trends in emerging agrifood and technologies and innovations



6.3 TRIGGERS

A holistic perspective on triggers of change for pre-emerging and emerging technologies and innovations: Delphi survey and FSN contributions

The Delphi survey and FSN contributions have provided valuable insights into another set of critical factors driving the emergence of technologies and innovations in agrifood systems – triggers of change. These triggers of change are hypothetical future events that could potentially affect the strength of currently observable drivers and the trajectory of trends. While both methods yielded similar findings, they also highlighted unique perspectives and priorities.

Main triggers

Several common themes emerged from the responses of the expert and multistakeholder community. Participants consistently emphasized the importance of the following triggers:

- governance and business environment related to agrifood pre-emerging and emerging technologies and innovations;
- rapid acquisition of new skills and the rise of human capital;
- removed barriers to technology adoption, including improved mechanisms for intellectual property rights and knowledge flow, as well as dissemination;
- societal consensus and ethical standards in place; and
- achieving true circularity and sustainability.

Additional triggers

Beyond the core themes, participants also identified several other potential triggers, including:

- Climate crisis: addressing the impacts of climate change on agrifood systems and developing climate-resilient technologies.
- International collaboration: fostering partnerships and knowledge exchange between countries to accelerate innovation.
- Local innovation: recognizing and supporting grassroots innovations that address specific regional challenges.
- Youth engagement: attracting young people to agriculture through innovative solutions and career opportunities.
- Open and trustworthy communication: transparent and reliable communication between stakeholders is essential for building trust and facilitating collaboration.
- Advancement of other technologies: synergies between emerging technologies can accelerate their adoption and impact.
- Funding and investments: adequate funding and investment are crucial for supporting the research, development and deployment of new technologies.
- Expanding horizons of vision: adopting anticipatory and foresight approaches.
- Interfaith peacebuilding: promoting peace and cooperation among different religious and cultural groups to address food insecurity.

6.4 WILD CARDS REVISITED

During the Delphi survey, we also asked experts and stakeholders to develop several so-called singular events, or "wildcards", i.e. low-probability but high-impact occurrences that could substantially disrupt or transform current systems and paradigms. A wildcard event is an unpredictable outlier that, while unlikely, could have significant consequences if it were to come to fruition. Due to their potential for severe impact, it's crucial not to disregard them, even if they seem improbable. In agrifood systems, these wildcards can bring about sudden and intense shifts, leading to challenges or opportunities for which stakeholders might not be prepared. When planning or strategizing for the future, it is essential to consider these wildcards not as certainties but as potential scenarios to be aware of. Incorporating such events into scenario planning or risk assessment can aid organizations and policymakers in building resilience and adaptability into their strategies.

Recognizing, understanding and preparing for wildcards can make the difference between being caught off guard and having adaptive strategies to address unexpected shifts in the agrifood systems.

The wildcards with potential for high impact on emerging technologies and innovations in the agrifood systems are identified as:

1. Exacerbating global conflicts and mass casualties
2. Discovery of macromolecule teleportation and very cheap energy sources at a quantum level
3. Floating cities, especially for small island nations
4. AI taking over humanity, leading to disturbed agrifood systems, famine and extinction
5. Failure of crop pollination on an international scale due to the loss of insects and bees
6. Widespread use of direct air carbon capture technology
7. Commercially available atmospheric water generator
8. Crop diseases affecting human health
9. Technology magnates' domination of synthetic food
10. The world coping with hunger, combating ageing and achieving full sustainability and circularity with no waste of resources by 2050

Wildcards can serve as a guide for allocating resources to areas that, while seemingly improbable now, could have profound future implications. This demands a balance between core research and development (R&D) activities and exploratory ventures for agrifood systems. To better understand the stakes linked to these events and the urgency to consider them, let's examine the potential implications of particular wildcards.

Wildcard 1: Exacerbation of global conflicts and mass casualties

Agrifood systems would be highly vulnerable to disruptions caused by global conflicts (Donnellon-May, 2024). Food shortages, price volatility and supply chain disruptions could severely impact food security, particularly in countries with limited domestic production capacity and already poor infrastructure, but also in cases of trade disruptions, tariff and export barriers, which can further exacerbate the social and political consequences of local supply spikes. Further consequences could include the destruction of farms and labour shortage (due to casualties, displacement and/or conscription). As the escalation of current conflicts has demonstrated, disruptions to production and food logistics flow can become politicized and provoke a backlash. Refugee flows could also increase competition for food and resources in the receiving communities, exacerbating existing vulnerabilities. Price volatility and market instability would particularly affect small farmers and vulnerable communities.

Wildcard 2: Discovery of macromolecule teleportation and very cheap energy sources at a quantum level

Cheap energy would revolutionize agricultural production, processing and distribution, potentially boosting yields and sustaining, in the long run, the cost advantage historically due to low labour costs (Hauber, 2024). Teleportation could facilitate to replace distribution with nutrient and water delivery in soil or even organisms. Regions with advanced agrifood systems could leverage cheap energy to develop further, focusing on precision farming, vertical farming and other high-tech solutions (The World Bank, 2024; Abiri *et al.,* 2023). Teleportation could reduce the environmental footprint of food transportation.

However, we would need to invest in capacity development, ethical considerations and ensuring equitable access to fully harness these technologies.

Wildcard 3: Floating cities, especially for small island nations

Small island nations as well as countries with extensive coastlines could benefit significantly from floating cities as a solution to land scarcity and rising sea levels. These cities could become hubs for innovative aquaculture and hydroponic farming, ensuring island communities' food security and economic opportunities. They could serve as models for sustainable development, incorporating renewable energy, water purification, innovative food production systems and introducing novel crops and animal varieties.

However, the high cost of construction and maintenance, as well as potential environmental impacts, would need to be carefully considered (van Hooijdonk, 2022).

Wildcard 4: Rogue AI taking over humanity, leading to disturbed agrifood systems, famine and extinction.

While AI presents numerous positive and potentially disruptive opportunities, this is an extreme vision where AI is used irresponsibly and unregulated, promoting vested interests and replacing human intelligence and governance that could lead to catastrophic consequences for humanity and agrifood systems. The impact would be devastating and universal, leading to the collapse of agrifood systems, widespread famine, overreliance on one technology, loss of human skills, decision-making capacity, jobs and extinction of humanity. Regional differences would become irrelevant in the face of such a global catastrophe.

Wildcard 5: Failure of crop pollination on an international scale due to the loss of insects and bees

Regions with diverse agrifood systems and significant reliance on insect pollination for many crops, would face substantial yield reductions, shortages of certain commodities, higher food prices and economic losses. This could exacerbate food insecurity and malnutrition, particularly in countries with large populations and limited agricultural resources (Tchonkouang *et al.,* 2024). Regions already facing water scarcity and desertification would see further declines in agricultural productivity due to pollination failure. This could worsen food insecurity, increase import reliance and exacerbate social and economic tensions. Small-scale farmers and rural communities, who often rely on pollinated crops for their livelihoods, would be particularly vulnerable. Even regions with advanced agricultural technologies and innovations would not be immune to the effects of pollination failure. Failure of crop pollination would also have devastating effects on biodiversity and ecosystems.

Wildcard 6: Widespread use of direct air carbon capture technology (DACC)

Regions with large carbon footprints and vulnerability to climate change impacts could benefit significantly from DACC technology. It could help reduce greenhouse gas emissions, improve air quality, support reforestation efforts and create new carbon capture and storage (Li and Yao, 2024) as well as economic opportunities. The technology could also create new carbon credit markets to stimulate carbon capture and utilization innovation. However, the high energy requirements, potential land-use conflicts and the effects on water resources and biodiversity associated with DACC deployment would need to be carefully managed. Public acceptance and regulatory frameworks would be crucial for successful implementation.

Wildcard 7: Commercially available atmospheric water generator (AWG)

In regions with water scarcity issues, AWGs could provide a supplementary water source for agriculture, irrigation and livestock, potentially improving crop yields and resilience to droughts. This could enhance food security and access to clean drinking water, improve livelihoods and better health outcomes, empower women and girls often in charge of fetching water and boost economic development in these regions.

However, the energy requirements of AWGs and their potential impact on local humidity levels would need to be carefully considered (Zhang, M *et al.,* 2022).

Wildcard 8: Crop diseases affecting human health

Climate change can exacerbate the frequency and magnitude of plant diseases affecting directly or indirectly human and animal health. They can cause food insecurity, labour shortages and a shift of investments from agriculture to health/crisis response, particularly in countries with limited healthcare infrastructure and weak food safety systems (UNESCAP, 2022).

This would likely affect small-scale farmers and vulnerable communities through income losses and food insecurity. Even the higher-income regions with advanced agricultural practices and robust food safety mechanisms would not be immune to economic losses for farmers, increased food prices for consumers and potential trade disruptions.

Wildcard 9: Technology magnates' domination of synthetic food

Small-scale farmers and traditional food producers participating in legacy culinary value chains could be marginalized, while consumers may have limited choices and face higher prices for conventional foods (Lv *et al.,* 2021). The convenience and affordability of synthetic food could attract consumers, potentially leading to changes in dietary patterns with related public health and agricultural practices concerns. If synthetic food becomes dominant, loss of cultural identity and economic opportunities is likely for the regions with many smallholder farmers and indigenous communities who rely on traditional agriculture for their livelihoods and would thus be particularly vulnerable. Furthermore, synthetic food's nutritional quality and cultural appropriateness need to be carefully considered even.

Wildcard 10: The world coping with hunger, combating ageing and achieving full sustainability and circularity with no waste of resources by 2050

This positive wildcard scenario envisions a future where humanity has successfully addressed major global challenges, including hunger, ageing and environmental sustainability. This would have transformative implications for agrifood systems worldwide, but hunger-affected regions would relatively benefit the most.

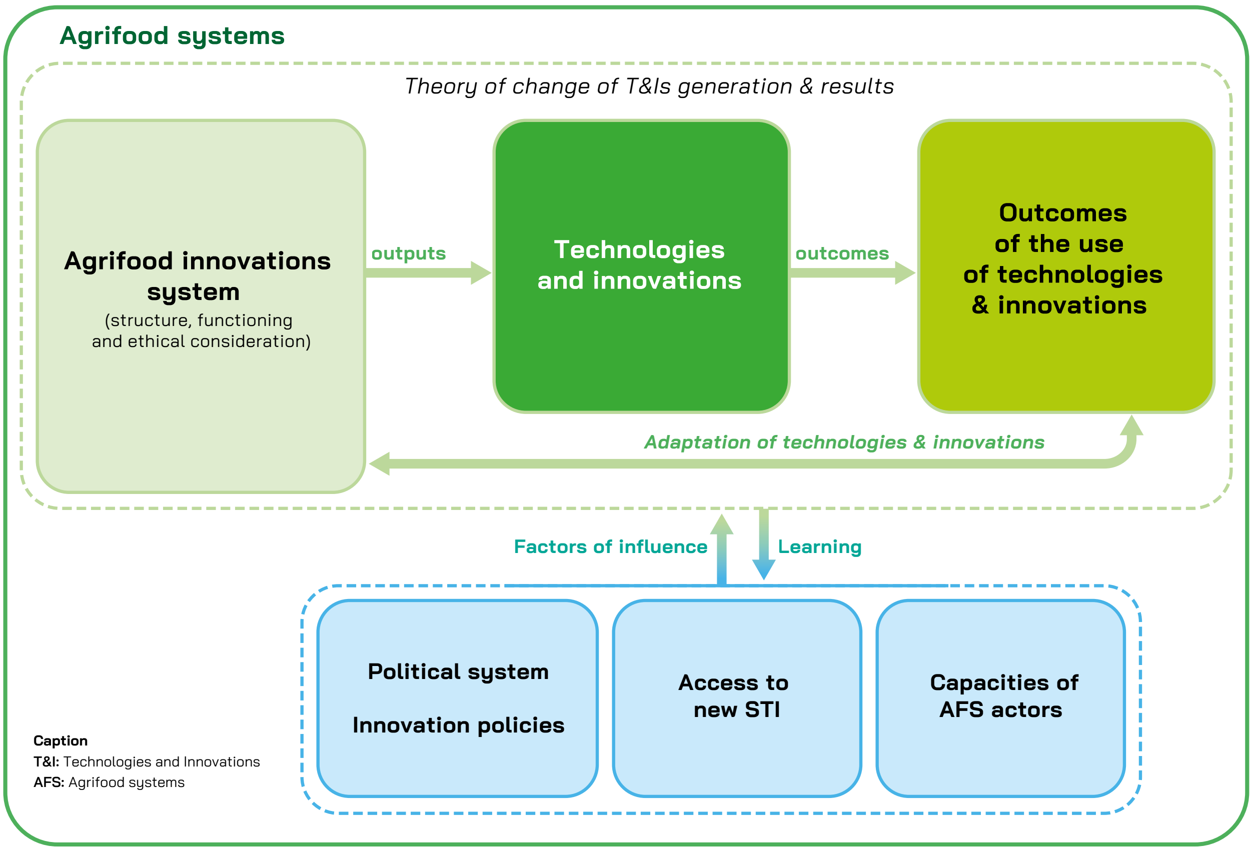
All the regions would experience significant improvements in food security, nutrition, livelihoods and public health. Sustainable and circular agricultural practices would reduce environmental impact, conserve resources and enhance resilience to climate change. Improved infrastructure, increased collaboration and knowledge sharing would foster innovation, productivity and job creation, poverty reduction and overall economic growth (FAO, 2020). As much as this outcome is still labelled as a wildcard, this report provides what we consider to be a roadmap for achieving this vision, emphasizing the importance of collaboration, co-innovation and a long-term perspective in shaping the future of agrifood systems.

6.5 SCENARIOS

6.5.1 A change-oriented approach to build and use the scenarios

Owing to the change-oriented theory of change literature and based on the output of the workshops, we developed a conceptual diagram for scenarios presentation and their narratives with a specific interest in causal relationships and processual perspective. Hence, we state that pre-emerging and emerging technologies and innovations are outputs from activities carried out by stakeholders involved in the agrifood innovation system (AIS) and contribute to generating outcomes that will impact the AIS through feedback effects. The potential outcomes can be new knowledge, new agricultural practices, or related to food-processing and retailing that will contribute to refining, adjusting, or even hindering the technologies and innovations for a more relevant, acceptable use of the innovation. For instance, ethical considerations regarding a given technology may shape temporal societal boundaries, which can evolve upon first outcomes popularized and observed on the agricultural, social, economic or environmental levels. Features from the broader agrifood systems also influence this causal process: the political system, the level of access to technologies and innovations and the level of capacities to innovate of the actors of the agrifood systems, especially their capacity to learn, reflect and navigate complexity.

Figure 16. Conceptual diagram to represent and summarize scenarios



6.5.2 Five scenarios on pre-emerging and emerging technologies and innovations of agrifood systems in the future

Five scenarios have been elaborated through a participatory and iterative process with representatives of different areas of professional knowledge (research institutes, farmer organizations, private sector, international agencies) and a broader multistakeholder perspective (including civil society organizations). The scenarios are contrasting, coherent, plausible and alternative future pictures focusing on technologies and innovations. The scenarios , presented on Figure 17, have benefited from the roader agrifood systems scenarios (FAO, 2022a).

Scenario A: struggling between technological illusions and sustainability. In 2050, the development of new technologies and innovations has a dual purpose: sustainability and productivity. Fine-tuned cooperation is established with increased participation from technology and innovations' users, while the private sector is more involved in multistakeholder platforms. Meanwhile, ethical and social issues still pose significant problems, primarily due to a lack of solid policy engagement and a challenging science-policy interface, as well as the availability of effective instruments to conduct relevant and inclusive monitoring, evaluation, or impact assessment and broaden financial inclusion. Research and innovation agendas become disconnected from development agendas, as research and innovation activities mainly target farm productivity issues, with increasing but still inadequate attention given to sustainability issues. Large companies develop their investment strategies, while smaller or start-up companies with insufficient public support and dysfunctional business environments are reluctant to invest. Concerning partnerships dedicated to technology and innovation design and implementation, varied paradigms prevail: co-innovation and multi-actor approaches emerge but are limited and are unlikely to support mechanisms at scale. Accessibility to new knowledge, technology and innovation is limited to wealthy farmers. There is good capacity for actors to generate technology and innovation regarding farm productivity, but it is poor or insufficient when supporting sustainability transitions of agrifood systems. As a result, emerging technologies and innovations only partially address significant challenges (climate change, disaster mitigation, inclusion), leading to technological disillusionment. As a result, misunderstandings persist and access to relevant information is impeded.

Scenario B: mess and muddle in technologies and innovations. In 2050, technology and innovation systems will not be driven by demand or results. Unfortunately, they target profitability for investors at an unprecedented level. Innovation focuses on highly profitable links in value chains, leaving the most vulnerable farmers and food processors unable to access the benefits of innovation and technological progress. Research, societal and innovation agendas are disconnected from development challenges and are guided by investors and financial indicators. Eager to capitalize on technology and innovation, banks and financial institutions set up easily accessible financing mechanisms, which fail to be profitable over the long term due to a low uptake of the technologies and innovations developed. The technologies and innovations landscape is then dominated by large companies with economies of scale, leaving no room for more fragile start-ups that receive little support. There is an unfavorable business environment for developing and diffusing new technologies and innovations. Regulation is scarce, insufficient or inefficient, which results in an ever-increasing race for higher profits and little concern for ethical or societal implications. Major financial interests from banks and insurance companies drive the funding of new technologies and innovations. Start-up enterprises that seek to challenge this status quo face insurmountable business obstacles. The research, design and implementation of new technologies and innovations are carried out in silos and led exclusively by private interests or through platforms of specially selected private companies at the exclusion of other stakeholders. No mandatory mechanisms exist to monitor technologies and innovations according to their performance or their economic, social, environmental and cultural impacts. Research findings become intellectual property and, therefore, are inaccessible. Technology and innovation become challenging to develop without open-access knowledge platforms and premium, high-quality, relevant, or reliable knowledge. Actors involved in implementing and using technology and innovation lack the appropriate capacities for adapting to their specific situations. Users and consumers, therefore, have limited options and suffer lock-ins from private interests in technologies and innovations. Within an environment of wide-scale political maneuvering and monopolistic ownership, mis- and disinformation run rampant, further worsened by the limited access to scientific knowledge, information and networking platforms.

Scenario C: sustainable prosperity of technologies and innovations. In 2050, innovation and technology development systems are driven by a focus on sustainability, one-health approaches and circularity in most economies. Technologies and innovations develop according to responsibility, inclusivity and functionality. Citizens lead governance and rely on fair and transparent dialogue with the private sector and civil society organizations, which also engage in global conversations. Research and innovation agendas are perfectly aligned with development challenges. This is further supported by renewed public-private-user partnership funding, relying on accountability based on performances and results (outcomes and impacts), including crowdfunding or specific funds allocated to smallholders. Multinational, local, small and start-up companies, research and farmers' organizations and food processors are all involved in supporting technology design and are innovation-oriented towards sustainability. Participatory and inclusive approaches are now mature and allow for a broad engagement in social and ethical national and global roundtables, enabling road map compliance. Innovation policy labs, where all stakeholders are a genuine part of the policy-making process, support decision-making and experimentation through multi-actors and localized partnerships. This new partnership results in the uptake of technologies and innovations that further consider social and ecological justice based on outreach and inclusiveness to deliver sustainable impact at scale. Monitoring is ensured by evolutive performance and impact management mechanisms. Access to new knowledge, technologies and innovations is open, inclusive and managed through transparent and professional mechanisms. Actors benefit from updated and free access to human capital development programmes for sustainable development.

Scenario D: AI in charge of agrifood systems and beyond. In 2050, regulations will increasingly favour automated decision-making in most aspects of life. Without human involvement, technology and innovation are managed mainly by autonomous artificial intelligence (AI) systems. Initial investments are made by AIagritech companies. AI also manages key decision-making on agrifood systems, implementation and real-time optimization, therefore called "algocratie". For instance, AI advises pursuing or switching from food production models, depending on agrifood systems' capacities, available natural resources, food demand and safety. The research and innovation agenda is aligned with what is deemed critical by the AI management and monitoring system. AI also dictates whether to pursue technology and innovation depending on its calculation of risk and benefit. AI decisions account for a vast array of data sources – where available – and rely on updates made on localized agrifood systems. Ethical considerations are also increasingly delegated to AI. While a higher agrifood systems efficiency has been achieved (concerning food waste, transportation, including cheaper autonomous transport, food safety, seeds and fertilizers use, etc.), diversity in human society is not sufficiently recognized, resulting in severe problems around inclusion and equity. This is partly because the methods for developing AI systems are based on advanced country situations and may not account for other contexts like living in remote areas, disregarded value chains or alternate farming models. AI automatically manages and rationalizes access to new knowledge, technology and innovation. Agrifood systems actors have restricted access to the knowledge, technology and innovation they need for their daily lives and activities. No sound partnership is engaged among stakeholders to design technologies and innovations, as farmers and agribusinesses independently use and experiment on technologies and innovations as AI dictates. They send and receive advice from AI for real-time adjustments. The capacities of actors are generally weak, except those in charge of designing and running the AI system. Besides this, cybercrime is on the rise and threatens actors in agrifood systems. Many fear the risk of ill-governance, as vested interests could steer the actions of AI and influence its decisions.

Scenario E: technologies and innovations – our best last chance. In 2050, climate change, disasters and conflicts happen faster and with a more significant impact than ever. In particular, this results from governments' inability to formulate and enforce viable and efficient policies and decisions that address numerous acute challenges and their failed role as knowledge brokers and governance coordinators. However, to fill this void, non-state actors – private sector and civil society organizations – have taken matters into their own hands. They are more vital than ever before and actively cooperate to collectively address global catastrophes and prevent future ones. The research and innovation agenda is now totally redirected to developing solutions to challenges considered most critical. Private sector and civil society representatives worldwide have elaborated on many potentially game-changing solutions that offer a high-level impact in short time frames. The private sector benefits from public emergency and recovery funds, private investments and capital funds created by significant banks accessible to major companies and start-ups. Partnerships for the design and implementation of technologies and innovations are dominated by expert and leader opinion, which values their experiential knowledge as there is no time for "traditional" research protocol, peer-reviewed academic research, or broad multistakeholder consultation. Access to knowledge, technology and innovation is excellent and inclusive, thanks to dedicated platforms that provide users with real-time operational information. Experiential learning and non-formal education bolster actors' capacity development. The solutions developed and promoted within technology and innovation often pose a high level of uncertainty and come at the cost of significant trade-offs, such as those related to inclusion or ethical concerns. Nevertheless, as this is the last chance for humanity to take action to survive, there is an overwhelmingly high level of societal consensus and support for applying the technology and innovation that promises fast solutions to humanity's most pressing challenges.

The five scenarios are used to envision desirable and undesirable futures, as well as the features within the agrifood systems that enable such positive or negative aspects.

Through a cross-cutting analysis, we reflect on some lessons derived from the scenarios:

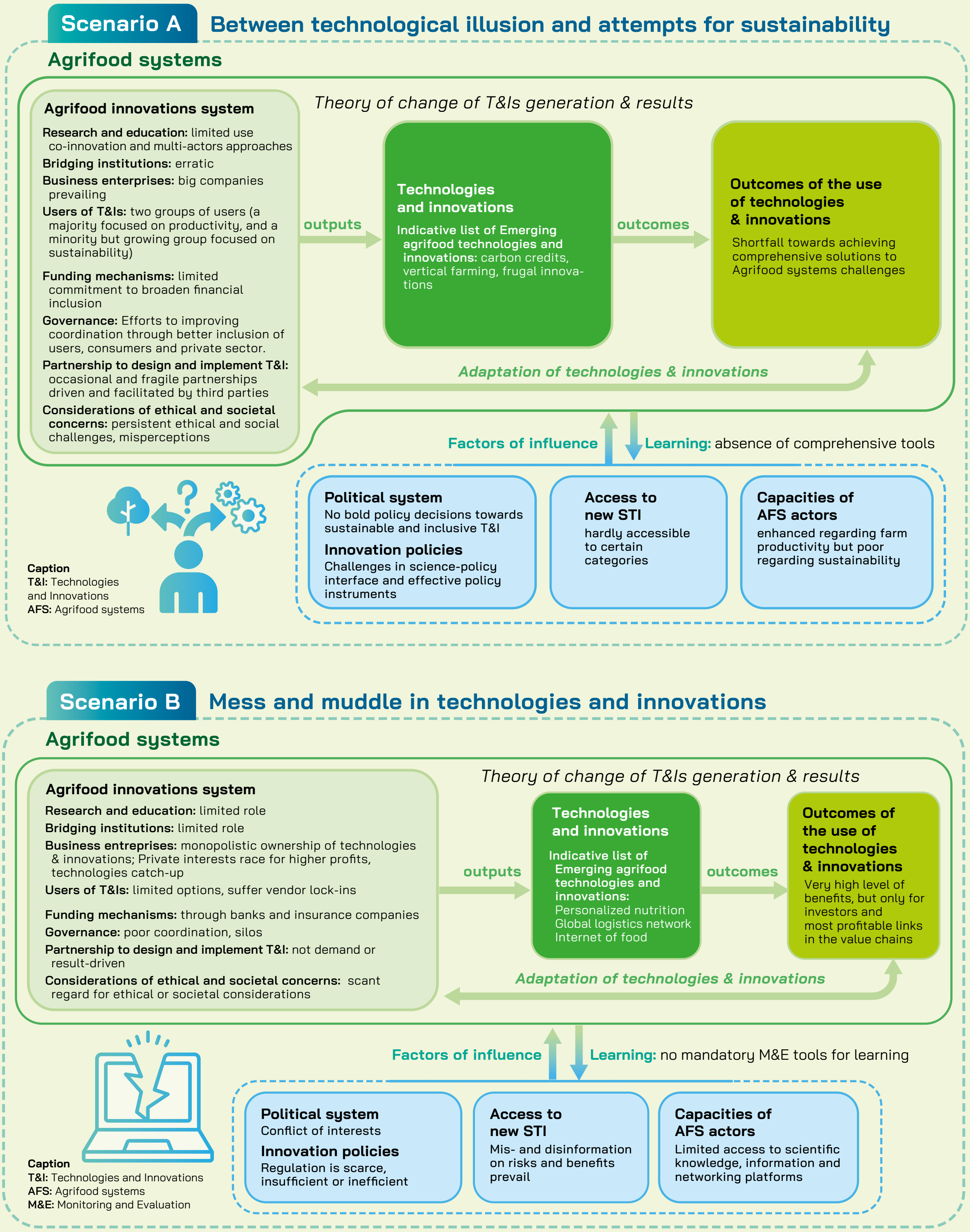
- Participatory and transparent governance and partnership for the design and implementation of technology and innovation are key to conveying an optimistic or a pessimistic future.

- Ethical and social concerns must be considered and addressed to ensure that technologies and innovations development is coherent with societal values and contributes to strengthening social cohesion and equity. Accountability and monitoring, evaluation and learning mechanisms are key to avoiding unintended negative consequences, adjustments and successful transformative actions.

- The role of stakeholders may vary from one scenario to another (as designers of new technologies and innovations, implementers, solution providers, copartners, regulators, gatekeepers, users, etc.). However, co-innovation is critical to accelerate the scaling up and out of the innovations and empowerment. The emergence and development of a technology or innovation require the specific contribution of diverse players upstream and downstream of the process.

- Scenarios may coexist as they reflect plausible futures that can happen in parallel at regional or national scales. They may also constitute different steps or phases of the development process.

Figure 17. Overview of five scenarios



Scenario C Sustainable prosperity of technologies and innovations

Agrifood systems

Theory of change of T&Is generation & results

Agrifood innovations system

- **Research and education:** inclusive and participatory research protocols
- **Bridging institutions:** pro-active for coordination, intermediation, advisory, funding, support for control & monitoring
- **Business entreprises:** pluralistic ecosystem of private sector, towards all kind of farming models
- **Users of T&Is:** get adapted option to their needs
- **Funding mechanisms:** Innovative P-P-P-consumers-users
- **Governance:** citizen-led; transparent dialogue and multistakeholder dialogue
- **Partnership to design and implement T&I:** co-and open innovation, multistakeholder partnerships
- **Considerations of ethical and societal concerns:** broad engagement, roundtables

outputs →

Technologies and innovations

Indicative list of Emerging agrifood technologies and innovations: Agrifood innovation policy labs

Novel pesticides, fertilizers, antibiotics including, nanotechnology substances

Novel biomass, nuclear energy, novel energy storage technologies

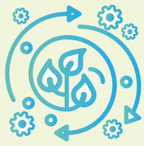
outcomes →

Outcomes of the use of technologies & innovations

Achievement of sustainability, one-Health and circularity

← *Adaptation of technologies & innovations*

Factors of influence ↑ ↓ **Learning:** real-time tools for adaptive management



Political system
accountable, inclusive and decentralised

Innovation policies
Global and harmonized policies, road maps compliance

Access to new STI
open and inclusive, managed through transparent and professional mechanisms

Capacities of AFS actors
Updated and free access to human capital development program

Caption
P-P-P: Public, private partnerships
T&I: Technologies and Innovations
AFS: Agrifood systems

Scenario D AI in charge of agrifood systems and beyond

Agrifood systems

Theory of change of T&Is generation & results

Agrifood innovations system

- **Research and education:** solution-centered research protocols
- **Bridging institutions:** AI bridges stakeholders through digital tools
- **Business enterprises:** AI-agritech companies
- **Users of T&Is:** no direct influence on the T&I
- **Funding mechanisms:** private funds
- **Governance:** automated decision-making by the AI
- **Partnership to design and implement T&I:** no partnerships, direct use of T&Is dictated by the AI.
- **Considerations of ethical and societal concerns:** delegated to AI

outputs →

Technologies and innovations

Indicative list of Emerging agrifood technologies and innovations: metaverse, VR and AR Artificial General Intelligence in agriculture, Quantum internet and computing Aerial robotics and drones

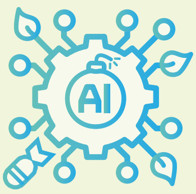
outcomes →

Outcomes of the use of technologies & innovations

optimized agrifood systems, availability of natural resources and food safety are respected

← *Adaptation of technologies & innovations*

Factors of influence ↑ ↓ **Learning:** dynamic learning based diversified and updated data sources



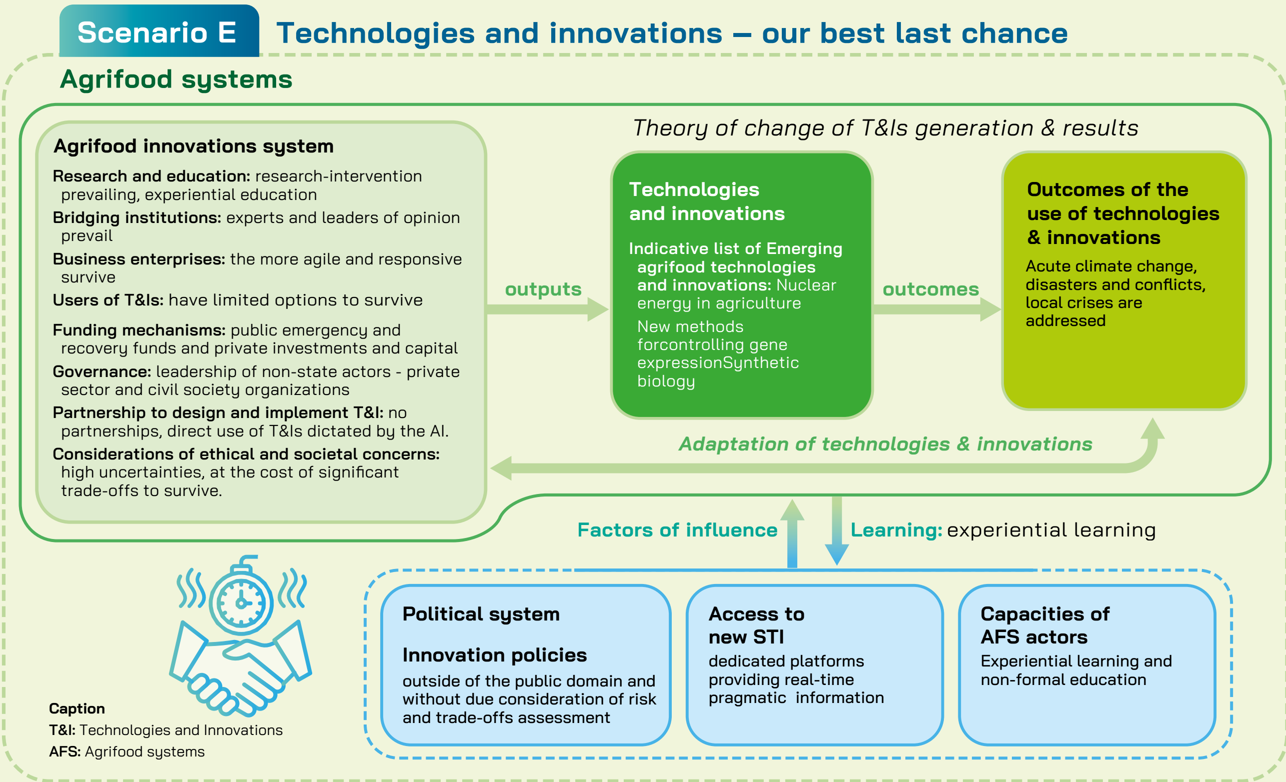
Political system
dynamic learning based diversified and updated data sources

Innovation Policies
Delegated to AI

Access to new STI
targeted access to the type of Knowledge, TIs made by the AI

Capacities of AFS actors
weak in general

Caption
AI: Artificial Intelligence
T&I: Technologies and Innovations
AFS: Agrifood systems



6.5.3 Temporal and sequential linkages among the scenarios

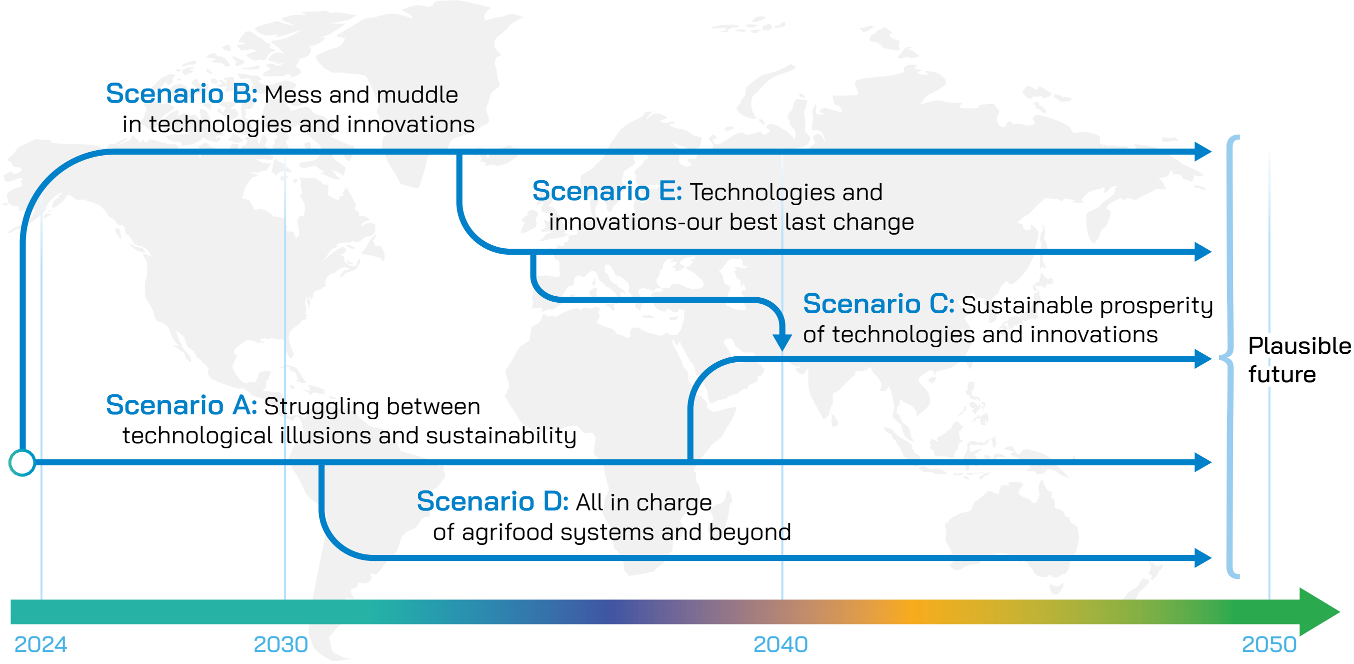
The five scenarios identified for pre-emerging and emerging technologies and innovations are quite contrasting, but there are several potential links, particularly if we adopt temporal and thematic perspectives.

Given the identified challenges in closing the STI gap[1] and the present drivers of technology and innovation emergence, some scenarios appear as evolutions, derivatives or consequences of other scenarios (Figure 18). For example, scenarios E (Technologies and innovations – our best last chance) and A (*Struggling between technological illusions and sustainability*) can be seen as a spur to improvement following the realization of the risks and limitations of Scenario B (*Mess and muddle in technologies and innovations*). Scenarios A and E can also be seen as intermediate steps towards Scenario C (*Sustainable prosperity of technologies and innovation*). Scenario C appears to be the one that could take the longest to achieve, given current shortcomings and the major changes and innovations required to make available the technologies and innovations that will ensure that sustainable development is not only real but irreversible. Scenarios B and A are fairly close to the situations we are currently experiencing in many parts of the world, which could worsen if adequate measures are not taken. Scenario A seems to reflect cases where awareness has already been raised, resulting in more or less significant but insufficient adjustment measures.

The fact that some scenarios, i.e. A and B, that are practically already underway remain among the plausible future in 2050 shows that without innovation and the necessary adjustments, already unenviable situations could deteriorate or at least persist. Scenario D (AI in charge of agrifood systems and beyond) is the one that draws most heavily on technology, in particular artificial intelligence. It could result from a desire to simplify the governance of agrifood systems and optimize their performance. Given the many potential pitfalls of this scenario and despite its potential benefits, it appears, along with Scenario C, to be the scenario that could take the longest to achieve. On the other hand, regarding Scenario D and at the pace of developments of AI, there could be a risk that it will become a reality not so far away from today, as it may become more and more available and invested in, while some countries may not have the institutional capacity in place to implement necessary regulations for the responsible use of AI. The dark side of scenario D could be one of the consequences of scenario A's excesses, particularly concerning using technologies and innovations with little ethics or insufficient restraint.

Finally, while the figure below highlights links between scenarios, showing that not all scenarios are equiprobable at all times, it also highlights that the scenarios are not necessarily exclusive. Several of them may coexist, even within the same country or region.

Figure 18. Potential temporal and sequential links between the different scenarios



1 by the participants of the Foresight multistakeholder workshop, June 2024 FAO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Paradigm shifts and transformations

7.1 FROM SCENARIOS TO GLOBAL TRANSFORMATIONS

While foresight scenarios offer excellent opportunities to broaden our understanding of the future's directions, scenarios are far from being the end goal of foresight-informed policymaking. For robust strategic planning, further steps are crucial, and they include understanding what the preferred future looks like and what transformations would allow us to build that preferred future no matter which of the future scenarios materializes. Furthermore, we can shape the disruptive pathways to achieve these transformations by being aware of the current challenges, the characteristics of the preferred future and the transformations needed. Strategic foresight tools – preferred future, backcasting and change agenda – have been deployed to that end. The results from those foresight exercises are presented below.

7.1.1 Understanding the present-day STI challenges: three critical barriers in closing the STI gap in agrifood systems

Three overarching challenges, specific to science, technology and innovation (STI) that significantly hinder progress in closing the STI gap emerged from the results of the foresight multistakeholder workshop "Future Food-I Lab in action: cultivating innovation for agrifood systems' transformation", held on 17 and 18 June 2024 in FAO headquarters, Rome, Italy and supported by other research findings. They reflect "the present day" situation and are highlighted below.

Resource constraints and infrastructure

Limited funding for research, development and innovation, especially in low- and mid-income countries (LMICs) countries, coupled with inadequate physical infrastructure (e.g., laboratories, research facilities) and digital infrastructure (e.g., broadband internet) to support STI activities, pose significant challenges. Another hurdle is ensuring that innovations reach the end-users, particularly in rural areas. The high costs of acquiring and implementing new technologies and innovations can make them inaccessible to many.

Governance, policy and institutional challenges

Concerns about data sovereignty and ownership, ineffective, incoherent or outdated policies and regulations that often lack a societal buy-in, overlapping or conflicting roles and responsibilities among different institutions involved in STI, resistance to change, lack of trust and open multilateral dialogue with the society and a reluctance to adopt new approaches or take risks are some of the governance, policy and institutional challenges hindering progress.

Social and cultural hindering factors

Engaging all stakeholders, including farmers, researchers, policymakers, non-governmental organizations and private sector actors, in the STI process is crucial but often challenging. Limited involvement of consumers in the development and adoption of new technologies and innovations, insufficient attention to the specific needs and priorities of farmers and other end-users, and gender disparities in access to education, resources and opportunities in the STI sector are additional social and cultural factors that contribute to the challenges in closing the STI gap.

7.1.2 Four key opportunities to close the STI gap in agrifood systems

Based on our findings, four overarching opportunities emerge that hold the potential to significantly contribute to closing the STI gap in agrifood systems. These opportunities are:

Innovative governance and consistent policy

Developing innovative governance models that align STI efforts with the specific needs and priorities of agrifood systems and their actors, including the most vulnerable, has been recognized as an overarching opportunity to accelerate the closure of the STI gap and advance the agrifood systems' transformation. Consistent policies and regulatory frameworks that support STI development and their responsible use, ensuring education programmes and equitable knowledge-generation and sharing initiatives are aligned and in place to leverage the inclusive decision-making capacity of all stakeholders, including small-scale businesses, women and youth, also represent significant opportunities.

Innovative financing and business models

Creating market and financial models that support the development and adoption of agrifood technologies and innovations and providing access to innovative financial instruments and services that boost the growth and development of small and medium-sized agrifood businesses have been found crucial for closing the STI gap, in particular in places struggling the most with resource constraints and infrastructure challenges.

Co-innovation for sustainability

Benefiting fully from a co-innovation approach that involves farmers, including women and other stakeholders in the development and adaptation of technologies, social, financial and policy innovations, integrating social and environmental considerations into STI development and use and promoting the development of local agrifood systems, have been found essential for closing the STI gap.

Human and social capitals

Leveraging the growing youth population's digital literacy, strengthening networks, communication channels, extension and advisory services and promoting peer-to-peer learning and knowledge exchange among farmers and other stakeholders are vital for developing the capacity and knowledge base needed to address the challenges and opportunities in agrifood systems. Likewise, universities and vocational training centres need strengthening to play their crucial role in ensuring equitable access to quality education and skills in many fields for all.

7.1.3 The preferred future for agrifood science, technology and innovation

The preferred future has been elaborated by experts and stakeholder communities through 7 sessions (see Chapter 2) in different regions, where the participants were requested to reflect on the five scenarios (presented in Chapter 6) and identify features within those that they would like to materialize the most or would avoid in any case. The following narrative emerged after this exercise.

Science, technology and innovation (STI) have transformed agrifood systems into sustainable, resilient and equitable powerhouses in this envisioned future. AI is integrated seamlessly with human expertise, augments rather than replaces, and optimizes processes and decision-making. Information on sustainability, powered by advanced data analytics, ensures efficient resource allocation, minimizing efforts and environmental impact. Circular economy principles guide production and consumption, reducing food loss and waste and promoting sustainable practices.

Gender equity is a cornerstone of this future, with women playing pivotal roles in all aspects of the agrifood innovation systems. Intergenerational knowledge sharing fosters a strong foundation for future prosperity, as young people have the skills and understanding to innovate and adapt. A robust political system characterized by inclusivity, accountability and evidence-based decision-making ensures that STI benefits are available, accessible and affordable to every member of all communities. Open access to STI *and citizen science and innovation initiatives empower individuals to contribute to research and development, fostering a collaborative and transparent ecosystem.*

Agrifood innovation systems, networks of innovation actors, are functional, efficient and collaborative, capable of diversifying innovation ecosystems quickly due to the substantial human and social capital. These systems are data-driven and informed by social science ethics, ensuring that innovation aligns with societal values and practical needs. The governance of STI is multilateral and decentralized, promoting inclusivity and local ownership of both new and traditional knowledge, as well as cultural identity and lifestyles. Dignity and human rights are central to this future, ensuring that all individuals have access to the benefits of innovation and are protected from its potential harms.

7.1.4 Five key transformation areas

The transition towards closing the science, technology and innovation gap to achieve sustainable, resilient and inclusive agrifood systems necessitates a multifaceted approach that addresses various interconnected aspects. This came clear from the results of the foresight change agenda exercise.

This transition can be conceptualized as a journey through five key transformation areas: governance and participation, ethical and social considerations, integrated, fact-based, fit-for-purpose knowledge, incentives and investment for impact and fostering systemic changes. They will be described below based on the participants' inputs.

1. Governance and participation

The first transition involves shifting from top-down, centralized governance to participatory, multistakeholder approaches. This transition is characterized by a move away from reactive governance and toward anticipatory governance capable of addressing uncertainties. Key elements of this transition include:

- **Innovation policy labs:** these platforms facilitate dialogue and collaboration among diverse stakeholders to develop and implement innovative policies.
- **Democratization:** ensuring all stakeholders have a voice and are empowered to participate in decision-making.
- **Participatory methods:** employing inclusive and participatory approaches, such as community-based participatory research, to involve diverse stakeholders in developing and implementing solutions.
- **Stakeholder engagement:** engaging with various stakeholders, including farmers, consumers, researchers, policymakers and civil society organizations.

Figure 19. Results from the change agenda foresight exercise

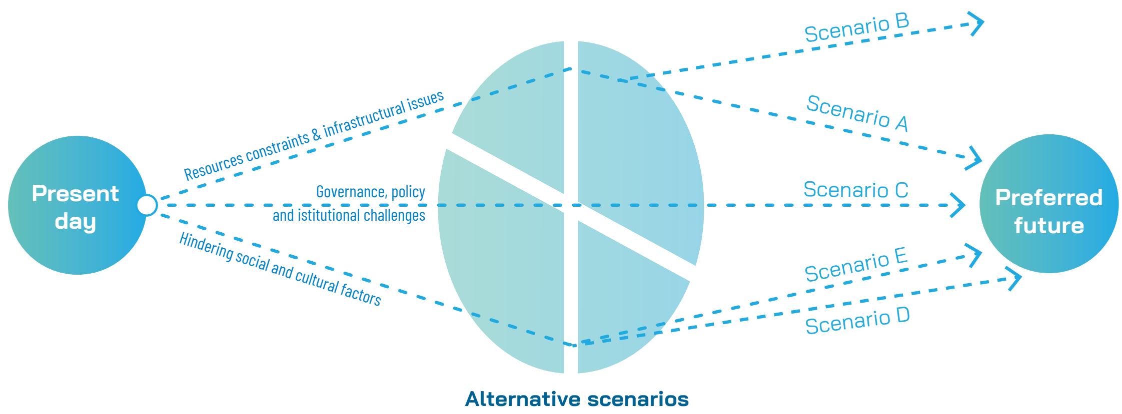
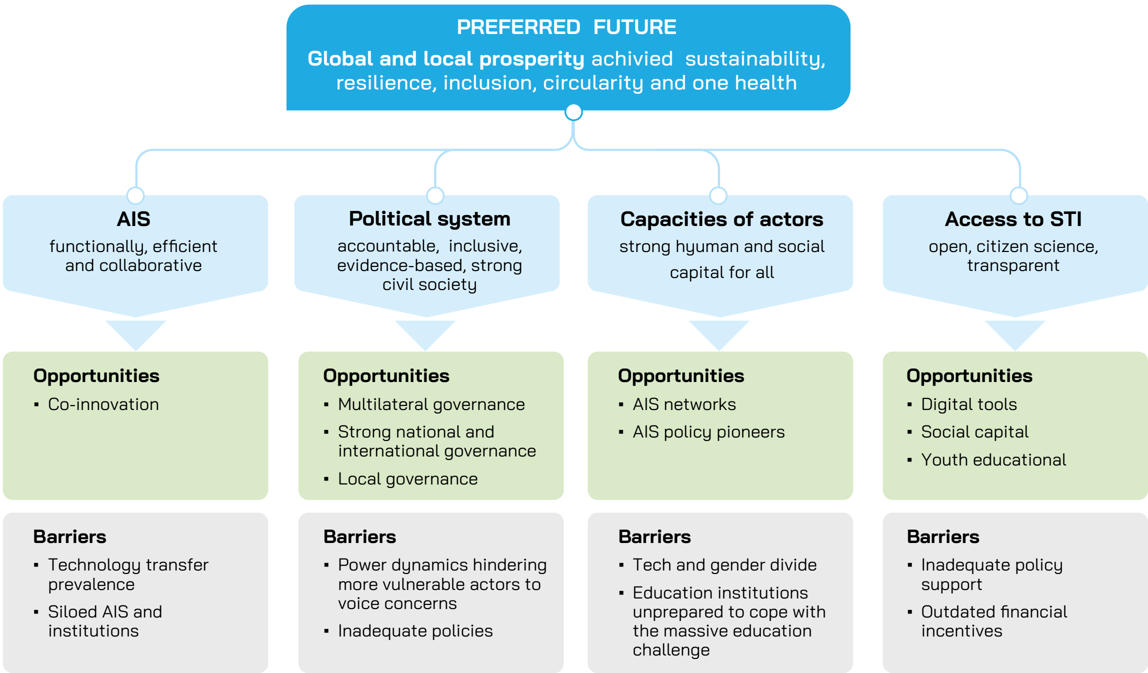


Figure 20. Results from the change agenda foresight exercise present a pathway that capitalises on opportunities and avoids or mitigates barriers



* *The opportunities and barriers for each core feature of the preferred future have been elaborated by the participant of the FAO multistakeholder foresight workshop in June 2024; hence, they are not deemed exhaustive. Their role is to help draw a roadmap based on capitalizing on opportunities and avoiding or mitigating the barriers in an anticipatory manner.*

- **Local and Indigenous knowledge integration:** incorporating traditional knowledge and practices into modern agricultural and food systems, avoiding an extractivist approach and protecting local and indigenous intellectual rights.

- **Contextualization of STI:** tailoring science, technology and innovation (STI) to meet different regions and communities' specific needs and challenges.

2. Ethical and social considerations

The second transition area focuses on shifting from profit-driven, male-dominated innovation to human-centred, gender-transformative, equitable approaches for all. This transition requires addressing ethical and social issues, mitigating risks and ensuring that innovation benefits all segments of society. Key elements include:

- **Social and ethical issues:** considering the broader social and ethical implications of innovation, such as impacts on livelihoods, food security (that may vary from a stakeholder to a stakeholder and from a community to a community and environmental sustainability.

- **Risk mitigation:** developing strategies to identify and mitigate potential risks associated with new technologies and innovations.

- **Regulations:** establishing appropriate regulations and guidelines to ensure that innovation is conducted responsibly and ethically.

- **Valuing low-tech innovation:** recognizing the importance of low-tech and traditional innovations that may be more suitable for specific contexts.

- **Inclusivity in distribution channels:** ensuring that all stakeholders, including small-scale farmers and marginalized communities, access fair and equitable distribution channels.

- **Open and trustworthy dialogue** between stakeholders, including the most vulnerable, is needed to adequately communicate the benefits and potential unintended negative consequences of proposed solutions, consider various stakeholders' concerns and demands, and adjust the research agenda accordingly.

3. Integrated, fact-based and fit-for-purpose knowledge

The third transition involves a shift from siloed and academic-driven knowledge to integrated, contextualized innovation based on facts, not factoids, usable and fit for purpose. This transition requires bridging the gap between local and scientific knowledge and tailoring STI to meet specific needs and challenges. Key elements include:

- **Connecting local and scientific knowledge:** fostering collaboration between local communities and researchers to integrate traditional knowledge with scientific insights while respecting cognitive justice.
- **Tailoring STI:** developing and adapting STI solutions to meet the specific needs and constraints of different regions, communities and individuals.
- **Farmer-led innovation:** empowering farmers to participate in innovation process and develop solutions.
- **Incentives for STI uptake:** providing incentives and support to encourage the adoption of appropriate STI solutions by farmers and other stakeholders.

4. Incentives and investment for impact

The fourth transition area focuses on shifting from profit-driven sectorial investments to impact-driven financing that targets achieving a sustainable agrifood system transformation and drives responsible use of technologies and innovations. This transition requires fostering responsible investments, scaling impact investments, identifying entry points and promoting macro- and microeconomic development. Key elements include:

- **Fostering responsible investments:** encouraging or urging investors to consider their investments' social and environmental impacts.
- **Scaling impact investments:** expanding the availability and accessibility of impact-driven financing.
- **Identifying entry points:** identifying opportunities for investment in sustainable agrifood system transformation.
- **Macroeconomic development:** supporting policies and initiatives that promote sustainable economic growth and development.
- **Incentives for STI uptake:** providing incentives and support to encourage the adoption of appropriate STI solutions.
- **Public-private partnerships:** fostering collaboration between public and private sector actors to accelerate innovation and investment.

5. Fostering systemic changes

The fifth transformation area involves a shift from unsustainable, fragmented systems to resilient, sustainable, equitable and integrated agrifood systems. This transformation requires a holistic approach that addresses the interconnectedness of different components of the agrifood system. Key elements include:

- **Diversified food production:** promoting a more diverse and resilient agrifood system that relies less on a small number of crops or production systems.
- **Sustainable resource use:** adopting practices that conserve and protect natural resources, such as water, soil and biodiversity.
- **Sustainable diets:** encouraging the adoption of healthy and sustainable diets that reduce environmental impacts and promote food security.
- **AI for food:** utilizing artificial intelligence to improve food production, distribution and consumption.
- **Climate-smart technologies and innovations:** developing and adopting technologies and innovations that help agriculture adapt to climate change and mitigate its impacts.

- **Emergency preparedness:** building resilience to shocks and stresses, such as natural disasters and economic crises.
- **Creation of e-markets:** developing digital platforms to connect farmers with consumers and facilitate the efficient and equitable trade of agricultural products.

Addressing these five transformation areas is believed to create a more sustainable, resilient and inclusive agrifood system that can meet the needs of future generations while protecting the environment and promoting social equity.

7.2 RESEARCH AND INNOVATION PRE-EMERGING AND EMERGING PARADIGM SHIFTS

This chapter introduces the Research and Innovation Paradigm Shift (RIPS) concept. RIPS refers to a change in the dominant framework or model through which technological and methodological advancements occur. These shifts influence practices, policies and the overall landscape of an industry. Understanding and anticipating these shifts allows stakeholders to navigate the complexities of future developments, ensuring they are prepared for various scenarios. Imagining different dominant future RIPS is crucial for shaping sustainable and prosperous agrifood systems. It facilitates a desired set of agrifood technology and innovation transitions. As much as the recent scholarship concentrates on paradigms of innovation such as open innovation, social innovation or responsible innovation (Chen *et al.*, 2018), we believe that it is not just the process or system of innovation that has paradigmatic characteristics but the simultaneous emergence of several technologies and innovations, such as in so-called industrial revolutions or perhaps even the occurrence of global disruptive events can also be labelled as a paradigmatic change.

The concept of innovation paradigm has evolved significantly in recent decades, shifting from a descriptive focus on historical transformations (like the shift from horse-drawn carriages to automobiles) to a normative focus on how innovation should be conducted (e.g., open innovation, sustainable innovation). While the latter is crucial for modern corporations and innovation management, it may inadvertently limit breakthrough potential by confining innovation within established frameworks. In this chapter, we adopt a distinct perspective, emphasizing the anticipation and initiation of RIPS. Inspired by Thomas Kuhn's notion of paradigm shifts in science, we propose that true breakthroughs often arise from challenging the status quo and actively shaping the future. This contrasts with merely reacting to changes as they occur. Our RIPS focus on disruptive change, creating space for innovations that may not fit established technological frameworks and opening doors for grassroots, local and low-tech solutions to gain prominence. The concept of "innovation paradigms" has shifted towards a normative focus, prescribing how innovation should be done. This can inadvertently favour established, high-tech approaches and overlook the value of non-technological and frugal innovations. RIPS, by contrast, takes a more descriptive and holistic view, acknowledging that transformative change can arise from various sources, including grassroots movements and local knowledge.

Therefore, RIPS represent changes in innovation processes and the simultaneous emergence of disruptive technologies and innovations, global events and local emergence that fundamentally alter industries and practices. We aim to future-proof innovation policy and foster preparedness for various scenarios by exploring potential RIPS in agrifood systems. This approach allows us to identify opportunities for significant advancements, prioritize investments and cultivate an environment that fosters continuous improvement and competitiveness. It also enables us to proactively address technological progress's sustainability, social equity and inclusivity implications, ensuring that innovation benefits all stakeholders and contributes to a more balanced and resilient agrifood systems.

In that meaning, RIPS in the agrifood systems encompass a broad spectrum of technological, non-technological and innovation advancements and systemic changes linked to positive reinforcement within clusters of emerging technologies and innovations and emerging innovation fields, as well as between them. RIPS is also based on exogenous stimuli that may have a paradigm-shifting influence. Each paradigm presents unique opportunities and challenges, reshaping the agrifood value chain from production and processing to distribution and retail. They can develop in separation or influence each other, growing simultaneously in the decades to come.

Furthermore, identifying and exploring future RIPS highlights opportunities for significant advancements in technology, innovation and practices. This exercise helps to future-proof innovation policy by informing the development of comprehensive and robust frameworks. Policies shaped by such foresight are more likely to be forward-thinking, adaptive and effective in fostering a sustainable agrifood systems.

From a sustainability perspective, different RIPS provide insights into how new technologies and innovations can minimize environmental impact. This understanding is vital for promoting resource efficiency, reducing waste and ensuring that agricultural practices contribute positively to ecological balance. It also aids in formulating policies that support sustainable development goals, aligning technological progress with environmental stewardship. In terms of social equity and inclusivity, considering diverse future scenarios ensures that the benefits of innovation are distributed fairly. It encourages the development of policies that make advanced technologies and innovations relevant and accessible to small-scale farmers and marginalized communities, preventing the (digital) divide from widening. By promoting inclusive innovation, these paradigms contribute to improved livelihoods and social well-being across different regions. This is why, in this extended version of our Harvesting Change synthesis report, we decided to present an analysis of seven tentative RIPS, zooming in on their respective impacts on pre-emerging and emerging agrifood technologies and innovations, sprinkled with some regional considerations for our readers to experiment with in a scenario-like fashion.

The exercise of envisioning various RIPS informs the development of comprehensive and robust policy frameworks. Policies shaped by such foresight are more likely to be forward-thinking, adaptive and effective in fostering a sustainable agrifood systems. Our existing frameworks for innovation stemming from the dominant paradigm favouring market competitiveness over small-scale producers and food security for all may not fully accommodate the transformative changes required for sustainable and equitable agrifood systems. Therefore, a deep exploration of potential RIPS is essential. By envisioning these shifts, we can proactively align them with societal needs and values, fostering preparedness for diverse scenarios and pathways. This approach helps identify opportunities for innovation and ensures that technological advancements benefit all stakeholders and contribute positively to the sustainability and resilience of the agrifood systems.

Alongside each presented RIPS, we also enclose information about the results of a validation survey, which was circulated among the participants of the FAO Multistakeholder Workshop on foresight (Rome, June 17-18, 2024), already mentioned in Chapter III, which also sought to validate the concept of RIPS.

7.2.1 Convergence of technologies: combining robotics, big data, AI, and advance biotechnologies

The first future RIPS that we examine assumes successful convergence of emerging technologies and innovations from diverse fields, including but not limited to robotics, AI, big data, biology, physics and other interdisciplinary domains, robotics AI and big data. It would revolutionize many industries, including agriculture, through precision farming, optimizing resource use and maximizing yields. On the one hand, AI-powered robots could automate tasks, while big data analytics can inform decision-making, leading to more sustainable and efficient food production. On the other hand, nanomaterials could enable precision farming at the cellular level. This convergence will also transform the supply chain, ensuring traceability, reducing waste and personalizing food products.

In the survey, it garnered a generally positive outlook from the participants.

- **Likelihood of emergence and dominance:** on average, respondents rated the likelihood of this RIPS emerging by 2035 at 6.44 out of 10, with 8 being the most frequent response. Looking ahead to 2070, the average perceived likelihood of this RIPS becoming dominant rose to 7.83, with the modal response being 10.
- **Perceived Impact:** in terms of its perceived impact on achieving inclusive, sustainable and resilient agrifood systems globally, the RIPS received an average rating of 0.75 on a scale from -3 (highly negative) to 3 (highly optimistic), with 2 being the most common response.
- **Regional Variations:** while the overall sentiment was positive, there were notable differences in the responses across different regions. Respondents from Europe and Central Asia expressed the highest confidence in the emergence of this RIPS by 2035, with an average rating of 8.33. On the other hand, those from Latin America were the least optimistic, with an average rating of 2. Regarding its dominance by 2070, participants from Asia, the Pacific and Sub-Saharan Africa displayed the most confidence, with an average rating of 9. Latin America, once more, provided the lowest average rating at 4. In terms of impact, respondents from Latin America anticipated the lowest, with an average rating of 0.

The survey results suggest that participants view the first RIPS with optimism, particularly its potential for future dominance. However, there's less consensus regarding its positive impact on inclusivity, sustainability and resilience in the global agri-food systems. The regional variations highlight the importance of considering diverse perspectives and tailoring strategies to specific contexts when promoting the adoption of RIPS. The relatively low average rating for the impact of the RIPS indicates a need for further exploration and communication about this system's potential benefits and challenges.

The participants also provided additional comments, highlighting the need for solutions that cater to the specific needs and constraints of subsistence farmers in tropical and subtropical regions. The concerns raised about potential market concentration and the impact on inclusivity and resilience emphasize the importance of carefully implementing and monitoring this RIPS.

Prominent pre-emerging and emerging technologies and innovations				
Synthetic biology	RNA interference	New methods for controlling gene expression	Environmental biotechnology	Artificial neurons
AI and big data analysis could identify and optimize metabolic pathways in organisms for targeted improvements in crops and livestock (Helmy *et al.*, 2020). Robots could then be used for high-throughput experimentation and automated manipulation of these engineered organisms.	AI could design efficient RNAi sequences to target specific genes in pests or diseases. Robots could then precisely deliver these RNAi molecules using techniques like microinjection or nanocarriers (Torres-Vanegas *et al.*, 2021). .	Big data from precision agriculture systems could inform the development of new gene editing tools (e.g., CRISPR) for desirable traits in crops and livestock (Clapp and Ruder, 2020). Robots could be programmed for precise gene editing procedures.	AI could analyze data from various sensors to optimize bioremediation techniques for cleaning up contaminated soil and water (Janga *et al.*, 2023). Robots could automate tasks like targeted delivery of bioremediation agents.	By mimicking the human brain's learning processes, AI could be used to develop "smart" biofertilizers and biopesticides that adapt to specific environmental conditions and pest outbreaks.

Advanced biotechnologies

AI and big data can optimize metabolic pathways in synthetic biology, design RNAi sequences and inform gene editing. Robotics can automate tasks and deliver biotechnologies with greater precision. These advancements bring faster innovation, improved efficiency and environmental sustainability.

Advanced digital technologies

This RIPS will drive advanced technological development. The combination of these technologies allows for hyper-precision agrifood systems. From resource use to pest control, every action could be tailored to the specific needs of each plant or micro-environment within a field. Real-time data analysis, automated tasks and optimized resource management significantly improve efficiency and productivity. This translates to higher yields, lower costs and a more sustainable agrifood systems. Early detection of diseases, targeted application of pesticides and precise monitoring of food quality throughout the supply chain could lead to safer and higher-quality food for consumers. Optimizing water usage, minimizing fertilizer application and promoting sustainable practices through AI-powered decision-making could significantly reduce of agrifood systems.

Prominent pre-emerging and emerging technologies and innovations				
6G-10G connectivity	**Aerial robotics and drones**	**Artificial General Intelligence (AGI) in agriculture**	**Digital twins**	**Internet of Food (IoF)**
This technology allows for real-time data transfer from sensors in fields, robots, and drones to AI analysis centers. This constant flow of information is crucial for optimizing decision-making and resource management.	Drones equipped with AI and high-resolution sensors could perform tasks like crop health monitoring, targeted pesticide application, and even automated pollination. Drones equipped with AI and high-resolution sensors perform tasks like precision scouting, microdosing of pesticides, and automated pollination.	AGI could analyze complex datasets from various sources, including weather patterns, soil composition, and historical yields, to predict and address agricultural challenges in a holistic manner.	Creating digital replicas of farms allows for real-time simulation and optimization of agricultural practices. By integrating data from sensors and AI models, digital twins could predict potential problems like pest outbreaks or water shortages, enabling farmers to take preventive measures.	IoF, powered by sensors and real-time data collection, could improve food traceability, optimize logistics, and minimize food waste.

Advanced geospatial technologies

Leveraging robotics, AI and big data within precision agriculture unlocks a new frontier for advanced geospatial technologies. This convergence empowers farmers with hyper-local field insights, enabling them to micro-target resource applications based on specific environmental needs. Real-time geospatial data and AI analysis facilitate data-driven resource allocation, irrigation and pest control decision-making. These advancements culminate in improved resource efficiency, reduced waste, yield optimization and enhanced animal welfare through precision livestock management.

Prominent pre-emerging and emerging technologies and innovations		
Realtime satellite imagery	**Autonomous GIS (Geographic Information Systems)**	**Advanced positioning systems**
High-resolution satellite images, updated frequently, provide a birds-eye view of fields. AI algorithms could analyze these images to identify crop health issues, assess soil moisture levels and even predict potential problems like pest outbreaks (Khan *et al.,* 2024).	Self-driving tractors or drones with advanced GPS and sensors could collect real-time data on soil conditions, plant health and field topography (Khan *et al.,* 2018). This data could then be integrated with other sources like satellite imagery and weather forecasts to create a comprehensive picture of the agricultural environment.	Real-Time Kinematic (RTK) positioning systems provide centimetre-level accuracy for robots and farm equipment (Duckett *et al.,* 2018). This allows for ultra-precise tasks like planting seeds in optimal locations or applying fertilizer exactly where needed.

Policy innovation

Policies could encourage practices that reduce agriculture's environmental footprint by promoting nature-based solutions and providing information on sustainable agriculture. Access to information, training and appropriate technologies and innovations could **empower farmers** to make data-driven decisions, improve their livelihoods and become more resilient to climate change. Policies supporting local agrifood systems and transparency in food production could give consumers greater choice and **access to healthy, sustainably produced food.** AI-powered logistics and optimized supply chains could **minimize food spoilage and waste** throughout the agrifood system.

Prominent pre-emerging and emerging technologies and innovations			
Innovation Policy Labs	**Territorial Food-to-Consumer Economy**	**Nature-Based and Ecosystem Innovations**	**Frugal Innovation**
By testing and evaluating new technologies and policy approaches in real-world settings, Innovation Policy Labs could inform the development of effective policies for the future of agrifood.	Policies could encourage the development of local agrifood systems that connect producers directly with consumers. AI and big data could optimize these local networks, matching supply with consumer demand.	Policies could incentivize practices that promote biodiversity and ecosystem health. AI could be used to model and optimize nature-based solutions like regenerative agriculture techniques, invest in habitat restoration, or use biocontrol methods for pest management.	AI could be used to design and optimize these frugal innovations for specific regional needs based on expert systems' knowledge of benchmark solutions.

New renewable energy and transportation

While combining robotics, AI and big data in precision agriculture won't directly revolutionize new renewable energy sources like nuclear power, it could indirectly influence the future of agrifood. AI-powered logistics could optimize transportation and the focus on efficiency could lead to more biomass for biofuels and minimize food spoilage throughout the supply chain. The bigger impact lies in sustainability. Precision agriculture could reduce reliance on fossil fuels through better farm management and precision water use, leading to a circular economy and a more climate-friendly agrifood system.

Prominent pre-emerging and emerging technologies and innovations			
Global logistics network	Teleportation of complex molecules	Novel biomass	Novel energy storage technologies
Robotics, AI and big data could optimize farm-to-consumer logistics through route planning and demand forecasting (Udeh *et al.*, 2024). Autonomous delivery vehicles and optimized transportation networks minimize food waste and ensure timely delivery of fresh produce.	Teleportation is highly theoretical at this point. robotics, AI, and big data as well as significant investment in fundamental research could make this process attainable in the long run.	By analyzing data on soil health, weather patterns and plant growth, AI could guide farmers in selecting the most efficient biomass crops and optimizing their cultivation for maximum yield (Javaid *et al.*, 2023).	The data collected through robotics, AI and big data in precision agriculture could be used to inform the development and deployment of novel energy storage technologies. For example, understanding farm energy consumption patterns could help design efficient energy storage solutions for powering agricultural robots and sensors (Kabir and Ekici, 2024).

Market and financial innovation

AI and big data could create transparent and verifiable food supply chains. Consumers could access information on the origin, environmental impact and production methods used for their food, potentially driving demand for sustainably produced goods. Farmers could leverage data analytics to target specific consumer segments with customized products and marketing strategies. This could create new market opportunities for niche agricultural products. Blockchain technology, combined with data from precision agriculture, could facilitate decentralized agrifood systems. This allows consumers to connect directly with farmers, potentially reducing reliance on traditional intermediaries and increasing profitability for farmers. AI-powered risk assessments and insurance products based on real-time data could improve farm resilience in the face of climate change and other challenges.

Prominent emerging technologies and innovations	
Carbon Credits for Sustainable Practices	Social Impact Bonds for Sustainable Agriculture
Data from precision agriculture could be used to verify carbon sequestration and emission reductions achieved through sustainable farming practices (Gudelė and Visockienė, 2024). This could create a robust market for carbon credits, incentivizing farmers to adopt these practices.	Investors could fund projects promoting sustainable agriculture, with repayment contingent on achieving specific environmental or social impact goals. This could attract new capital to the sector and support the development of sustainable agricultural practices.

Food manufacturing technologies and nutrition

Data collected from individuals (e.g., genetics, health conditions, dietary needs) could be used to create personalized nutrition and 3D-printed food options that optimize overall health. AI-powered food design could incorporate essential vitamins and minerals into processed food, potentially addressing micronutrient deficiencies. The ability to personalize food textures, flavours and nutrient profiles could increase the appeal and variety of healthy food options, encouraging more nutritious choices. Personalized nutrition solutions could effectively address dietary restrictions, allergies and specific health conditions, ensuring inclusivity in the future of food.

Prominent pre-emerging and emerging technologies and innovations		
3D Printing of Food	**4D Nanoscale Printing**	**Personalized nutrition**
Local crop data from precision agriculture allows AI to design 3D-printed food using the most nutritious ingredients (Yoo and Park, 2021). AI could personalize portions based on individual needs.	This technology could fortify crops at a cellular level based on data from precision agriculture, addressing nutrient deficiencies. It could also print food with targeted functionalities for personalized health needs.	AI could create data-driven nutrition plans that consider an individual's needs and the seasonal variations in nutrients from locally sourced ingredients (Theodore Armand *et al.*, 2024).

Micro- and nanotechnology and nanobiotech

The convergence of robotics, AI and big data in precision agriculture empowers significant advancements in micro-nanotechnology and nanobiotechnology within the agrifood systems. Data-driven insights could guide nanorobots for targeted tasks, optimize water management with nanosensors and create intelligent food packaging with extended shelf life. Precision delivery of nano-based fertilizers, pesticides and antibiotics could minimize environmental impact. This synergistic approach holds immense potential to revolutionize food production, fostering sustainability, reducing food waste and enhancing food safety.

Prominent pre-emerging and emerging technologies and innovations		
Nanorobotics	**Nanomaterials for water technologies**	**Nano pesticides, fertilizers and antibiotics**
AI-powered data analysis from precision agriculture could guide nanorobots to target specific areas of crops or soil. Sensor networks in fields could provide real-time data on crop health and pest presence, allowing AI to optimize the deployment and actions of nanorobots. AI could coordinate swarms of nanorobots for tasks like large-scale weed control or disease detection.	AI could analyze data from nanosensors embedded in soil to create intelligent irrigation systems that adapt to changing weather conditions and crop needs. Real-time data on water salinity and quality from precision agriculture could inform the optimization of nanofiltration membranes in desalination plants.	AI-powered analysis of plant diseases could inform the development of targeted antimicrobial nanomedicines.

Potential benefits and challenges

Potential benefits:

- Precision agrifood systems techniques enabled by this convergence allow for precise application of water, fertilizers and pesticides, minimizing waste and reducing environmental impact. This mainly benefits regions with scarce water resources, like Northern Africa and the Near East. Precision agriculture could lower production costs and potentially lower consumer food prices.
- AI-powered data analytics can identify optimal planting times, predict crop diseases and optimize harvesting schedules, leading to increased yields and improved crop quality. This is crucial for regions facing food security challenges like Sub-Saharan Africa. Increased agricultural productivity could boost economic growth in rural areas and create new markets for technology providers.

- Robotics can automate labour-intensive tasks like planting, harvesting and weeding, reducing labour costs and increasing efficiency. This is particularly advantageous for regions with ageing farming populations like Europe and North America.
- Big data analytics can provide farmers with valuable insights into soil health, weather patterns and market trends, enabling them to make informed decisions about crop selection, planting and marketing. This benefits all regions but is especially valuable for areas with diverse agrifood systems like Asia and the Pacific.

Potential challenges:

- The adoption of these technologies and innovations requires significant upfront investment in equipment, software and training, which may be prohibitive for smallholder farmers in regions like Latin America and Sub-Saharan Africa. Investments in renewable energy to power these technologies and innovations will also be important. Large agribusinesses with resources to adopt these technologies and innovations might gain greater control over the food chain, potentially squeezing out smaller farms.
- Implementing and maintaining these technologies and innovations require specialized knowledge and skills that may not be readily available in all regions, particularly in the Global South. Reliance on imported technologies and innovations and knowledge from developed nations could create new economic and social vulnerabilities.
- Collecting and analyzing vast amounts of agricultural data would raise concerns about privacy and security, especially in regions with less-developed data protection regulations.
- Automating agricultural tasks could lead to job displacement in regions with high agricultural employment, potentially exacerbating existing socioeconomic inequalities.
- A decline in traditional farming practices could impact rural communities' social fabric and cultural identity, including rural habitation patterns. Overreliance on technologies and innovations could also hamper resilience in case of system failure.

7.2.2 Biomimicry: developing sustainable solutions inspired by nature

Biomimicry will revolutionize agrifood systems by implementing nature-inspired solutions for sustainable agriculture. Farmers can reduce reliance on harmful chemicals and create resilient ecosystems by emulating natural processes like nutrient cycling and pest control. Biomimicry also inspires innovative food production, packaging and distribution designs, minimizing waste and environmental impact.

This second RIPS also garnered positive expectations in our survey.

- **Likelihood of emergence and dominance:** the average perceived likelihood of its emergence by 2035 was 6.5 out of 10, with 6 being the most frequent response. Regarding its dominance by 2070, the average perceived likelihood was 7.2, with a dominance of 8.
- **Perceived impact:** the perceived impact of the second RIPS on achieving inclusive, sustainable and resilient agrifood systems was rated an average of 1.22 on the -3 to 3 scale.
- **Regional variations:** global respondents showed the highest confidence in the emergence of this RIPS by 2035 and its dominance by 2070, with average ratings of 8.17 and 9, respectively. Global respondents were the least optimistic about its emergence by 2035, with an average rating of 5.33. Asia and Pacific as well as North American respondents perceived the highest positive impact from this second RIPS, with an average rating of 2. Latin American respondents anticipated the lowest impact, with an average rating of 0.

The second RIPS also received a generally positive reception, with participants anticipating its emergence and dominance. However, a broader range of opinions on its potential impact suggests a need for further dialogue and information sharing.

Regional differences persist, emphasizing the importance of context-specific approaches in promoting and implementing RIPS.

Participants' additional feedback on Biomimicry underscores the importance of farmer engagement and trust-building. While the potential for sustainable and environmentally friendly solutions is recognized, concerns about opposition from established industries and the need for significant investment in research and technology transfer are also highlighted.

Advanced biotechnologies

Biomimicry could significantly enhance biotechnologies for a sustainable agrifood future. Synthetic biology could create nitrogen-fixing microbes and bio-based materials by studying nature's solutions. RNAi could be inspired by plant defences for targeted pest control and silencing allergens. New gene editing methods could introduce stress tolerance and biomimicry-inspired sensors into crops. Environmental biotechnology could leverage biomimicry for efficient bioremediation and self-sustaining wastewater treatment. Artificial neurons could be designed to detect plant diseases and optimize resource use based on bio-inspired sensors.

Prominent pre-emerging and emerging technologies and innovations				
Synthetic biology	**RNA interference**	**New methods for controlling gene expression**	**Environmental biotechnology**	**Artificial neurons**
Biomimicry could inspire the creation of synthetic microbes that produce biodegradable packaging materials or biofuels, promoting a circular economy within agrifood systems and eliminating dependence on artificial nitrogen fertilizers (Soto *et al.,* 2021).	Biomimicry could guide the development of RNAi techniques to silence specific genes in crops that code for allergens, creating hypoallergenic food options for consumers with allergies (Christiaens *et al.,* 2022).	Biomimicry could guide the creation of gene editing tools to equip crops with biosensors and introduce stress-responsive traits into crops, improving their resilience to salinity, drought, or extreme temperatures (Govindan *et al.,* 2024).	Biomimicry could inspire the design of self-sustaining bioreactors that utilize microbial communities for wastewater treatment, more energy-saving or efficiently degrade agricultural waste products and pollutants (Akpasi *et al.,* 2023).	Biomimicry could inspire the development of bio-inspired sensors (Lu, K *et al.,* 2023).

Advanced digital technologies

Studying nature's communication networks could optimize data flow in 6G–10G agricultural networks. Biomimicry could inspire efficient flight patterns for agricultural drones and inform AGI algorithms for real-time pest detection. It could also guide the creation of accurate digital twins and bio-inspired food spoilage detection systems within the Internet of Food. Biomimicry could accelerate protein structure prediction using quantum computing by mimicking protein folding processes.

Prominent pre-emerging and emerging technologies and innovations			
Aerial robotics and drones	**Artificial General Intelligence in agriculture**	**Internet of Food**	**Quantum computing**
Biomimicry could inspire the development of autonomous navigation algorithms for agricultural drones, leading to more efficient data collection, targeted interventions and improved overall farm operations (Tanaka *et al.,* 2022; Rob, 2016).	By studying how plants respond to environmental stimuli, we could inform the development of more robust and efficient AGI learning models.	Biomimicry could inspire the development of IoF sensor systems that could detect spoilage at an early stage (Dung *et al.,* 2018). By studying the natural odour and gas emissions of fruits and vegetables as they ripen and spoil, we could design IoF sensors with biomimicry-inspired detection capabilities.	Biomimicry could inspire the development of quantum computing algorithms that could accelerate protein structure prediction by mimicking the natural process of protein folding (Yang *et al.,* 2023). This enables the design of novel bio-based solutions like fertilizers, pesticides, or crops with enhanced traits.

Advanced geospatial technologies innovations

This paradigm does not have a tremendous impact on the development of geospatial technologies and innovations. Biomimicry could, however, inspire the development of new methods for collecting and analyzing geospatial data, leading to a more comprehensive understanding of agricultural landscapes and crop health. Bio-inspired algorithms for analysing satellite imagery could detect crop diseases.

Policy innovation

Biomimicry could inspire policies that promote regenerative agriculture, closed-loop systems and reduced food waste, leading to a more sustainable agrifood system.

Prominent pre-emerging and emerging technologies and innovations			
Territorial food-to-consumer economy	**Access to information on sustainability matters**	**Nature-based and ecosystem innovations**	**Frugal innovation**
Biomimicry principles could inspire closed-loop water systems within these territories.	Educational programs and online platforms showcasing successful biomimicry applications could raise awareness and inspire broader adoption of sustainable practices.	Studying natural ecosystems could inform policies that incentivize regenerative agriculture practices like cover cropping and promote ecosystem restoration around agricultural lands.	Biomimicry could inspire low-cost technologies like water-harvesting systems mimicking desert plants, suitable for smallholder farmers. Knowledge-sharing networks could further accelerate biomimicry adoption.

New renewable energy and transportation

Bio-inspired solutions could reduce emissions and resource use within the food supply chain. Biomimicry could inspire the creation of novel biomass sources and efficient energy storage solutions for powering agrifood operations. Biomimicry-inspired solutions could help us utilize agricultural waste for renewable energy generation.

Prominent pre-emerging and emerging technologies and innovations		
Nuclear energy in agriculture	**Novel biomass**	**Novel energy storage technologies**
Studying how organisms (like extremophiles) thrive in harsh environments could inspire the development of safer and more efficient nuclear waste disposal methods (Butterworth *et al.,* 2023).	Studying the efficient photosynthesis processes of plants or the fast-growing capabilities of certain algae could inspire the development of high-yield, biomimicry-inspired biomass crops for renewable energy generation within the agrifood systems (Javed *et al.,* 2022).	Studying the energy storage capabilities of biological systems (Dodón *et al.,* 2021) like an electric eel's electrocytes or how plants store energy in chemical bonds could inspire the development of novel and more efficient energy storage solutions for renewable energy used in agrifood systems.

Market and financial innovation

Biomimicry-verified practices could generate tradable carbon credits or attract investment through social impact bonds. Studying how natural ecosystems sequester carbon could inspire the development of biomimicry-verified agricultural practices that enhance soil carbon storage (Rodrigues *et al.,* 2023). This could create tradable carbon credits for farmers implementing these practices, creating a new revenue stream.

Food manufacturing technologies and nutrition

Biomimicry-inspired 3D printing could reduce waste by creating food on demand and minimizing overproduction. Biomimicry could lead to personalized food solutions that cater to individual dietary needs.

Prominent pre-emerging and emerging technologies and innovations		
3D printing of food and liquids	**4D nanoscale printing**	**Personalized nutrition**
Biomimicry could help develop new, edible and biodegradable materials for 3D printing food inspired by nature's use of chitin in insect exoskeletons (Lin, 2022).	Learning from natural mechanisms like timed seed dispersal could inspire 4D printing of food with controlled nutrient release, enhancing its nutritional value.	Studying how organisms like coral reefs maintain complex microbial communities could inspire personalized nutrition approaches considering an individual's gut microbiome (Mohamed *et al.,* 2023).

Micro- and nanotechnology and nanobiotech

Biomimicry-inspired solutions could enhance resource efficiency and reduce reliance on chemical inputs in agriculture. Biomimicry could lead to food packaging and storage advancements, minimizing spoilage and waste.

Prominent pre-emerging and emerging technologies and innovations			
Nanorobotics	**Nanomaterials for water technologies**	**Nanomaterials for food packaging**	**Nano pesticides, fertilizers and antibiotics**
Studying how viruses deliver genetic material into cells could inspire biomimicry-designed nanorobots for targeted delivery of pesticides, fertilizers, or nutrients directly to plant roots or specific pests, minimizing environmental impact.	Mimicking natural filtration mechanisms in organisms like kidney membranes could inspire the development of biomimicry-designed nanofilters (Jakšić, Z. and Jakšić, O, 2020) for more efficient and sustainable water purification in agriculture.	Studying how nature preserves food could lead to biomimicry-inspired nanocoatings for food packaging that extend shelf life, reduce spoilage and minimize waste (Mohammad and Ahmad, 2024).	Studying natural pest defence mechanisms could inspire the development of more targeted and biodegradable nanopesticides that are less harmful to beneficial insects and the environment (Rathore *et al.*, 2024).

Potential benefits and challenges

Potential benefits:

- Biomimicry can inspire more sustainable farming practices that mimic natural ecosystems. This is particularly relevant for regions like Latin America and Sub-Saharan Africa, where biodiversity is crucial for agricultural resilience.
- Nature offers numerous examples of efficient water and energy use. Biomimetic designs for irrigation systems and greenhouses can significantly reduce water consumption and energy needs. This is especially important for arid regions like Northern Africa and the Near East.
- By studying plant adaptations to harsh environments, scientists can develop crop varieties that are more resilient to drought, pests and diseases. This is crucial for regions such as Sub-Saharan Africa, which is vulnerable to climate change impacts.
- Biomimicry can inspire the design of new food production systems that mimic natural processes.
- Biomimicry can help develop alternative pest control methods inspired by natural predators and plant defences. This can reduce reliance on harmful pesticides and promote ecological balance.
- Biomimicry can lead to innovative solutions for water harvesting, energy production and agricultural waste management.
- Biomimicry can inspire the development of closed-loop systems that minimize waste and maximize resource utilization. This can be particularly beneficial in densely populated regions with limited land availability, like Asia and the Pacific.
- Biomimetic designs for packaging materials can be developed from biodegradable materials found in nature, reducing waste and pollution. This is a global concern, but especially relevant for regions with high plastic consumption, such as Asia and the Pacific.

Potential challenges:

- Regions with significant income disparities,, require careful policy interventions to ensure equitable access to these advancements for small-scale farmers. Investment in rural infrastructure and education is paramount.
- Implementing biomimicry requires extensive research and development to identify and

translate suitable natural models into practical solutions. This can be costly and time-consuming.

- While biomimetic solutions may work well on a small scale, scaling them up to meet the needs of large-scale agricultural operations can be challenging, especially considering differences between local ecosystems.
- The adoption of biomimetic technologies and innovations may require changes to existing regulations and standards. This can be a slow process and may vary across different regions.
- Raising awareness and providing training on biomimicry principles to farmers, researchers and policymakers is crucial for widespread scaling.

7.2.3 Open- and open-source innovation (e.g., fostering collaborative development and knowledge sharing)

Further mainstreaming of open-source innovation and full embracement of open innovation, with mainstreaming of innovation in networks, cross-fertilized by diverse stakeholder perspectives, would help democratize the technologies and innovations for agrifood system by providing farmers and researchers with free access to tools and knowledge, fostering collaboration and accelerating innovation. This approach will reduce costs, increase transparency and empower local communities to develop solutions tailored to their needs and resources.

This third RIPS also garnered positive expectations in our survey.

- **Likelihood of emergence and dominance:** the average perceived likelihood of its emergence by 2035 was 6.43 out of 10, with 7 and 8 being the most frequent responses. The standard deviation of 2.2 suggests a moderate level of agreement among participants. Regarding its dominance by 2070, the average perceived likelihood was 7.17, with a mode of 7. The standard deviation of 2.47 indicates a slightly higher degree of variability in opinions compared to the first two RIPS.
- **Perceived impact:** the perceived impact of the third RIPS on achieving inclusive, sustainable, and resilient agri-food systems was rated an average of 1.34 on the -3 to 3 scale, with 2 and 3 being the most common responses.
- **Regional variations**: 'Global' respondents showed the highest confidence in the emergence of this RIPS by 2035, with an average rating of 8.33. 'Sub-Saharan Africa' and 'Asia and Pacific' respondents were less optimistic, with average ratings of 5.84 and 6.5, respectively. 'Global' respondents again expressed the highest confidence in the RIPS becoming dominant by 2070, with an average rating of 9.67. 'Europe and Central Asia' respondents showed the most variability in their responses, with a standard deviation of 3.21 and the lowest average rating of 4.67. 'Sub-Saharan Africa, Global' and 'North America' respondents perceived the highest positive impact from this third RIPS, with an average rating of 2.67 and 3, respectively. Latin America respondents anticipated the lowest impact, with an average rating of 0.Participants this RIPS' potential for emergence and dominance, although with slightly less certainty compared to the first RIPS. The perceived impact shows a wider range of opinions, indicating a need for further discussion and clarification.

The third RIPS maintains the overall positive perception of the probability observed in the previous two. Participants see its potential for emergence and dominance. The perceived impact shows a broader range of opinions, indicating a need for further discussion and clarification.

Advanced biotechnologies

Collaborative knowledge sharing through open platforms could accelerate research cycles, foster a broader range of scientific expertise and reduce costs. By overcoming challenges like data standardization and biosecurity concerns, open-source approaches hold immense potential to cultivate a more secure and sustainable food future.

Prominent pre-emerging and emerging technologies and innovations				
Synthetic biology	**RNA interference**	**New methods for controlling gene expression**	**Environmental biotechnology**	**Artificial neurons**
Open-source platforms could facilitate the sharing of genetic constructs and standardized protocols, accelerating the design and development of beneficial microbes for food production or bioremediation.	Open databases of RNAi targets and their effects on plant and animal genes could support the development of targeted pest and disease control methods.	Open-source CRISPR libraries and protocols could democratize access to gene editing tools, enabling researchers worldwide to contribute to crop improvement for drought resistance, nutrient enhancement, etc.	Open-source data on biodegradation pathways and engineered microbes could accelerate the development of solutions for bioremediation of agricultural pollutants.	Open-source software and hardware designs for biocomputers could empower researchers to develop more efficient and accurate tools for agricultural data analysis, optimizing crop yields and resource management.

The comments on the third RIPS, Open and Open-Source Innovation, emphasize the need for a cultural shift in the research community towards genuine collaboration and knowledge sharing with practitioners. The concerns about potential power imbalances and the need for equitable distribution of benefits underscore the importance of inclusive approaches in promoting innovation.

Advanced digital technologies

Open-source collaboration could accelerate the development and scaling of advanced digital technologies in agrifood systems. Sharing knowledge and resources through open platforms could speed up innovation, tap into a broader range of expertise and reduce costs. This fosters faster development of technologies like 6G connectivity for real-time data collection, open-source drone designs for precision agriculture and AI algorithms for disease detection. Overall, open-source innovation could make these advanced digital technologies more accessible and promote a more efficient, sustainable and inclusive global agrifood systems.

Prominent pre-emerging and emerging technologies and innovations					
6G-10G connectivity for agriculture	**Aerial robotics and drones**	**Artificial General Intelligence in agriculture**	**Digital twins**	**Quantum computing**	**Internet of Food**
Open-source platforms could facilitate collaboration on developing and deploying network infrastructure, enabling real-time data collection and analysis for precision agriculture in remote areas.	Open-source software and hardware designs could accelerate the development of affordable and efficient drones for crop monitoring, spraying, and field data collection.	Sharing AI algorithms and datasets openly could empower researchers to develop more robust and adaptable AI solutions for tasks like disease detection and yield prediction.	Open-source software libraries and simulation models could enable the creation of more accurate and accessible digital twins of farms, fostering better decision-making and resource management.	Open-source quantum algorithms and software could empower researchers to explore applications in agriculture, such as complex crop modeling and optimizing fertilizer use.	Open data standards and communication protocols could accelerate the development of a truly interconnected IoF ecosystem, ensuring seamless data exchange and real-time food chain traceability.

Advanced geospatial technologies

Sharing knowledge and resources through open platforms could speed up innovation, improve data quality through collaboration and make these technologies more affordable. This fosters faster development of real-time satellite imagery for crop health monitoring, user-friendly tools for data analysis and high-precision positioning systems for automation. Overall, open-source innovation could unlock the full potential of geospatial technologies, empowering farmers with data-driven decision-making tools for a more efficient and sustainable agrifood systems.

Prominent pre-emerging and emerging technologies and innovations		
Real-time satellite imagery	**Autonomous GIS**	**Positioning systems**
Open platforms could facilitate collaboration between space agencies and research institutions, leading to faster development of standardized data formats and improved image processing algorithms. This allows farmers to access real-time insights into crop health, soil moisture, and potential pest outbreaks.	Open-source software development could accelerate the creation of user-friendly tools for data analysis and decision-making. Farmers could leverage these tools for tasks like yield prediction, optimized resource management, and targeted interventions	Open-source hardware designs and data sharing protocols could lead to the development of more affordable and accessible high-precision positioning systems. This allows for precise in-field data collection and automation of agricultural tasks.

Policy innovation

Sharing knowledge and resources through open platforms allows for faster policy development, inclusion of diverse perspectives and continuous improvement based on data and feedback. This fosters effective policy solutions for Innovation Policy Labs, local agrifood systems, access to sustainability information and nature-based innovations. Through collaborative policymaking, open-source innovation could empower stakeholders to create a more sustainable, equitable and resilient agrifood systems.

Prominent pre-emerging and emerging technologies and innovations				
Innovation Policy labs	**Territorial food-to-consumer economy**	**Access to information on sustainability matters**	**Nature-based and ecosystem innovations**	**Frugal innovation**
Open platforms could facilitate the exchange of best practices and co-crPEATISon of new policy approaches for fostering innovation in the agrifood system.	Open data and knowledge sharing could empower local communities to develop sustainable and efficient agrifood systems tailored to their specific needs.	Open-source platforms could be used to disseminate knowledge on sustainable agricultural practices, empowering farmers and consumers to make informed decisions.	Open collaboration could accelerate research and development of nature-based solutions like regenerative agriculture and ecosystem restoration, fostering more sustainable food production.	Open platforms could help share knowledge about low-cost, resource-efficient solutions developed in resource-constrained regions, promoting their wider adoption.

New renewable energy and transportation

Sharing knowledge on nuclear energy for remote farms, optimizing logistics networks through open data platforms and exploring novel biomass sources are some possibilities. This fosters faster advancements, improved efficiency and reduced costs for these technologies and innovations in the agrifood systems. However, challenges include building technical expertise, data security and standardization

Prominent pre-emerging and emerging technologies and innovations				
Nuclear energy in agriculture	Global logistics network	Teleportation of complex molecules	Novel biomass	Novel energy storage technologies
Open platforms could facilitate collaboration between nuclear research institutions and agricultural scientists. This could lead to knowledge sharing on developing safer and more efficient small-scale nuclear reactors to power agricultural processes like desalination or greenhouse heating in remote areas.	Open data platforms could improve transparency and efficiency in agricultural supply chains. Sharing real-time data on transportation capacity, weather conditions, and storage facilities could optimize logistics networks, reducing food spoilage and transportation emissions.	Open collaboration between physicists and agricultural researchers could accelerate research into this technology for potential applications in preserving highly perishable agricultural products.	Sharing data on the growth rates, energy output, and environmental impact of various biomass crops could accelerate the development of sustainable biofuels for agricultural equipment.	Sharing knowledge on material science, battery technology, and grid integration could lead to more efficient and cost-effective energy storage for powering farms and rural communities.

Market and financial innovation

Open-source innovation could unlock new revenue streams, attract investment and promote a sustainable agrifood systems. This fosters faster innovation, improved transparency, increased accessibility for small producers and standardization for scaling these financial instruments. Challenges include data quality, technical expertise and regulations. Open data platforms, incl. distributed ledger technology-based securities systems, could facilitate transparent monitoring, reporting and verification (MRV) of carbon sequestration practices. This could empower farmers and aquaculture operators to participate in carbon credit markets and generate new income streams.

Food manufacturing technologies and nutrition

Sharing knowledge on 3D printing food and 4D nanoscale printing through open platforms could lead to more accessible and diverse food options. Open data sharing and open-source apps could also empower individuals with personalized dietary recommendations. This fosters faster innovation, increased accessibility, diverse food options and transparency. Challenges include data security, standardization and regulations.

Prominent pre-emerging and emerging technologies and innovations	
3D printing of food and liquids	**Personalized nutrition**
Open-source platforms could accelerate the development of 3D printing hardware and software, making this technology more accessible and affordable for food manufacturers. Collaboration could lead to the creation of open-source recipes and printing techniques for a wider variety of nutritious and personalized food options.	Open data platforms could facilitate the sharing of anonymized genetic and health data, allowing researchers to develop more accurate and personalized dietary recommendations.

Micro- and nanotechnology and nanobiotech

Sharing knowledge on nanorobotics, water filtration materials, food packaging and targeted nano-pesticides/fertilizers through open platforms could lead to faster innovation, reduced costs and improved environmental sustainability. This fosters the development of more efficient and eco-friendly solutions for a future of safe and secure food production. Challenges include assessing environmental and health risks, establishing regulations and building public trust.

Potential benefits and challenges

Potential benefits:

- Open-source platforms could allow farmers, researchers and entrepreneurs to access and modify agricultural technologies, tools and data without prohibitive licensing fees. This would benefit Sub-Saharan Africa and Asia-Pacific small-scale farmers, who often lack the resources to invest in proprietary technologies.

- Enabling diverse stakeholders to contribute their expertise and ideas could lead to the rapid development and deployment of solutions tailored to specific local challenges, such as drought-resistant crops in Northern Africa and the Near East or sustainable farming practices in Latin America. Additionally, indigenous knowledge could be integrated with modern technologies.

- By eliminating licensing fees and promoting the sharing of resources, open-source innovation could lower the cost of technology adoption, making it more accessible to farmers in all regions, including those in developing countries.

- Open-source innovation can promote sustainable practices by encouraging the development of environmentally friendly technologies and sharing knowledge about regenerative agriculture techniques. This is crucial for all regions, especially those facing environmental challenges, like Europe and Central Asia.

Potential challenges:

- Open-source models may not provide sufficient financial incentives for innovators, potentially hindering investment in research and development. This is a concern in regions with strong intellectual property protection regimes like North America.

- Ensuring the quality and reliability of open-source technologies can be challenging without formal certification processes. This is a concern in all regions, particularly in those with less developed regulatory frameworks.

- Access to the internet and digital infrastructure is a prerequisite for participating in open-source projects. This can be a barrier in regions with limited connectivity, particularly in rural areas of Sub-Saharan Africa and parts of Asia.

7.2.4 Citizen science: engaging citizens in data collection and problem-solving

Citizen science as a new RIPS would empower individuals to actively participate in shaping the agrifood systems through data collection, monitoring and problem-solving initiatives. Farmers and consumers gain access to valuable local knowledge and insights by engaging citizens in research and decision-making, leading to more effective and sustainable solutions.

Citizen science also received a positive outlook in our survey, although slightly less optimistic than the previous ones.

- **Likelihood of emergence and dominance:** the average perceived likelihood of its emergence by 2035 was 6.11 out of 10, with 6 being the most frequent response. Regarding its dominance by 2070, the average perceived likelihood was 6.74, with a dominance of 7 and 8.
- **Perceived impact:** the perceived impact of the fourth RIPS on achieving inclusive, sustainable, and resilient agri-food systems was rated an average of 1.17 on the -3 to 3 scale. The standard deviation of 1.76 suggests a wide range of views on the potential impact.
- **Regional variations:** 'Global' and 'Sub-Saharan Africa, Global' respondents showed the highest confidence in the emergence of this RIPS by 2035, with average ratings of 7.83 and 8, respectively. 'Europe and Central Asia' respondents were the least optimistic and showed the most variability in their responses, with an average rating of 4.67 and a standard deviation of 3.51. 'Global' respondents again expressed the highest confidence in the RIPS becoming dominant by 2070, with an average rating of 9. 'Europe and Central Asia' respondents provided the lowest average rating at 3.67. Similar to the previous RIPS, 'Sub-Saharan Africa, Global' respondents perceived the highest positive impact from this fourth RIPS, with an average rating of 2.67. 'Europe and Central Asia' respondents showed the most variability in their responses, with a standard deviation of 2.65,

Citizen science projects could engage many people in data collection, particularly for geographically dispersed phenomena. This could be valuable for environmental biotechnology projects monitoring soil health, pest outbreaks, or the impact of new biotechnologies on local ecosystems. Citizen scientists with diverse backgrounds and local knowledge could contribute fresh perspectives and identify problems researchers might miss. This could be crucial for sparking innovation in synthetic biology or new methods for controlling gene expression. Citizen science projects could increase public awareness and understanding of advanced biotechnologies, fostering trust and acceptance in the agrifood systems.

The feedback on the fourth RIPS, **Citizen Science**, highlights the potential for democratizing scientific research and integrating local knowledge. However, concerns about power imbalances and the need for transparent governance structures and capacity development among farming communities have also been raised.

Prominent pre-emerging and emerging technologies and innovations

Synthetic biology	RNA interference	New methods for controlling gene expression	Environmental biotechnology	Artificial neurons
Citizen scientists could help collect data on the diversity of local plants and microbes, potentially leading to the discovery of novel genes or enzymes with valuable applications in synthetic biology (Theissinger *et al.*, 2023).	Citizen science projects could be used to monitor the spread of plant diseases or invasive species, informing the development of targeted RNAi approaches for pest control.	Citizen scientists could contribute data on local environmental conditions and agricultural practices, helping researchers develop gene editing techniques that are more resilient to environmental variations, especially in areas where official data sources are unavailable or of lower quality.	Citizen science projects could be instrumental in monitoring the impact of new biotechnologies on the environment (Jimenez *et al.*, 2022), allowing for early detection and mitigation of potential risks (Kouzinopoulos *et al.*, 2024).	While the direct contribution of citizen science to artificial neurons themselves might be limited, citizen science projects could help gather data on complex biological systems, informing the development of more sophisticated AI models for applications in agrifood.

Advanced digital technologies

Citizen science projects could be a cost-effective way to collect vast amounts of geographically dispersed data, crucial for training and validating AI models used in digital technologies like digital twins and the Internet of Food. Citizen scientists could provide real-world data to verify the accuracy of information collected by aerial robotics and drones.

Additionally, citizen science projects could be used to test the effectiveness of new agricultural practices suggested by AI or digital twins in diverse environments. Citizen scientists with local knowledge could identify problems or limitations with advanced digital technologies that researchers might miss. This feedback loop could be crucial for refining and improving these technologies for broader adoption.

Prominent pre-emerging and emerging technologies and innovations				
6G-10G connectivity for agriculture	Aerial robotics and drones	Artificial General Intelligence in agriculture	Digital twins and Internet of Food	Quantum computing
Citizen science projects could be used to identify areas with poor connectivity, helping guide infrastructure development for future high-bandwidth agricultural applications.	Citizen scientists could be trained to collect data using drones, assisting in tasks like monitoring crop health or mapping fields. They could also report on potential safety concerns or ethical issues related to drone use in agriculture.	Citizen science projects could contribute vast datasets for training AGI models in agriculture. Additionally, citizen scientists could provide feedback on the interpretability and fairness of AGI-driven decisions, ensuring responsible development.	Citizen science projects could be used to collect data on local environmental conditions, soil health, and consumer preferences. This data could be integrated into digital twins and the Internet of Food, creating more accurate and localized simulations and agrifood system models.	Citizen science projects could help identify research areas in agrifood that could benefit from the unique capabilities of quantum computing, such as complex crop modeling or optimizing fertilizer application.

Advanced geospatial technologies

Citizen scientists could provide on-the-ground observations to verify the accuracy of information derived from real-time satellite imagery. This could be particularly helpful in identifying crop types, detecting early signs of disease or pest infestation and validating the effectiveness of land management practices. Citizen science projects could be designed to collect geospatial data relevant to agriculture, such as soil moisture levels, pest presence, or local weather patterns. This data could be used to train and improve the accuracy of Autonomous GIS systems for tasks like variable-rate fertilizer application or automated crop health monitoring. Citizen scientists with local knowledge could identify limitations or biases in how geospatial technologies are used in agriculture. This feedback could be crucial for improving the user-friendliness, accessibility and cultural sensitivity of these technologies.

Prominent pre-emerging and emerging technologies and innovations		
Realtime satellite imagery	**Autonomous GIS**	**Positioning systems**
Citizen scientists could be trained to identify specific features in satellite imagery, such as invasive plant species or irrigation leaks (Cardoso *et al.*, 2024). This could help generate real-time alerts and enable faster responses to potential problems.	Citizen science projects could be designed to collect data on local field boundaries, crop types, or specific soil conditions. This data could be used to create highly detailed and localized maps that are crucial for the effective operation of Autonomous GIS systems.	Citizen scientists could report on the accuracy and functionality of positioning systems used in agricultural machinery. This feedback could help developers improve the reliability and user experience of these technologies.

Policy innovation

Citizen science could transform policymaking in agrifood by providing valuable data and fostering public engagement. Citizen projects could inform policies on local agrifood systems, sustainable practices and access to information. This data could be used to tailor policies to regional needs, like supporting local innovations or promoting nature-based solutions. Citizen science empowers citizens to contribute to policy decisions, leading to more evidence-based, inclusive and effective approaches for a sustainable future of agrifood systems.

Prominent pre-emerging and emerging technologies and innovations				
Innovation Policy labs	**Territorial food-to-consumer economy**	**Access to information on sustainability matters**	**Nature-based and ecosystem innovations**	**Frugal innovation**
Citizen science data could help tailor policies that address specific regional needs in sustainable agriculture or identify promising local innovations for broader support (Mourad *et al.*, 2020).	Citizen science projects could track local food production and consumption patterns (Reynolds *et al.*, 2021), informing policies that promote shorter food supply chains and connect consumers with local producers.	Citizen science data could be used to create localized information resources on sustainable agricultural practices, tailored to specific regions and challenges.	Citizen scientists could provide valuable insights into local ecosystem health, informing policies that promote sustainable land management and biodiversity conservation.	Engaging local communities in problem-solving through citizen science could lead to developing low-cost, resource-efficient solutions for agricultural challenges in developing regions (van de Gevel *et al.*, 2020).

New renewable energy and transportation

Citizen science could be a valuable tool for gathering data, raising awareness and promoting sustainable practices that indirectly contribute to developing and adopting new renewable energy and transportation solutions in the agrifood systems. Citizen science is less likely to directly revolutionize new renewable energy sources or teleportation technologies within agriculture.

Market and financial innovation

Citizen science projects could generate large datasets on agricultural practices, environmental conditions and consumer behaviour. Citizen science projects could increase public understanding of complex market and financial instruments, like carbon credits or social impact bonds. Citizen science projects could identify emerging consumer preferences and local food production and sustainability challenges.

Prominent pre-emerging and emerging technologies and innovations	
Carbon credits in agriculture and aquaculture	**Social impact bonds**
Citizen science projects could collect data on sustainable farming practices that sequester carbon. This data could be used to verify carbon credits issued to farmers and ensure the legitimacy of carbon markets. Citizen science data could educate the public on how carbon credit markets work and their role in climate change mitigation.	Citizen science projects could track the social and environmental impact of agricultural investments. This data could be used to assess the effectiveness of social impact bonds that aim to achieve specific social or environmental goals in the agrifood systems.

Food manufacturing technologies and nutrition

Citizen science projects could collect data on consumer preferences, dietary needs and attitudes towards new food technologies. This data could inform the development and marketing of 3D-printed food and personalized nutrition plans. Citizen scientists with diverse backgrounds could identify potential challenges or limitations with new food manufacturing technologies, such as taste, texture, or acceptance. Citizen science projects could collect data on individual dietary habits, health conditions and genetic variations. This data could be used to develop more accurate and personalized nutrition plans. Additionally, citizen scientists could provide feedback on the usability and accessibility of personalized nutrition apps or programmes.

Micro- and nanotechnology and nanobiotech

Citizen science could play a supporting role in developing and applying micro-nanotechnology and nanobiotechnology in agrifood systems. Citizen science projects could be designed to collect data on the environmental impact of nanomaterials used in agriculture, such as nanofertilizers or food packaging. This data could inform policy decisions and research efforts to minimize potential risks.

Potential benefits and challenges

Potential benefits:

- Citizen scientists could contribute to large-scale data collection efforts, monitoring soil health, water quality, pest outbreaks and crop yields. This would be particularly valuable in regions like Sub-Saharan Africa and parts of Asia and the Pacific, where agricultural research and monitoring resources are often limited.
- Engaging local communities in research taps into their traditional knowledge and understanding of local ecosystems, leading to more contextually relevant and effective solutions. This would be crucial in regions with diverse agricultural practices like Latin America, Asia and the Pacific.
- Citizen science projects could raise awareness about agrifood issues, empowering individuals to make informed consumer choices and advocate for sustainable practices. This would be important in regions with high consumer demand and environmental concerns, like Europe and North America.
- Engaging citizens in research could foster a sense of ownership and empowerment, encouraging them to become active participants in shaping their agrifood systems. This could drive social innovation and bottom-up solutions in all regions.

Potential challenges:

- Ensuring the accuracy and reliability of data collected by citizen scientists would require robust protocols, training and quality control measures.
- Reaching marginalized communities and ensuring equitable participation could be challenging, especially in regions with limited access to technology and education. For example, Sub-Saharan Africa would require mobile technology solutions.

- Securing long-term funding for citizen science projects could be difficult, as they often rely on volunteer contributions and limited grants. Maintaining the long-term engagement of citizen scientists would require effective communication, incentives and feedback mechanisms.

- Effective coordination between scientists, citizens and policymakers would be crucial for translating citizen science data into actionable insights and policy changes. Latin America, Northern Africa and the Near East could incentivize university-community collaboration to address regional priorities.

7.2.5 Geoengineering, modification of weather and climate

We consider the hypothetical advent of geoengineering in the coming decades as a potentially profoundly disruptive event, which would require a paradigm shift in life science and agricultural research and innovation. Geoengineering, through deliberate weather and climate modification, could both benefit and harm the future agrifood system. Coordinated geoengineering efforts could mitigate extreme weather events, stabilize growing conditions and increase crop yields at the cost of limited weather pattern disruptions. Still, chaotic implementation could deeply damage ecosystems, alter rainfall patterns and create new agricultural challenges.

Geoengineering RIPS also garnered a positive outlook.

- **Likelihood of emergence and dominance**: the average perceived likelihood of its emergence by 2035 was 4.58 out of 10, with 4 being the most frequent responses. Regarding its dominance by 2070, the average perceived likelihood was 5.67, with a mode of 5.

- **Perceived impact:** the perceived impact of the fifth RIPS on achieving inclusive, sustainable and resilient agrifood systems was rated an average of -0.03 on the -3 to 3 scale, with 1 being the most common responses.

- **Regional variations:** global respondents showed the highest confidence in the emergence of this RIPS by 2035, with an average rating of 4.88. They also expressed the highest confidence in it becoming dominant by 2070, with an average rating of 6.77. Europe and Central Asia as well as the Americas respondents were the least optimistic about its emergence by 2035, with average ratings of 2.69 and 4, respectively, and even lower for 2070. Regarding impact, Sub-Saharan Africa and Global respondents perceived the highest positive impact from this RIPS, with an average rating of 5.85 and 4,88 respectively. Europe and Central Asia respondents anticipated the lowest impact, with an average rating of 2.

The comments on the fifth RIPS, Geoengineering, Modification of Weather and Climate, reveal a mixed perspective. While some see the potential for improving agricultural productivity and adapting to climate change, others express concerns about unintended consequences and the need for careful ethical and environmental considerations.

Advanced biotechnologies

Unforeseen climate changes could disrupt ecosystems, requiring crops with new tolerances. Synthetic biology could engineer these resilient crops. New gene expression methods could allow crops to adapt to these changes. Geoengineering's impact on soil health might necessitate bioremediation techniques from environmental biotechnology. The vast amount of data generated by geoengineering efforts could be analyzed by AI powered by artificial neurons, optimizing crop management in this new environment.

Prominent pre-emerging and emerging technologies and innovations			
Synthetic biology	**New methods for controlling gene expression**	**Environmental biotechnology**	**Artificial neurons**
Geoengineering could lead to more extreme weather events like droughts, floods, or saltier soil. Synthetic biology allows scientists to engineer crops with genes for stress tolerance to these conditions (Castañón, 2022).	Advanced techniques for gene expression control could allow for the development of crops that could dynamically adjust their internal processes based on environmental cues in contexts affected by unpredictable geoengineering practices (Dong, 2024).	Geoengineering efforts might result in increased pollution or disruption of microbial communities. Environmental biotechnology could involve developing microbes that could break down pollutants created by geoengineering projects or introduce new microbes to restore ecological balance in disrupted ecosystems (Rafeeq *et al.*, 2023).	Deep learning algorithms could analyze vast weather and climate datasets to predict these changes and optimize planting times, irrigation schedules, or fertilizer applications (Islam *et al.*, 2023).

Advanced digital technologies

Geoengineering's impact on advanced digital technologies in agrifood systems is complex. While it could provide valuable climate data for digital twins and the Internet of Food, the unpredictable outcomes and ethical concerns pose significant risks.

Advanced technologies like AI and robotics could help assess geoengineering risks and model potential consequences. The focus should be on sustainable practices and using digital tools to mitigate the risks of geoengineering in the future of agrifood systems.

Prominent pre-emerging and emerging technologies and innovations			
6G-10G connectivity for agriculture	**Aerial robotics and drones**	**Artificial General Intelligence in agriculture**	**Internet of Food**
Advanced high-bandwidth connectivity like 6G or 10G could provide the infrastructure for real-time data collection and analysis from a more comprehensive network of automated agricultural sensors in a changing environment (Zhang, F *et al.*, 2022) and provide feedback on the local results of geoengineering.	Unforeseen changes in weather patterns due to geoengineering could necessitate more sophisticated drone navigation systems. Advanced aerial robotics and drones with weather-resilient features and high-resolution sensors could be crucial for crop monitoring, precision agriculture practices and disaster response in a changing climate.	AGI could revolu-tionize agriculture by enabling real-time decision-making and com-plex problem-solving in response to rapidly changing environmental conditions. AGI sys-tems could opti-mize irrigation based on real-time weather data or predict potential pest outbreaks to minimize crop loss-es (Lu, G *et al.*, 2023).	Disruptions to traditional food supply chains due to geoengineering could highlight the need for improved traceability and transparency. The Internet of Food, a network of connected devices collecting data throughout the food supply chain, could ensure food safety and optimize logistics in a potentially disrupted agrifood systems (Khan *et al.*, 2023).

Advanced geospatial technologies

Rapid environmental changes might necessitate frequent monitoring and early warning, making real-time satellite imagery invaluable. Autonomous GIS could integrate and analyse the vast amount of data from various sources, helping farmers manage resources effectively. Precise positioning systems become even more crucial for adapting practices to a changing environment. Overall, geoengineering creates a situation where real-time data and adaptability are key and advanced geospatial technologies could provide the tools and information for successful agriculture in this new landscape.

Prominent pre-emerging and emerging technologies and innovations	
Realtime satellite imagery	**Positioning systems**
Rapid environmental changes due to geoengineering could necessitate more frequent monitoring of agricultural land. Real-time satellite imagery could provide high-resolution, up-to-date data on crop health, soil moisture levels (Bandak *et al.,* 2023), and other critical factors. This information allows farmers to make informed resource allocation and crop management decisions.	Unforeseen changes in weather patterns or extreme weather events caused by geoengineering could disrupt traditional farming practices that rely on historical data. Precise positioning systems like GPS would become even more crucial for implementing new practices like variable-rate seeding or targeted pesticide application (Nijak *et al.,* 2024).

Policy innovation

Geoengineering might necessitate the rapid development of new technologies through innovation labs. Disruptions to traditional food production zones could push policies towards territorial agrifood systems. Transparency concerns surrounding geoengineering highlight the need for open data access and its impact. Nature-based solutions and frugal innovation for resource-constrained regions will be crucial.

Prominent pre-emerging and emerging technologies and innovations		
Innovation Policy labs	**Territorial food-to-consumer economy**	**Access to information on sustainability matters**
Geoengineering, especially unplanned consequences, could necessitate rapid development of new agricultural technologies to adapt to changing conditions. Policy labs focused on innovation could play a crucial role in fostering research and development of climate-resilient crops, advanced sensors for real-time monitoring, and decision-making tools for farmers in a geoengineered environment.	Geoengineering could disrupt traditional food production zones, requiring reevaluation of existing food-to-consumer networks. Policies promoting territorial agrifood systems, where production and consumption occur closer together, could enhance resilience in a changing climate.	Policies that ensure open data access regarding geoengineering efforts and their impact on agriculture will be essential. This allows for informed decision-making by farmers, consumers, and policymakers.

New renewable energy and transportation

Increased energy demands might necessitate safe, sustainable nuclear power for desalination or agricultural robots. Unforeseen weather changes could disrupt transportation, requiring a more resilient global logistics network. Teleportation of food could revolutionize the supply chain. Novel biomass sources could become crucial if traditional agriculture is disrupted. Geoengineering might necessitate better energy storage solutions for intermittent renewables.

Prominent pre-emerging and emerging technologies and innovations		
Global logistics network	**Novel biomass**	**Novel energy storage technologies**
Unforeseen changes in weather patterns due to geoengineering could disrupt existing transportation infrastructure across all modes of transport.	Geoengineering could disrupt traditional agricultural practices, necessitating alternative sources of biomass. Research into novel biomass sources, like using fast-growing algae (Santhakumaran *et al.,* 2018) or dedicated energy crops grown on non-arable land, could provide sustainable feedstock for biofuels or bio-based products.	Renewable energy sources are often intermittent. Geoengineering efforts focusing on solar radiation management could lead to less predictable weather patterns, emphasizing the need for efficient energy storage. Advanced energy storage technologies like next-generation batteries or pumped hydro storage will be crucial for storing renewable energy generated during peak periods and utilizing it when needed in agriculture, such as powering irrigation systems or controlled-environment farms.

Micro- and nanotechnology and nanobiotech

Advancements in micro-nanotech and nanobiotech have the potential to address challenges and enhance efficiency in a changing agrifood landscape caused by geoengineering. Nanorobots used pre-emptively on areas slated for geoengineering interventions could improve crop resilience to environmental stresses caused by geoengineering. Nanomaterials for water treatment and advanced food packaging with extended shelf life become crucial for efficient water management and minimizing spoilage. Unforeseen changes due to geoengineering might necessitate targeted nano pesticides, fertilizers and antibiotics.

Prominent pre-emerging and emerging technologies and innovations	
Nanorobotics	**Nano pesticides, fertilizers and antibiotics**
Nanorobots could perform tasks at the cellular level, like targeted nutrient delivery or pest control improving crop resilience to environmental stresses caused by geoengineering.	Unforeseen changes in pest or disease profiles due to geoengineering could necessitate new tools for sustainable crop protection. Nanopesticides or fertilizers with targeted delivery mechanisms could minimize environmental impact while maximizing effectiveness (Yadav *et al.,* 2023). Nano-antibiotics could combat potential new diseases emerging in a geoengineered environment.

Potential benefits and challenges

Potential benefits:

- Geoengineering could modify temperature and light conditions to extend growing seasons in certain areas, increasing agricultural productivity. Techniques like solar radiation management could potentially reduce the intensity and frequency of droughts, heatwaves and floods, safeguarding crops and livestock from climate-related losses. This could benefit vulnerable regions like Sub-Saharan Africa and South Asia.
- In Asia and the Pacific, geoengineering could mitigate extreme weather events and create stable conditions for rice cultivation, enhancing the effectiveness of genetically modified rice varieties designed for resilience.
- In regions like Sub-Saharan Africa, where malnutrition is a major concern, geoengineering-induced changes in crop nutrient content could pose challenges to food security and require innovative solutions for nutritional supplementation.

- Geoengineering could generate vast amounts of climate data, which can be analysed using AI and big data analytics to predict crop yields, optimize resource use and manage risks. This could enhance precision agriculture and improve decision-making for farmers and policymakers.

Potential challenges:

- Geoengineering interventions could trigger unpredictable and potentially harmful side effects, such as disrupting rainfall patterns, altering ocean currents, or depleting the ozone layer. These effects could have devastating consequences for agriculture and ecosystems globally.
- Unpredictable climate shifts could necessitate the development of more resilient crop varieties through advanced biotechnologies, especially in vulnerable regions like Sub-Saharan Africa.
- The benefits and risks of geoengineering are unlikely to be evenly distributed. Some regions may experience positive effects, while others may suffer adverse consequences, leading to potential conflicts and inequalities.
- Advanced digital technologies like AI and machine learning could be used to model and predict the impacts of geoengineering, aiding in decision-making and risk management. AI could help farmers adapt to unpredictable weather patterns but could also be used to manipulate markets based on climate forecasts.
- Geoengineering interventions could alter weather patterns and land use, necessitating advanced geospatial technologies like satellite imagery and remote sensing to monitor and assess changes in agricultural landscapes. In Latin America, geoengineering could impact the Amazon rainforest and geospatial technologies could be used to track deforestation and evaluate the ecological impact.
- Geospatial technologies could monitor the effectiveness of interventions and detect early warning signs of unintended consequences.

7.2.6 Dual power: AGI and quantum computing

The advent of quantum computers could potentially revolutionize research and innovation agrifood systems by allowing the rapid analysis of complex data, leading to the development of optimized crop varieties, fertilizers and pest control strategies. Achieving Artificial General Intelligence (AGI) could automate a broad range of complex decision-making processes, optimizing resource allocation and supply chains for increased efficiency and sustainability. This RIPS focuses on the potential of these pre-emerging and emerging technologies to reshape industries and solve complex problems beyond what we can now imagine through the convergence of integration of existing technologies like robotics, AI and big data.

This sixth RIPS garnered a positive outlook in our survey.

- **Likelihood of emergence and dominance:** the average perceived likelihood of its emergence by 2035 was 6.31 out of 10, with 7 being the most frequent response. Regarding its dominance by 2070, the average perceived likelihood was 7.08, with a mode of 9.
- **Perceived impact:** the perceived impact of the sixth RIPS on achieving inclusive, sustainable and resilient agrifood systems was rated an average of 0.53 on the -3 to 3 scale.
- **Regional variations:** global and Sub-Saharan Africa, Global respondents showed the highest confidence in the emergence of this RIPS by 2035, with average ratings of 7.33. Europe and Central Asia respondents showed the most variability in their responses. Regarding dominance by 2070, Europe and Central Asia and Sub-Saharan Africa, the respondents expressed the highest confidence, with average ratings of 7.67. Regarding impact, Sub-Saharan Africa, Global respondents perceived the highest positive impact from this sixth RIPS, with an average rating of 2. Europe and Central Asia respondents displayed the most variability in their responses and also the lowest average rating of 0.

There was generally a positive reception, with participants anticipating its emergence and dominance. However, a range of opinions on its potential impact suggests a need for further dialogue and information sharing. Regional differences persist, highlighting the importance of context-specific approaches in promoting and implementing RIPS.

The feedback on the sixth RIPS, The Development of Quantum Computers and the Emergence of AGI, reflects concerns about equitable access and distribution of advanced technologies. While the potential for increased efficiency and improved climate adaptation is recognized, the need for careful management to avoid exacerbating inequalities is emphasized.

Advanced biotechnologies

This convergence can unlock a new era of innovation for more sustainable, efficient and resilient food production. Quantum computing's power could accelerate the design of new organisms in synthetic biology, while AGI could improve the precision of gene editing techniques such as RNA interference. This could lead to crops with improved disease resistance, higher yields, or enhanced drought tolerance. These advancements could accelerate bioremediation techniques and create a "thinking" agrifood system through artificial neuron networks analyzing real-time data to optimize practices.

Prominent pre-emerging and emerging technologies and innovations

Synthetic biology	RNA interference	New methods for controlling gene expression	Environmental biotechnology	Artificial neurons
Quantum computers could accelerate the design and optimization of synthetic organisms for agriculture.	AGI's ability to analyze vast datasets could lead to the development of more precise and efficient RNAi techniques. This could enable targeted manipulation of genes in crops to improve disease resistance or nutritional value.	AGI's problem-solving capabilities, coupled with the power of quantum computing for simulations, could pave the way for safer and more precise methods of gene editing. This could lead to the development of crops with desirable traits without disrupting the genome.	Quantum computing's ability to model complex systems and AGI's data analysis could accelerate the development of targeted biotechnologies for environmental cleanup.	Artificial neuron networks could be designed to analyze data from sensors in farms and make real-time decisions about irrigation, fertilization, or pest control.

Advanced digital technologies

The synergy between quantum computing and Artificial General Intelligence (AGI) promises a paradigm shift for advanced digital technologies in agrifood systems. This convergence could unlock the potential of big agricultural data by enabling AGI to extract real-time insights for optimized resource use and crop yields. Intelligent robotics and drones, empowered by AGI, could perform complex tasks and navigate challenging environments. Additionally, quantum computing could bolster security within the Internet of Food by facilitating unbreakable encryption methods.

Prominent pre-emerging and emerging technologies and innovations	
6G-10G connectivity for agriculture	**Artificial General Intelligence in agriculture and Digital twins**
Quantum computing's ability to handle complex calculations could revolutionize data analysis in agriculture. AGI systems could use this power to identify real-time patterns, leading to more precise irrigation, fertilization, or pest control decisions (Lu, G *et al.,* 2023).	Digital twins coupled with AGI could evolve into true "thinking farms". Digital twins could simulate various scenarios based on weather forecasts, soil conditions and market demands and suggest optimal resource allocation and crop production approaches (Peladarinos *et al.,* 2023).

Advanced geospatial technologies

Quantum computers and AGI could significantly enhance geospatial technologies in agrifood systems. This could mean extracting deeper insights from satellite imagery for stress detection and irrigation optimization or transforming GIS systems into dynamic tools using AGI. Quantum computing holds promise for ultra-precise positioning for autonomous farm equipment.

Prominent pre-emerging and emerging technologies and innovations	
Realtime satellite imagery	**Autonomous GIS**
AGI systems would use quantum computing to extract insights from real-time satellite imagery. This could enable early crop stress detection, identification of optimal planting areas and even real-time soil moisture monitoring for more targeted irrigation.	AGI's problem-solving abilities could transform GIS into truly autonomous systems that automatically analyze vast amounts of geospatial data, including satellite imagery, weather forecasts and soil maps (Li and Ning, 2023). This could create dynamic, real-time maps that predict crop yields, identify areas at risk of pests or disease and suggest optimal land management practices.

Policy innovation

Policy Labs could leverage quantum computing to fast-track assessments of new technologies. AGI-powered logistics could optimize food distribution and empower farmers with actionable sustainability insights. Policymakers could use quantum computing to model ecosystems and guide policies for a more sustainable future.

Prominent pre-emerging and emerging technologies and innovations		
Territorial food-to-consumer economy	**Access to information on sustainability matters**	**Nature-based and ecosystem innovations**
AGI-powered logistics systems could analyse real-time data on food production, consumer preferences and transportation networks (Dadi *et al.,* 2021). This could optimize food distribution, reduce waste and strengthen local food economies.	AGI-powered information platforms could analyze vast datasets and translate complex sustainability research into localized, actionable insights for farmers. This could empower them to make informed decisions that benefit both their bottom line and the environment.	Quantum computing could be used to model ecological systems and predict the impact of different policy interventions. This could inform the development of data-driven policies for promoting nature-based solutions and ecosystem resilience.

New renewable energy and transportation

This convergence can create a more efficient, sustainable and secure agrifood systems powered by new renewable energy and transportation advancements. AGI-optimized logistics could minimize food spoilage during transport. Quantum computing could aid the discovery of novel biofuels and design next-generation energy storage for sustainable farms. Teleportation of complex molecules, while speculative, could revolutionize food access in remote areas.

Prominent pre-emerging and emerging technologies and innovations	
Global logistics network	**Teleportation of complex molecules**
AGI-powered logistics systems could analyze vast datasets on weather patterns, transportation infrastructure, and consumer demand. This could enable the creation of intelligent routing systems that minimize food spoilage during transport and optimize resource use throughout the supply chain.	Advancements in quantum teleportation could enable the transfer of complex molecules like food across vast distances. This could revolutionize access to fresh produce in remote areas.

Market and financial innovation

Quantum computers and AGI could significantly enhance market and financial innovation in agrifood systems. This could include using quantum computing to verify carbon capture for a more robust carbon credit market. Additionally, these advancements could inform financial products for climate resilience or support the development of decentralized finance platforms for the agrifood systems. For example, quantum computing's power could be used to analyze satellite imagery and sensor data to measure carbon capture by agricultural practices precisely (Gudelė and Visockienė, 2024). This could create a more robust and transparent carbon credit market, incentivizing sustainable farming methods.

Micro- and nanotechnology and nanobiotech

AGI-guided nanorobots for targeted pest control or designer nanomaterials for water purification. Additionally, these advancements could lead to smarter food packaging with nanosensors to monitor spoilage and extend shelf life. Quantum simulations could also be used to design safe and effective nanofertilizers or nano-pesticides. Quantum computing could, for example, aid in the design of intelligent nanorobots capable of targeted pest and disease control, potentially reducing reliance on chemical applications. Nanorobots would patrol crops identify and eliminate threats with laser precision.

Potential benefits and challenges

Potential benefits:

- AGI, combined with quantum computing's computational power, could analyze vast datasets from sensors, satellites and drones to optimize complex agricultural models, leading to more efficient water use, fertilizers and pesticides. This would benefit regions with limited resources like Northern Africa, the Near East and Sub-Saharan Africa.
- Quantum computing could accelerate the discovery of new crop varieties with desired traits like drought resistance, pest resistance and improved nutritional value. AGI could aid in analyzing complex genetic data and predicting the performance of new crop varieties in different environments. This would be crucial for regions facing food security challenges like Sub-Saharan Africa and South Asia.
- Quantum computers and AGI could precisely monitor and control agricultural processes, from planting to harvesting. This could lead to increased yields, reduced waste and improved quality. Robotics powered by AGI could automate labour-intensive tasks, addressing labour shortages in regions like North America and Europe.
- Quantum computing could simulate molecular interactions to design personalized nutrition plans and novel food products tailored to individual needs and preferences. AGI could assist in analyzing health data and recommending optimal diets. This would be relevant for regions with diverse dietary needs and health concerns, like Asia and the Pacific.
- Quantum simulations could accurately model complex climate systems, helping predict extreme weather events and their impact on agriculture. This could inform adaptive strategies for farmers in regions vulnerable to climate change, such as Sub-Saharan Africa and South Asia.

Potential challenges

- Quantum computing and AGI could be cutting-edge technologies requiring significant research and development investment. Ensuring equitable access to these technologies for all regions, especially developing ones, would be a major challenge.
- Using AGI in decision-making could raise ethical concerns about transparency, accountability and potential biases. Job displacement due to automation would be another concern, particularly in regions with high agricultural employment.
- The rapid pace of technological development could necessitate the development of new regulatory frameworks to address the unique challenges posed by quantum computing and AGI in the agrifood systems.
- The vast amount of data generated and processed by quantum computers and AGI could raise concerns about data privacy and security. Data protection mechanisms would be essential to prevent misuse of sensitive agricultural information.

7.2.7 The agrifood farm: a holistic agrifood system

The agrifood farm or on-farm agrifood system RIPS envisions a future where the traditional farm is transformed into a self-sustaining, interconnected ecosystem. By integrating various pre-emerging and emerging technologies and innovations, agrifood farms could optimize resource utilization, minimize waste and enhance overall productivity. This holistic approach promotes a circular economy, where resources are recycled and reused within the farm, reducing environmental impact and improving resilience. This visionary concept envisions a single farm as a complete agrifood system, encompassing production, processing, distribution and consumption. It aims to create a more sustainable, equitable and resilient agrifood systems using territorial resources and keeping the value addition with the primary producers.

By integrating the entire agrifood system, agrifood farms can capture more product value, reduce food miles, enhance food safety, support local communities and build resilience against market fluctuations.

Key features of the agrifood farm include:

- On-farm processing: Farms can have processing facilities to add value to their products, such as mills, bakeries, or dairies.
- Direct-to-consumer sales: Farms can sell their products directly to consumers through on-farm stores, online marketplaces, or community-supported agricultural programmes.
- Autonomous systems: Farms can utilize autonomous vehicles, robots and AI-powered systems to optimize production, reduce labour and improve efficiency.
- Data-driven insights: Farms can leverage data analytics and AI to gain insights into consumer preferences, optimize resource use and predict market trends.

While implementing the agrifood farm concept may present challenges, such as infrastructure costs and skill acquisition, the potential benefits are significant. By collaborating with other farmers, cooperatives (for instance, under the decentralized autonomous organizations concept enabled by blockchains), or government agencies and local AISs, agrifood farms can overcome these challenges and create a more sustainable and equitable agrifood system.

The seventh RIPS also received a positive outlook, although slightly less optimistic than the earlier ones.

- **Likelihood of emergence and dominance:** the average perceived likelihood of its emergence by 2035 was 6.14 out of 10, with 7 being the most frequent response. Regarding its dominance by 2070, the average perceived likelihood was 6.64.
- **Perceived impact:** the perceived impact of the seventh RIPS on achieving inclusive, sustainable and resilient agrifood systems was rated an average of 0.78 on the -3 to 3 scale.
- **Regional variations:** global respondents showed the highest confidence in the emergence of this RIPS by 2035, with an average rating of 7.83. Europe and Central Asia respondents were the least optimistic and showed the most variability in their responses. Regarding dominance by 2070, Sub-Saharan Africa respondents expressed the highest confidence, averaging 6.65. Europe and Central Asia respondents provided the lowest average rating at 4.33. Regarding impact, North America respondents perceived the highest positive impact from this eighth RIPS, with an average rating of 3. Sub-Saharan Africa respondents provided the lowest average rating at -0.3 and also showed the most variability in their responses.

Respondents maintained an overall positive outlook but with slightly lower average scores for emergence and dominance than earlier ones. The perceived impact also shows a wide range of opinions. Regional differences persist, with “Global” respondents consistently expressing high confidence in the prospects of this RIPS. The lower scores and higher variability were observed in some regions, particularly Europe and Central Asia.

Policy innovations

Prominent pre-emerging and emerging technologies and innovations			
Territorial food-to-consumer economy	Access to information on sustainability matters	Nature-based and ecosystem innovations	Frugal innovation
Encourages local agrifood systems, reducing transportation emissions and promoting economic resilience. Smaller-scale processing facilities enable greater control over production methods, ensuring freshness, quality, and traceability. Value-added products, such as jams, pickles, and fermented goods, extend the shelf life of perishable items and generate additional income for farmers.	Provides businesses with comprehensive data on sustainable sourcing, processing methods, and waste management practices. This information empowers farmers to make informed decisions, adopt regenerative agriculture techniques, and reduce their environmental impact. Additionally, it enhances transparency and traceability throughout the supply chain, allowing consumers to make ethical choices.	Integrates natural processes into food production and waste management systems. Fermentation techniques, such as sourdough bread and kombucha, preserve food while enhancing flavor and nutritional value. Composting transforms organic waste into nutrient-rich soil amendments, reducing the need for synthetic fertilizers. Anaerobic digestion generates biogas for energy production and reduces greenhouse gas emissions from food waste.	Emphasizes resource efficiency and cost-effectiveness in small-scale food processing operations. Energy-efficient tools, such as solar dryers and hand-powered grinders, minimize reliance on fossil fuels. Local resources, such as indigenous plants and locally available materials, are utilized for packaging and processing. Traditional knowledge, passed down through generations, guides sustainable practices and ensures cultural preservation.

New renewable energy and transportation

Prominent pre-emerging and emerging technologies and innovations		
Global logistics network	Novel biomass	Novel energy storage technologies
Reduced reliance on extensive global logistics networks, potentially impacting their growth and reach. However, efficient logistics would still be crucial for transporting specialized inputs or products that cannot be produced or processed on-farm, ensuring a balance between local self-sufficiency and global trade.	The Agrifood Farm model, with its focus on resource optimization and waste reduction, could stimulate the development and utilization of novel biomass sources generated within the farm ecosystem. The integration of biomass processing technologies could further enhance the farm's self-sufficiency and contribute to a circular economy.	The decentralized and self-sufficient nature of Agrifood Farms could drive the adoption of novel energy storage technologies to ensure a consistent and reliable power supply for on-farm operations. Technologies such as microgrids, battery storage systems, and hydrogen fuel cells could play a crucial role in enabling energy independence and resilience.

Advanced digital technologies

Prominent pre-emerging and emerging technologies and innovations		
Internet of Food	**6G-10G in agriculture**	**Aerial robotics and drones**
The Agrifood Farm concept, with its emphasis on interconnectedness and data-driven decision-making, could significantly accelerate the development and adoption of the Internet of Food. The seamless integration of sensors, devices, and data analytics within the farm ecosystem would enable real-time monitoring, optimized resource management, and enhanced traceability throughout the food value chain.	The increased demand for high-speed, low-latency connectivity for data-intensive applications on Agrifood Farms could drive the development and deployment of 6G-10G networks in rural areas. These advanced networks would enable real-time data transmission, remote monitoring and control of autonomous systems, and seamless connectivity for various smart farming technologies	The Agrifood Farm concept, with its focus on efficiency and sustainability, could lead to increased utilization of aerial robotics and drones for various tasks such as crop monitoring, precision spraying, and delivery of inputs. The integration of drones with other technologies like AI and data analytics could further enhance their capabilities and contribute to optimized farm management practices.

Advanced geospatial technologies

The agrifood farm concept, focusing on holistic and localized food production, could provide fertile ground for the flourishing of advanced geospatial technologies, particularly Autonomous GIS. The self-contained nature of these farms necessitates precise and efficient management of resources within a defined area. With its ability to collect, process and analyze geospatial data without human intervention, Autonomous GIS could play a pivotal role in optimizing various aspects of farm operations. For instance, drones or robots with GIS capabilities could autonomously survey the farm, collecting real-time data on soil health, crop growth and pest infestations. This data could then be processed and analyzed to generate actionable insights, enabling farmers to make informed decisions about irrigation, fertilization and pest control, maximizing yields and minimizing environmental impact.

Integrating autonomous GIS with other pre-emerging and emerging technologies like AI and IoT could further enhance its capabilities, enabling predictive modelling, scenario planning and decision support systems that empower farmers to make proactive and adaptive management choices. The localized nature of agrifood farms provides an ideal testing ground for the development and refinement of autonomous GIS technologies, paving the way for their wider adoption in the broader agricultural landscape

Food manufacturing and nutrition

The agrifood farm concept, emphasising localized production and consumption, could lead to a shift towards decentralized food manufacturing and processing. This could empower farmers to add value to their produce on-farm, reducing reliance on large-scale, centralized food manufacturing facilities. Technologies like small-scale processing equipment, 3D food printing and AI-powered recipe optimization could enable this transformation. Focusing on producing food closer to the point of consumption could also lead to a greater emphasis on freshness, nutritional value and reduced food waste, aligning with the growing consumer demand for healthier and more sustainable food choices.

The agrifood farm model, with its potential for on-farm data collection and analysis, could facilitate the implementation of personalized nutrition initiatives. By gathering data on individual consumer preferences, dietary needs and health conditions, farmers could tailor their production and processing to offer customized food products. Technologies such as AI-powered recommendation engines, nutrigenomics and personalized food printing could play a crucial role in enabling this shift towards personalized nutrition, promoting healthier eating habits and improving overall well-being.

Advanced biotechnology

Advanced biotechnology can benefit the agrifood farm by enabling sustainable and localized food production. It can develop crops with improved nutritional value, resilience and tolerance to environmental stresses. Additionally, it can allow on-farm production of high-value compounds and enhance precision breeding techniques.

Environmental biotechnology can support the agrifood farm model by providing solutions for waste management, pollution remediation and sustainable resource utilization. Bioremediation, biofertilizers and biopesticides can maintain soil health and promote ecological balance. Integrating it with remote sensing and GIS can enhance sustainability and resilience.

Market and financial innovation

The agrifood farm concept, focusing on localized production and consumption, could lead to the emergence of innovative market and financial models that support small-scale farmers and promote sustainable practices. The direct-to-consumer sales model inherent in agrifood farms could facilitate the development of alternative supply chains and community-supported agriculture (CSA) programmes, reducing reliance on traditional intermediaries and empowering farmers to capture a more significant share of the value chain. The need for upfront investment in infrastructure and technology could drive the scaling of innovative financing mechanisms such as crowdfunding, impact investing and blockchain-based microfinance platforms.

The agrifood farm concept, emphasizing social and environmental outcomes, could create opportunities to implement social impact bonds. These innovative financial instruments tie funding to achieving specific social or environmental goals, such as improving soil health, reducing greenhouse gas emissions, or enhancing local food security. The self-contained and data-rich nature of agrifood farms could facilitate measuring and verifying these outcomes, making them attractive to impact investors and enabling farmers to access additional funding for sustainable practices.

Potential benefits and challenges

Potential benefits:

- Increased value capture: By integrating production, processing and distribution, agrifood farms can capture a more significant share of the value generated by their products, improving profitability for farmers.
- Reduced food miles: Shorter supply chains can reduce transportation costs, emissions and food waste, promoting sustainability.
- Enhanced food safety: Controlled environments and on-farm processing can improve food safety standards.
- Community support: Agrifood farms can create local jobs, stimulate economic growth and strengthen community ties.
- Resilience: Diversified operations and direct-to-consumer sales can help farms weather market fluctuations and disruptions.

Potential challenges:

- Infrastructure costs: Establishing processing facilities and implementing advanced technologies and innovations can require significant upfront investments.
- Skill acquisition: Farmers may need to acquire new processing, marketing and business management skills to operate agrifood farms successfully.
- Market access: Ensuring a market for holistic, on-farm agrifood system products may require effective marketing strategies and partnerships.
- Competition: Agrifood farms may compete with larger, established food processors and distributors.

7.2.8 Dark RIPS: The impact of the onset of recurrent plant or veterinary disease pandemic on agrifood research and innovation systems

When exploring Research and Innovation Paradigm Shifts (RIPS), it is essential to consider whether adverse events, such as looming crises, qualify as paradigm shifts. Based on the other examples in this chapter, RIPS are viewed as positive transformations that drive progress and innovation in desired directions. However, questioning this assumption reveals that adverse events can constitute RIPS because they fundamentally alter the trajectory of research and innovation, often more abruptly and profoundly than planned advancements.

Some events, like the onset of recurrent plant or veterinary disease pandemics on critical species, would also force a revaluation of existing systems and practices and thus could be qualified as RIPS. Such pandemics can severely disrupt the agrifood systems by causing significant crop yields and livestock population losses, leading to food shortages and price spikes. These crises' unpredictable onset and duration create a radically different paradigm that can last for years. This compels the agrifood systems to prioritize emergency responses, invest in developing disease-resistant varieties and implement stricter biosecurity measures. In this way, the adverse event drives innovation and reshapes agricultural practices just as an aspirational RIPS would.

A widespread plant or animal disease pandemic can severely disrupt the agrifood systems by causing significant crop yields and livestock population losses, leading to food shortages and price spikes. Such an event, whose onset and duration would be hard to predict, could create a radically different RIPS to last perhaps for years on end. The need for stricter biosecurity measures, increased surveillance and the development of disease-resistant varieties could drive innovation and reshape agricultural practices. Additionally, it might necessitate a shift towards more localized and diversified food production systems to reduce vulnerability to global supply chain disruptions.

Including negative RIPS in our analysis is essential, as it recognizes the full range of forces that can drive significant change. Presented to the survey respondents, the onset of recurrent plant or veterinary disease pandemic as RIPS garnered relatively high results.

- **Likelihood of emergence and dominance:** the average perceived likelihood of its emergence by 2035 was 6.33 out of 10, with 7 being the most frequent response. Regarding its dominance by 2070, the average perceived likelihood was 7.14, with a mode of 8.
- **Perceived impact:** the perceived impact of the eighth RIPS on achieving inclusive, sustainable and resilient agrifood systems was rated an average of 0.53 on the -3 to 3 scale, with a mode of 2.
- **Regional variations:** global respondents showed the highest confidence in the emergence of this RIPS by 2035, with an average rating of 7.33. Europe and Central Asia respondents showed the most variability in their responses. Regarding dominance by 2070, Global and Sub-Saharan Africa, Global respondents expressed the highest confidence, with average ratings of 8.17 and 8, respectively. Europe and Central Asia respondents displayed the most variability in their responses. Regarding impact, North America respondents perceived the highest positive impact from this seventh RIPS, with an average rating of 2. Sub-Saharan Africa, Global respondents displayed the most variability in their responses.

This RIPS maintains the generally positive trend observed in the previous ones. Participants see its potential for emergence and dominance, although with some variability in opinions. The perceived impact shows a range of views, suggesting a need for further discussion and clarification. Regional differences persist, highlighting the importance of tailored approaches in promoting and implementing RIPS. The consistently higher confidence expressed by global respondents might reflect a broader awareness or optimism about this particular shift.

The comments on the Onset of recurrent plant or veterinary disease pandemic on key species highlight the importance of preparedness and early warning systems to manage and mitigate the impact of potential outbreaks. The development of ecologically functional agroecosystems is seen as a crucial preventive measure.

Advanced biotechnologies

A grave, recurring plant or animal disease pandemic would significantly accelerate advancements in biotechnologies like synthetic biology and RNA interference. Scientists could engineer disease-resistant crops or use RNAi to silence harmful viral genes. Gene editing and environmental biotechnologies could also be used to combat pathogens. AI-powered diagnostics could aid in faster outbreak control.

Prominent pre-emerging and emerging technologies and innovations				
Synthetic biology	**RNA interference**	**New methods for controlling gene expression**	**Environmental biotechnology**	**Artificial neurons**
The urgency to develop disease-resistant crops would propel research in synthetic biology. Scientists could engineer plants with genes for natural resistance or introduce genes that trigger RNA interference pathways to silence harmful viral genes (Akbar *et al.,* 2022).	Existing RNAi techniques for targeted gene silencing could be significantly improved. AGI could design highly specific and efficient RNAi molecules to combat new and emerging pathogens in plants and animals.	New methods for gene editing, like CRISPR, could be harnessed to introduce targeted mutations that confer disease resistance in key agricultural species (Jhu *et al.,* 2023). Quantum computing could play a role in simulating these edits and predicting potential off-target effects.	Research into harnessing beneficial microbes or their byproducts could be intensified. Engineered bacteria or bacteriophages (viruses that infect bacteria) would combat specific plant or animal pathogens in a more targeted and environmentally friendly way.	AI-powered diagnostic tools that utilize artificial neural networks could be developed to rapidly identify and differentiate between different pathogens, allowing for quicker intervention and control of outbreaks.

Advanced digital technologies

A plant or animal disease pandemic would significantly boost advanced digital technologies in agrifood systems. 6G–10G connectivity could enable real-time monitoring for disease outbreaks. AI and drone swarms could be used for disease prediction, targeted interventions and remote monitoring. Digital twins and the Internet of Food could further track and manage disease threats. Quantum computing could accelerate research for new disease resistance.

Prominent pre-emerging and emerging technologies and innovations			
6G-10G connectivity for agriculture	**Aerial robotics and drones**	**Artificial General Intelligence in agriculture**	**Internet of Food**
The need for real-time data collection and monitoring of crops and livestock would propel the development and deployment of next-generation connectivity solutions like 6G and 10G networks. This would enable constant monitoring of plant and animal health, allowing for early detection of disease outbreaks.	Aerial robotics and drones equipped with advanced sensors and AI capabilities could be deployed for rapid disease scouting, targeted pesticide application, and remote monitoring of affected areas. This could minimize human exposure to pathogens and optimize resource use.	AGI could be used to analyze vast datasets on weather patterns, crop health, and animal movement patterns. This could potentially enable the prediction of disease outbreaks and inform targeted interventions to prevent large-scale pandemics.	Quantum computing could accelerate research into disease resistance by simulating complex biological processes and identifying potential targets for new vaccines or treatments.

Advanced geospatial technologies

Disease pandemics would likely pressure advancements in geospatial technologies, leading to a more comprehensive disease monitoring and tracking system. Real-time satellite imagery with AI could enable early disease detection from space. Autonomous GIS integrated with drones could target interventions precisely. High-accuracy positioning systems could track infected animals or crops.

Prominent pre-emerging and emerging technologies and innovations		
Realtime satellite imagery	**Autonomous GIS**	**Positioning systems**
Enhanced real-time satellite imagery analysis with AI could enable early detection of crop diseases by identifying subtle changes in plant health from space. This could allow for quicker intervention and prevent outbreaks from spreading.	Autonomous GIS could be integrated with drones or farm equipment. This would enable real-time disease mapping and targeted application of pesticides or other interventions, minimizing environmental impact and optimizing resource use.	Advanced positioning systems with centimeter or even millimeter accuracy could track the movement of infected animals or crops throughout the supply chain. This could be crucial for containing outbreaks and preventing further spread.

Policy innovation

The focus might shift towards strengthening local agrifood systems through policies promoting territorial food-to-consumer economies. This would reduce dependence on long-distance transportation, potentially making agrifood systems less vulnerable to pandemic disruptions. Additionally, ensuring widespread access to information on sustainable practices would be crucial. Expanded extension services and digital platforms could provide farmers with real-time data on disease outbreaks, best practices for prevention and control and sustainable farming techniques. Furthermore, the urgency could lead to a prioritization of nature-based solutions.

Prominent pre-emerging and emerging technologies and innovations		
Territorial food-to-consumer economy	**Access to information on sustainability matters**	**Frugal innovation:**
Policies promoting territorial food-to-consumer economies could be strengthened. This would encourage the development of local food production and distribution networks, reducing dependence on long-distance transportation and potentially making agrifood systems more resilient to disruptions caused by pandemics.	Ensuring widespread access to information on sustainability matters would be crucial. This could involve expanding extension services and digital platforms to provide farmers with real-time data on disease outbreaks, best practices for prevention and control, and sustainable farming techniques.	The need for affordable solutions in developing regions would likely drive frugal innovation. This involves developing low-cost, locally adapted technologies and approaches that are accessible to small-scale farmers.

New renewable energy and transportation

Nuclear power could provide clean energy for food production, particularly in water-scarce regions. The focus would shift to resilient logistics networks and even explore speculative teleportation for essential food components in times of crisis. Additionally, novel biomass sources and advancements in energy storage could create more sustainable agrifood systems.

Prominent pre-emerging and emerging technologies and innovations	
Global logistics network	**Teleportation of complex molecules**
The need to ensure food security during disruptions would likely drive investment in a more resilient global logistics network. This could involve advancements in cold chain infrastructure, autonomous delivery systems, and improved coordination between countries to maintain food flows during outbreaks.	Teleportation of complex molecules could accelerate research in disease pandemic. Essential food components or medicine could be "teleported" across vast distances in times of crisis.

Food manufacturing technologies and nutrition

A disease pandemic would likely drive advancements in food manufacturing technologies that offer diversified and potentially more nutritious food sources. 3D printing could customize nutritious meals on-demand, potentially reducing reliance on traditional agriculture during pandemics.

Additionally, 4D nanoscale printing could hold promise for printing food with specific micronutrients tailored to individual needs. Personalized nutrition solutions, with advancements in genetic testing and dietary analysis, could create customized meal plans to optimize health and potentially improve disease resistance.

Prominent pre-emerging and emerging technologies and innovations	
3D printing of food and liquids	**4D nanoscale printing**
The need for diversified and readily available food sources could propel the development of 3D printing of food and liquids. Printing customized, nutritious meals on-demand, potentially could reduce reliance on traditional agriculture and mitigate disruptions caused by pandemics.	4D nanoscale printing could hold immense potential for personalized nutrition. Imagine printing food with specific micronutrient profiles tailored to individual dietary needs, particularly for vulnerable populations during outbreaks.

Micro- and nanotechnology and nanobiotech

A disease pandemic would likely accelerate advancements in micro-nanotechnology and nanobiotechnology, developing powerful tools for disease control, water purification, food preservation and sustainable agriculture. Microscopic nanobots could patrol crops or livestock to detect and eliminate pathogens. Nanomaterials could revolutionize water purification, creating highly efficient filters for clean water access. Food packaging could be enhanced with nanotech to extend shelf life, improve safety and even monitor spoilage. Nano-powered solutions like targeted pesticides or antibiotics could deliver precise treatments for plant and animal diseases.

Prominent pre-emerging and emerging technologies and innovations		
Nanorobotics	**Nanomaterials for water technologies**	**Nano pesticides, fertilizers and antibiotics**
The need for targeted interventions could lead to the development of nanorobots capable of detecting and eliminating pathogens in plants or animals. Microscopic robots could patrol crops or livestock, identifying and neutralizing disease threats before outbreaks occur.	Water scarcity and potential contamination concerns during pandemics could be addressed by advancements in nanomaterials for water technologies. Highly efficient filters could utilize nanomaterials to purify water at the point of use, ensuring a clean water supply for both agriculture and human consumption.	Advancements in nano pesticides, fertilizers, and antibiotics could deliver targeted solutions for plant and animal diseases. Nanoparticles could contain precise doses of pesticides or antibiotics that attack specific pathogens without harming surrounding healthy cells or the environment.

Potential benefits and challenges

Potential Benefits:

- A pandemic could spur investment in research and development for disease-resistant crops and livestock, improved diagnostics and more effective vaccines. This could benefit all regions but would be particularly crucial for regions with limited research capacity, such as Sub-Saharan Africa.
- The crisis could lead to stricter biosecurity measures at borders, farms and processing facilities, reducing the risk of future outbreaks. This would benefit all regions, especially those with extensive agricultural trade, like Europe and North America.
- The vulnerability exposed by a pandemic could encourage diversification of crops and livestock breeds, reducing reliance on monocultures and promoting more resilient agrifood systems. This would benefit all regions, particularly those with limited agricultural biodiversity, like Northern Africa and the Near East.

Potential challenges:

- A pandemic could decimate crops and livestock, leading to significant shortages of essential food items. This would drive up prices, potentially causing food insecurity and social unrest, particularly in regions heavily reliant on imports or vulnerable populations, such as Sub-Saharan Africa and Asia.
- A pandemic could cripple agricultural production and trade, leading to economic losses, job cuts and increased poverty, particularly in regions where agriculture is a primary economic activity, like Latin America and parts of Asia.
- Countries might impose trade restrictions to prevent the spread of disease, disrupting global supply chains and exacerbating food shortages. This could be particularly problematic for regions that are dependent on agricultural exports.
- The loss of crops and livestock could lead to increased deforestation and land degradation as farmers try to compensate for lost production. This could exacerbate environmental problems in regions already facing ecological challenges.

Incorporating negative RIPS into the foresight exercise is essential. Crises like recurrent plant or veterinary disease pandemics can act as catalysts for significant change, forcing the adoption of new technologies and innovations that might not emerge under normal circumstances. By preparing for such negative scenarios, stakeholders can turn potential crises into opportunities for innovation, ultimately contributing to more robust and adaptable agrifood systems.

Focusing solely on aspirational RIPS may leave the system unprepared for unforeseen challenges while concentrating only on negative RIPS might hinder the pursuit of beneficial advancements. Therefore, blending both approaches provides a more realistic and resilient pathway forward. It enables the agrifood systems to strive towards desirable futures while being equipped to handle and learn from adverse events, ensuring sustainable progress regardless of challenges.

7.2.9 Concluding on the RIPS foresight: what, when, how

The additional comments provided by the survey participants offer valuable insights into their perspectives on the various Research and Innovation Paradigm Shifts (RIPS) presented. The recurring themes and specific observations extracted from these comments enrich the quantitative survey results, providing a deeper understanding of each RIPS's perceived potential and challenges.

Key themes from the comments

The qualitative feedback underscores several crucial aspects that need to be considered for the successful implementation of RIPS:

- Farmer engagement: the comments emphasize the critical role of actively involving farmers, particularly those in resource-constrained settings, in the research and innovation process. Building trust and ensuring that farmers benefit from participation are key factors in fostering adoption.
- Practical and accessible solutions: the need for developing solutions that are relevant, appropriate, practical and affordable for farmers is highlighted. This includes considering factors such as cost, complexity and local knowledge.
- Funding and investment: adequate funding and investment are recognized as crucial enablers for the emergence and dominance of RIPS, underscoring the need for increased financial support for research and innovation in agriculture.
- Sustainability and resilience: the importance of prioritizing sustainability and resilience in agrifood systems is emphasized, including promoting practices that conserve natural resources, enhance biodiversity and mitigate the impacts of climate change.
- Challenges and barriers: the comments identify potential challenges and barriers to adopting certain RIPS, such as limited access to technology and innovation, lack of awareness and policy constraints. Addressing these challenges will facilitate the widespread implementation of these shifts.

Specific observations on RIPS

The comments also provide specific insights into individual RIPS:

- Regenerative and circular agrifood production systems: The importance of considering the social and economic dimensions of this RIPS and its environmental benefits is emphasized.
- Nature-positive agrifood value chains: the importance of involving subsistence farmers and ensuring their trust in the process is emphasized to achieve the high probability of this RIPS emerging.
- Resilient and adaptive agrifood systems: the potential for this RIPS to address climate change and biodiversity loss is mentioned, but also the need for careful consideration of its implications for smallholder farmers.
- Personalized nutrition and health: concerns are raised about the feasibility of this RIPS, citing its reliance on technology and potential negative impacts on traditional farming practices.
- Inclusive digital agrifood economies: the potential of this RIPS to enhance food security and nutrition, particularly in developing countries, is highlighted.

- Transformative education and skills development: the need for solutions that rebuild natural, social and human capital while creating physical and financial capital, particularly for subsistence farmers in tropical and subtropical regions, is highlighted.

Overall conclusions

The survey results strongly support validating all eight Research and Innovation Paradigm Shifts (RIPS). The generally positive outlook expressed by participants, particularly regarding the likelihood of emergence and future dominance of these RIPS, suggests that they are perceived as plausible and potentially transformative pathways for the agrifood systems. The additional comments reinforce this validation, with respondents highlighting the importance of these shifts in addressing key challenges such as food security, sustainability and climate change.

The perceived impact of the RIPS also indicates their potential to contribute to inclusive, sustainable and resilient agrifood systems. While there is some variation in opinions, the average ratings for impact are generally positive, suggesting that participants recognize the potential benefits of these shifts. The qualitative comments further emphasize the potential of RIPS to drive positive change, particularly in areas such as farmer empowerment, access to practical solutions and sustainable resource management.

Most impactful and probable RIPS

- Mid-term (2035): the second RIPS, Biomimcry, stands out as the most probable to become dominant in the short term. The first RIPS, Convergence and the third one, Open- and open-source innovation also show strong potential for emergence by 2035, with a high average likelihood rating. The additional comments support the importance of the first RIPS in addressing the needs of subsistence farmers and promoting sustainable practices.

- Long-term (2070): the first RIPS, Convergence, also appears to be the most probable to become dominant in the long term, maintaining its high impact rating. The second RIPS, Biomimicry, and the third RIPS, Open- and open-source innovation, also exhibit high likelihood of becoming dominant by 2070.

- Impact: open- and open-source innovation and Biomimicry followed by Citizen science are the most impactful RIPS in achieving inclusive, sustainable and resilient agrifood sector globally, according to the survey.

Key takeaways

- Validation of RIPS: the survey results and additional comments strongly validate the concept of RIPS, indicating that they are seen as credible and potentially transformative pathways for the agrifood systems.

- Positive Impact: participants generally perceive the RIPS as having a positive impact on achieving inclusive, sustainable and resilient agrifood systems. The qualitative feedback further emphasizes the potential benefits of these shifts.

- Regional Variations: the persistent regional variations in responses highlight the importance of considering diverse perspectives and tailoring strategies to specific contexts when promoting and implementing RIPS.

- Farmer-Centric Approach: the emphasis on farmer engagement and the need for practical and accessible solutions in the comments underscores the importance of adopting a farmer-centric approach in research and innovation. Ensuring farmers are actively involved and benefit from the process will be crucial in achieving the desired outcomes.

In conclusion, the survey results and additional comments offer encouraging evidence for the validity and potential impact of the proposed Research and Innovation Paradigm Shifts. They highlight the importance of collaborative efforts, context-specific approaches and farmer-centric solutions in driving the transition towards inclusive, sustainable and resilient agrifood systems. By addressing the identified knowledge gaps, regional variations and implementation challenges, stakeholders can work together to harness the transformative power of RIPS and shape a more equitable and sustainable future for agrifood systems.

7.3 Synergies among the key transformations and paradigm shifts (RIPS) in agrifood systems

The five transformations outlined above are interconnected and mutually reinforcing, creating synergies to accelerate progress toward a sustainable, resilient and inclusive agrifood systems. It also means that the overall positive impact will hardly be achieved if transformations happen only in one or a few areas and without a holistic view and strategy. These transitions are closely linked to emerging paradigm shifts in research and innovation, including the convergence of technologies, biomimicry, open innovation, citizen science, geoengineering, the predominance of plant and animal diseases and on-farm food systems.

1. Convergence of Technologies

- **Governance and participation** can are provide tools for broader engagement (especially when various expertise is needed) and transparency.
- **Ethical and social considerations** rexist about data privacy, algorithmic bias and the potential for unintended consequences.
- **Integrated, fact-based and fit-for-purpose knowledge** facilitates the integration of diverse data sources and knowledge systems, leading to more comprehensive and relevant insights.
- **Incentives and investment for impact** can create new business opportunities and investment models but also requires careful regulation to ensure ethical and responsible development.
- **Fostering systemic changes** can enable the development of integrated and systemic solutions to address complex challenges but may also require careful consideration of social and environmental impacts.

2. Biomimicry

- **Governance and participation** can promote participatory approaches by emphasizing the importance of local knowledge and community engagement.
- **Ethical and social considerations** are aligned with ethical sustainability principles, local knowledge about local ecosystems and respect for nature.
- **Integrated, fact-based and fit-for-purpose knowledge** provides inspiration for innovative solutions based on natural principles well-suited to specific contexts.
- **Incentives and investment for impact** can create new business opportunities and investment models based on biomimetic principles.
- **Fostering systemic changes** can contribute to creating more sustainable and resilient systems that mimic the regenerative processes found in nature.

3. Open Innovation

- **Governance and participation** can promote participatory, inclusive and equitable approaches by involving diverse stakeholders in the innovation process.
- **Ethical and social considerations** require careful consideration of ethical and social implications, such as data privacy and intellectual property rights (to avoid extractivism while ensuring open access and benefits for all).
- **Integrated, fact-based and fit-for-purpose knowledge** can facilitate the co-creation and sharing of knowledge and resources, leading to more rapid development and adoption of innovative solutions.
- **Incentives and investment for impact:** new business models and investment oppotunities can be created.
- **Fostering systemic changes** can accelerate the development and adoption of innovative solutions that address systemic challenges.

4. Citizen Science

- **Governance and participation** directly supports participatory governance by involving citizens in research and decision-making processes.
- **Ethical and Social Considerations** can be raised related to data privacy and the potential for exploitation of volunteer labour, as well as put all the burden of transformation on citizens, thus preventing a profound systemic transformation.
- **Integrated, fact-based and fit-for-purpose knowledge** contributes to generating local and contextualized knowledge.
- **Incentives and investment for impact** additional resources and support may be required to ensure the quality and reliability of citizen science data. Furthermore, participatory processes demand more time and empowerment, which are not always compatible with current return on investment views.
- **Fostering systemic changes** can empower communities to take action on local issues and contribute to broader systemic change.

5. Geoengineering

- **Governance and participation** raise concerns about the potential for top-down decision-making and limited public participation.
- **Ethical and social considerations** can be harnessed to settle concerns about the potential for unintended consequences and social and environmental risks.
- **Integrated, fact-based and fit-for-purpose knowledge** requires careful scientific assessment and monitoring to understand the potential impacts of geoengineering interventions.
- **Incentives and investment for impact** significant investments and international cooperation may be required.
- **Fostering systemic changes** can address systemic challenges related to climate change but also raises concerns about the potential for unintended consequences and reliance on technological solutions.

6. The development of quantum computers and the emergence achievement of AGI

- **Governance and participation:** could enhance governance by providing tools for analyzing complex data and simulating different scenarios, enabling more informed and participatory decision-making.
- **Ethical and Social Considerations:** raises ethical concerns about job displacement, algorithmic bias, and the potential for misuse.
- **Integrated, fact-based and fit-for-purpose knowledge** can facilitate the integration of diverse data sources and knowledge systems, leading to more comprehensive and relevant insights for decision-making in agrifood systems.
- **Incentives and Investment for Impact** can create new business opportunities and investment models, but responsible development and deployment are crucial. It's important to create incentives that align with social and environmental goals, especially taking into account the relatively low perception of how conducive AGI and quantum computers are to a more inclusive agrifood system.
- **Fostering systemic changes** enable the development of integrated and systemic solutions to address complex challenges in agrifood systems, although at a cost of perhaps letting the control on the systemic changes out of hand of humans at forsaking explainability.

7. The agrifood farm

- **Governance and participation** can promote participatory governance by epowering local communities and fostering collaboration among stakeholders. It can create opportunities for shared decision-making and local ownership of agrifood systems.
- **Ethical and Social Considerations** are aligned to promote sustainability, local food security, and equitable distribution of benefits. It prioritizes the well-being of communities and the environment.

- **Integrated, fact-based and fit-for-purpose knowledge** encourages the integration of local knowledge and context-specific solutions. It promotes a holistic understanding of the farm ecosystem and its interactions with the surrounding environment.
- **Incentives and investment for impact** attract investment by demonstrating its potential for positive social and environmental impact
- **Fostering systemic changes** inspires wider adoption of agroecological practices and contributes to a more equitable and resilient agrifood system at scale, which has systemic consequences.

8. Plant and animal pandemics

- **Governance and participation** emphasizes the need for local-level preparedness and community engagement in disease surveillance and prevention.
- **Ethical and Social Considerations** exist about the protection of animal welfare, the potential for food shortages and price gouging, and the equitable distribution of resources, especially for the most vulnerable populations.
- **Integrated, fact-based and fit-for-purpose knowledge** highlights the need for integrated health surveillance systems across geographies species and sectors, coupled with data-driven decision-making.
- **Incentives and investment for impact** would likely set out an avalanche of investment in research and development of vaccines, diagnostic tools, and disease-resistant varieties.
- **Fostering systemic changes** can accelerate the shift towards more localized and diversified food production systems, reducing systemic reliance on long supply chains.

7.4 PARADIGM SHIFTS AND THEIR LEADINGS TRANSFORMATIONS

Convergence of technologies: the leading transformation in this paradigm is **governance and participation.** As technologies and innovations grow in complexity, it becomes increasingly important to ensure that decision-making processes are inclusive and participatory and involve different expertise. This transition is crucial for addressing technological advancements' ethical and social implications and ensuring that benefits are distributed equitably.

Biomimicry: the leading transformation in this paradigm is **integrated, fact-based and fit-for-purpose knowledge.** Biomimicry draws heavily on natural systems and processes, requiring a deep understanding of ecological relationships and the ability to apply this knowledge to human-designed systems. This transition is essential for developing innovative solutions that are sustainable and resilient.

Open innovation: the leading transformation in this paradigm is **governance and participation.** Open innovation relies on collaboration and participation from various stakeholders, including researchers, businesses and communities. This transformation is crucial for ensuring that innovation is responsive to societal needs and avoids unintended negative consequences, avoiding power capture and leaving no one behind.

Citizen science: the leading transformation in this paradigm is **governance and participation.** Citizen science directly involves communities in research, empowering them to participate in decision-making and contribute to knowledge creation.
This transformation is essential for building trust, openness to different kinds of knowledge and legitimacy in scientific research and innovation processes.

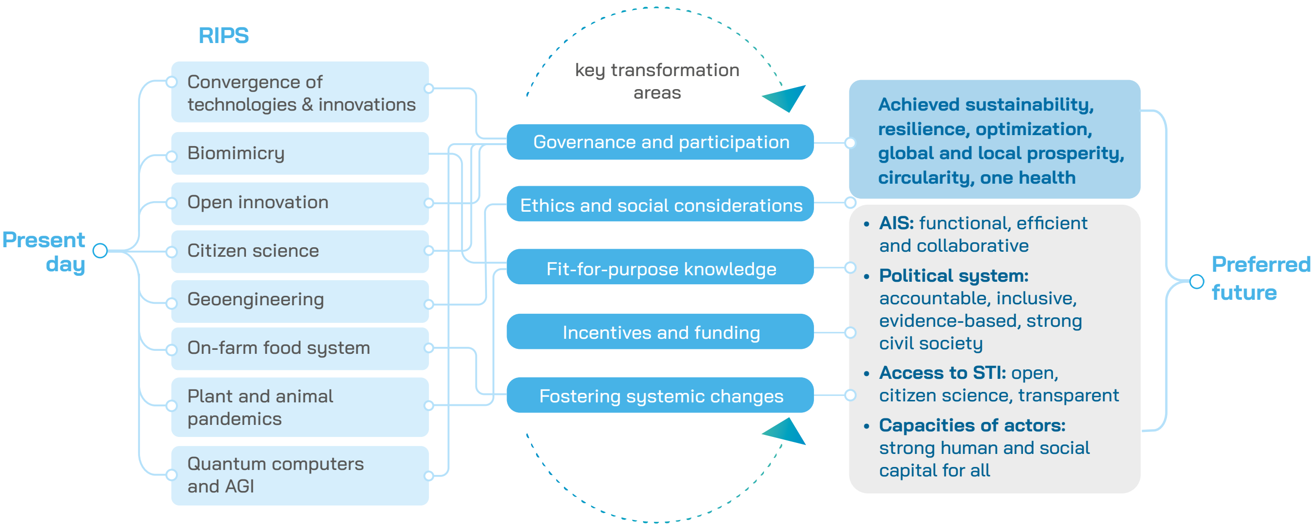
Geoengineering: the leading transformation in this paradigm is **ethical and social considerations.** Geoengineering interventions have the potential for significant environmental and social impacts, making it imperative to consider ethical and social implications carefully. This transformation is crucial for ensuring that geoengineering is conducted responsibly.

On-farm agrifood systems: the leading transformation is **fostering systemic changes.** On-farm agrifood systems require a shift towards more localized and decentralized agrifood systems that prioritize local production and consumption.

Plant and animal pandemics: the increasing prevalence of plant and animal diseases, driven by climate change and globalization, poses significant challenges to agrifood systems. Leading transformation here is **integrated, fact-based and fit-for-purpose knowledge.** Addressing plant and animal pandemics requires a deep understanding of disease epidemiology, prevention and control measures.

In conclusion, while all five transitions are interconnected and important, the leading transition in each paradigm reflects the unique challenges and opportunities presented by that particular approach. By understanding the interplay between these transitions and paradigm shifts, we can develop more effective strategies for addressing agrifood systems' complex challenges. The observations from the relationship between RIPS and the transformations are presented in the Figure 21.

Figure 21. Relationship between RIPS and key transformations in STI in agrifood systems to achieve the preferred future.



**While all RIPS address all five transformations, each has a lead transformation. For most of the cases, it is governance and participation. At the same time, incentives and funding do not take the lead in any cases, indicating the leading role of a mindset change rather than financial support.*

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8

Future-proofing regions: strategic insights on maximizing opportunities and bridging divides

This chapter focused on global drivers and their regional prioritisation that can influence the emergence of technologies and innovations in agrifood systems, as well as the disparities among the six studied regions. It also explores scenarios related to pre-emerging and emerging technologies and innovations.

By synthesizing Delphi results, surveys, regional workshops and systemic analysis, we identify potential levers of action that can facilitate the innovation process and accelerate the impact of pre-emerging and emerging technologies and innovations. It is important to recognize that current regional challenges and drivers do not necessarily dictate the future. Transformative shifts, unexpected events and disruptive policies or citizen-led initiatives can significantly alter the course of technological development. Therefore, we explore multiple plausible pathways of change, highlighting the importance for region-specific considerations.

Table 4. Drivers that may influence the development and introduction of PETIAS regionally and globally

		NORMALIZED SCORE* provided by Delphi respondents (higher value for more crucial drivers)						
Driver that may influence the emergence of agrifood technologies and innovations	Global ranking	GLOBAL	Asia and Pacific	Europe and Central Asia	Latin America	North America	Northern Africa and Near East	Sub-Saharan Africa
Climate change	1	1.00	1.00	1.00	0.93	0.93	1.00	1.00
Population dynamics and urbanization	2	0.78	0.80	0.33	1.00	0.87	0.73	1.00
Economic growth, structural transformation and the macroeconomic outlook	3	0.72	0.80	0.93	0.73	0.93	0.20	0.80
Public investment in agrifood systems	4	0.64	0.33	1.00	0.33	0.67	0.87	0.80
Food prices	5	0.59	0.47	0.67	0.73	0.60	0.53	0.73
Innovation and science	6	0.58	0.73	0.80	0.73	0.93	0.07	0.40
Scarcity and degradation of natural resources	7	0.55	0.20	0.73	0.87	0.47	0.60	0.67
Geopolitical instability and escalating conflicts	8	0.47	0.40	0.67	0.33	0.33	0.73	0.67
Inequalities that are widespread and deep-rooted	9	0.41	0.40	0.00	0.73	0.33	0.60	0.73
Consumption and nutrition patterns	10	0.40	0.33	0.80	0.07	1.00	0.40	0.13
Big data generation, control, use and ownership	11	0.33	0.53	0.53	0.27	0.87	0.00	0.20
Rural and urban poverty	12	0.29	0.33	0.00	0.60	0.13	0.53	0.60
Capital and information intensity of production	13	0.26	0.27	0.27	0.67	0.40	0.07	0.33
Epidemics and degradation of ecosystems	14	0.19	0.40	0.20	0.33	0.33	0.20	0.20
Uncertainties	15	0.17	0.07	0.00	0.20	0.20	0.60	0.47
Cross-country interdependencies	16	0.12	0.13	0.60	0.40	0.13	0.00	0.00
Input and output market concentration	17	0.03	0.00	0.33	0.00	0.33	0.0	0.13
The "sustainable ocean economies"	18	0.00	0.20	0.07	0.20	0.20	0.00	0.00

**Scores were calculated based on a question in which respondents were asked to select the top five drivers they believe are crucial for the development and introduction of pre-emerging and emerging technologies and innovations for each region, ranked by order of importance. The values were normalized, with 1 representing the drivers considered most important by the respondents and 0 representing the least important.*

8.1 GLOBAL DRIVERS AND THEIR REGIONAL DIMENSIONS SHAPING THE EMERGENCE OF TECHNOLOGIES AND INNOVATIONS IN SIX REGIONS

This subchapter explores the set of interacting drivers per region that can influence the emergence and development of technologies and innovations.

8.1.1 Asia and Pacific

The primary drivers that expected to influence the emergence of technologies and innovations in Asia and the Pacific region by 2050 are climate change, population dynamics and urbanization, economic growth, structural transformation and the macroeconomic outlook.

The Asia and Pacific region, a melting pot of diverse economies, rapid urbanization and escalating population growth, stands at a pivotal point in shaping its agrifood systems. The interaction of four key drivers – climate change, population dynamics and urbanization, economic growth and macroeconomic outlook – will significantly impact the emergence of technologies and innovations in this dynamic region.

A looming spectre over the region, climate change is exerting immense pressure on agricultural productivity, food security and rural livelihoods. Rising temperatures, shifting rainfall patterns and increasingly frequent extreme weather events threaten the stability of the region's agrifood systems. The Intergovernmental Panel on Climate Change (IPCC) has warned of rising floods, droughts, sea-level rises and crop failures which underscore the urgent need to address climate change's devastating impacts. According to the World Bank, agricultural yields in Southeast Asia could decline by up to 20 percent by 2050 due to climate change, exacerbating food security challenges.

Population dynamics and urbanization are reshaping the region, increasing food demand and driving changes in dietary preferences. By 2050, the population in the region is projected to reach 5.2 billion. Coupled with rapid urbanization, this is intensifying demand for increased food production and quality, while also generating demand for technologies and innovations that create jobs for youth and women. Rising consumption of meat and dairy products adds further stress on land and water resources.

Economic growth and structural transformation, hallmarks of the region's development, are creating both opportunities and challenges for the agrifood systems. As countries shift from agriculture-based economies to more diversified ones, rising incomes and changing consumer preferences are driving demand for higher-value, processed foods. This shift creates opportunities for value-added agricultural products but also calls for innovative production and processing methods to meet these demands.

The macroeconomic outlook in the Asia and Pacific region, shaped by global economic conditions, trade policies and financial markets, also plays a crucial role in influencing the region's agrifood systems. High levels of economic integration make the region vulnerable to fluctuations in commodity prices, affecting both farmers' profitability and food affordability for consumers.

To successfully navigate these challenges and capitalize on the emerging opportunities, the region may prioritize investments in research and development, policy reforms and international cooperation. Climate-smart agriculture technologies and innovations – such as nature-positive and real-time satellite imagery, positioning systems, autonomous GIS systems, environmental biotechnologies (e.g. drought-resistant crops) and sustainable farming practices – are critical to mitigating the impacts of climate change. Technologies like vertical farming, improved logistics, urban agriculture policies and sustainable consumption patterns are essential for addressing rising food demand. Economic growth, combined with advances in science and innovation, is likely to drive the adoption of personalized nutrition, omics technologies and artificial general intelligence in agriculture. Addressing the challenge of big data in agriculture may require significant investments in connectivity infrastructure, such as 6G–10G networks, expected to mature by 2043.

Moreover, the region may foster a conducive environment for innovation and entrepreneurship in the agrifood systems. This involves providing adequate financing, supporting research and development and establishing favorable regulatory frameworks. International cooperation will also be critical for tackling global challenges like climate change and food security. Through collaboration, countries in the region can share knowledge, resources and best practices to build more resilient and sustainable agrifood systems.

8.1.2 Europe and Central Asia

Key drivers for the emergence of technologies and innovations include climate change, public investment in agrifood systems, economic growth, structural transformation and the macroeconomic outlook, innovation and science, consumption and nutrition patterns.

Europe and Central Asia, a region with diverse economies, historical significance and varying levels of development, faces a complex interplay of drivers that will shape the future of agrifood technologies and innovations. The drivers identified – climate change, public investment in agrifood systems, economic growth, structural transformation and macroeconomic outlook, innovation and science, and consumption and nutrition patterns – are closely interconnected and will significantly influence the region's agrifood systems.

Climate change, a global challenge with widespread consequences, will have acute impacts in Europe and Central Asia. Rising temperatures, shifting precipitation patterns and more frequent extreme weather events will disrupt agricultural production, impact food security and exacerbate rural poverty. The region's vulnerability to climate change will be intensified by its geographical diversity and ecosystems.

Public investment in agrifood systems will be a crucial driver for technological and innovative advancements. Governments in Europe and Central Asia must recognize the importance of supporting the agrifood systems through targeted investments in research and development, infrastructure and education. Such investments will foster innovation, increase agricultural productivity and enhance food safety.

Economic growth and structural transformation will also play pivotal roles in shaping the region's agrifood systems. As economies grow and diversify, there will be a shift towards higher-value agrifood products and increased demand for processed foods. This shift presents opportunities for innovation and value-added activities but also requires investments in pre-emerging and emerging technologies and infrastructure.

The macroeconomic outlook in Europe and Central Asia will be influenced by global economic conditions, emerging economies in Central Asia and Caucasus, trade policies and financial markets. These factors will significantly affect the region's agrifood systems, particularly in terms of investment, consumer spending and commodity prices.

Innovation and science will play a pivotal role in driving technologies and innovations and advancements in the agrifood systems. Investments in research and development can lead to breakthroughs in areas such as AGI, cell-based food, environmental biotechnology and food processing. Collaboration between academia, industry and governments can foster a culture of co-innovation, accelerating the scaling up of fit-for-purpose and sustainable innovations promoting circularity.

Consumption and nutrition patterns will also evolve in Europe and Central Asia. As incomes rise and dietary preferences evolve, there will be increasing demand for healthier, more sustainable food products, personalized nutrition, innovations in the consumer-to-food economy and nature-based and ecosystem innovations. These changes present opportunities for innovative food products that meet to consumer preferences while addressing environmental and health concerns.

The interplay of these drivers will shape the future of agrifood in Europe and Central Asia in complex and dynamic manner. To navigate these challenges and seize the opportunities, the region must prioritize investments in research and development, education and infrastructure. Collaboration among governments, businesses and research institutions will be essential to foster innovation and accelerate its scaling up. Additionally, policies promoting sustainable agriculture, food security and rural development will be crucial for building resilient and equitable agrifood systems.

By capitalizing on these opportunities, Europe and Central Asia can position themselves at the forefront of agrifood innovation and secure a sustainable and prosperous future for their populations.

8.1.3 Latin America

The main drivers in Latin America were identified as population dynamics and urbanization, climate change, scarcity and degradation of natural resources, economic growth, structural transformation and the macroeconomic outlook, innovation and science.

The identified drivers are deeply interconnected and will significantly shape Latin America's agrifood systems, influencing the emergence of technologies and innovations.

Population dynamics and urbanization are two of the most pressing challenges for Latin America. The region's population is projected to reach 750 million by 2030, with a significant portion concentrated in urban areas. Rapid urbanization is driving up food demand while placing strain on agricultural resources. Changing dietary preferences, especially in the increased consumption of meat and processed foods, are further exacerbating the pressure on agrifood systems. This rising demand, both within the region will be accompanied by rising food demand in export markets. Meeting these demands sustainably will be a major challenge and may require bold decisions and trade-offs related to technologies and innovations concerning cell-based food and omics, real-time satellite imagery, autonomous GIS (mature by 2037), AI and precision agrifood systems.

Climate change poses another major challenge to Latin America, which is highly vulnerable to its impacts, including rising temperatures, altered precipitation patterns and more frequent extreme weather events. These factors disrupt agricultural production, threaten food security and worsen rural poverty. According to the Intergovernmental Panel on Climate Change (IPCC), climate change could reduce agricultural yields in Latin America by up to 10 percent by 2050 (IPCC, 2022). As climate change already disrupts existing farming practices, the livelihoods of millions are at risk. Smallholder farmers, who constitute 70 percent of the agricultural workforce in the region, are particularly vulnerable due to limited access to resources and adaptive technologies and innovations. This is coupled with high levels of food insecurity and malnutrition in some countries in Central America and Caribbean. As climate change impacts intensify, nature-positive innovations, financial tools such as social bonds and policy innovations will become increasingly critical to supporting agrifood systems and rural livelihoods.

The scarcity and degradation of natural resources, such as water and land, are also significant challenges for Latin America. Overexploitation, deforestation and pollution are depleting these essential resources, making it difficult to sustain agricultural production. Water scarcity, particularly in the arid and semi-arid regions, underscores the need for environmental biotechnologies and innovation policies that promote sustainable resource use.

Economic growth and structural transformation are also shaping Latin America's agrifood systems. As economies diversify, there is increasing demand for higher-value agricultural products and processed foods. This shift presents opportunities for innovation and value-added activities but also requires investments in modern technologies and infrastructure, in particular logistics.

The macroeconomic outlook in Latin America is influenced by global economic conditions, trade policies, and financial markets. The region's significant role as a food exporter will likely grow, driven by global demand, which could pressure natural resources, energy sources and commodity prices.

Innovation and science are critical for driving technologies and innovations and advancements in the agrifood systems. While innovation is a key driver of agrifood systems transformation, many countries in Latin America and the Caribbean lag behind in innovation capacity related to their level of development state (WIPO, 2024b). Prioritizing innovation, co-innovation and policy innovation for sustainability is crucial to achieving sustainable development and food security through policies and investments.

8.1.4 North America

The main drivers in North America were climate change, public investment in agrifood systems, population dynamics and urbanization, concerns over geopolitical instability and increasing conflict and growing global inequalities.

North America, known for its diverse economies, rapid urbanization and significant environmental challenges, is positioned at the forefront of technological and innovative advancements in agrifood systems. The identified drivers are deeply interconnected and will influence the region's agrifood innovation landscape.

Despite its diversity, North America is home to several high-income countries, such as the United States and Canada, that are already leaders in innovation, as highlighted by the Global Innovation Index (WIPO, 2024b). These countries have a strong track record of technological advancements across various sectors, including agrifood systems. Their investment in research and development, combined with supportive regulatory environments and access to capital, have enabled the rapid scaling up of innovative agrifood technologies and innovations.

However, even in these high-income countries, there are significant challenges to overcome. Climate change, population growth and urbanization continue to place increasing pressure on agrifood systems. In addition, concerns over geopolitical instability and global inequalities are relevant to North America, though to a lesser extent than in other regions, especially in relation to potential disruptions in trade and supply chains.

To address these challenges while building on its existing strengths, North America must continue prioritizing investments in research and development, education and infrastructure. Given the region's emphasis on public investment, climate change and global inequalities, expanding investments in pre-emerging and emerging technologies and innovations – such as nature-based and ecosystem innovations, environmental biotechnologies and social impact bonds – can complement well-developed digital, biotech and renewable energy ecosystems. Policies promoting sustainable agriculture, food security and rural development are also essential for building a resilient and equitable agrifood systems.

By leveraging its existing strengths in innovation and addressing the challenges it faces, North America can continue to play a leading role in shaping the future of agrifood systems globally.

8.1.5 North Africa and Near East

The main drivers in North Africa and Near East were identified as climate change, public investment in agrifood systems, population dynamics and urbanization, geopolitical instability and increasing conflicts, scarcity and degradation of natural resources.

North Africa and the Near East, regions characterized by diverse economies, rich traditions and varying levels of development, are facing a complex interplay of factors that will shape the future of agrifood technologies and innovations.

Climate change, a global challenge with widespread repercussions, is particularly severe in North Africa and the Near East. Rising temperatures, shifting precipitation patterns and more frequent extreme weather events are disrupting agricultural production and water availability, impacting food security and exacerbating rural poverty. The region's vulnerability to climate change is exacerbated by its geographical location and diverse ecosystems.

Public investment in agrifood systems is essential for driving advancements in technologies and innovations. Governments in North Africa and the Near East should prioritize targeted investments in research and development and infrastructure, such as next-gen (6-10G) connectivity, logistics and education. Such investments can catalyze innovation, enhance sustainable agricultural productivity and improve food safety.

Population dynamics and urbanization are also critical factors reshaping the region's agrifood systems. The rapid population growth of North Africa and the Near East is leading to increased food demand. Coupled with urbanization, this growth is placing considerable strain on agricultural resources and driving up food prices. Combined with climate change and resource scarcity, these factors are fostering the emergence of technologies and innovations such as vertical farming and circular economy models.

Geopolitical instability and increasing conflicts present major challenges. These conflicts disrupt trade, supply chains and investment, negatively affecting food security and agricultural production. Additionally, conflicts-related displacement populations humanitarian crises exacerbate food insecurity. Technologies such as the Internet of Food, advanced logistics, real-time satellite imagery, aerial robotics and drones offer potential solutions to mitigate these impacts.

Scarcity and degradation of natural resources, particularly water and land, pose significant challenges in North Africa and the Near East. Water scarcity, especially in the arid and semi-arid areas, remains a critical issue. Environmental biotechnologies, nanomaterials for optimized water use, nature-positive innovations and precision agrifood systems could be considered in addressing these challenges.

To build a resilient and equitable agrifood systems, policies promoting sustainable agriculture, food security and rural development are crucial. Decentralized approaches, as innovation policy labs, could help remove barriers to innovation.

8.1.6 Sub-Saharan Africa

The main drivers were identified as climate change, population dynamics and urbanization, public investment in agrifood systems, economic growth, structural transformation and the macroeconomic outlook and widespread, deep-rooted inequalities. They are intricately intertwined and will significantly shape the region's agrifood innovation landscape.

Climate change is a pressing concern in Sub-Saharan Africa, with rising temperatures, shifting precipitation patterns and more frequent extreme weather events. These factors disrupt livelihoods, impacting vulnerable communities and smallholders as well as the agricultural production, food security and exacerbating rural poverty. According to the Intergovernmental Panel on Climate Change (IPCC), climate change could reduce agricultural yields in Sub-Saharan Africa by up to 20 percent by 2050 (IPCC, 2022).

Population dynamics and urbanization are also significant factors influencing the region's agrifood landscape. Sub-Saharan Africa is experiencing rapid population growth, leading to increased demand for food, jobs and education for youth. Inequalities, which are widespread and deep-rooted, compound these challenges. The population growth, coupled with urbanization and inequalities, is placing a strain on agricultural resources and driving up food prices. The region's expanding population will require innovative solutions such as global logistics networks to ensure food security, reduce food waste while introducing policy and financial innovations like social impact bonds.

Given the region's environmental challenges, nature-based and ecosystem innovations such as environmental biotechnologies and frugal innovations could play a vital role. These solutions can improve agricultural productivity, reduce environmental degradation and increase resilience to climate change.

Public investment in agrifood systems is a crucial driver for technological and innovative advancements. Despite struggling with limited public funds, governments in Sub-Saharan Africa must prioritize targeted investments in research and development, infrastructure and education that shall be done on solid evidence, e.g. information on sustainability matters. Such information can catalyze innovation, improve agricultural productivity and enhance food safety.

Economic growth and structural transformation are also key factors influencing the region's agrifood landscape, and tightly linked to public investments in innovation. International cooperation in research and development, fair trade practices, and policies that strengthen local innovation capacities are key. The inequalities can lead to social unrest, political instability and economic turmoil, which can have a negative impact on food security and agricultural development.

8.2 A TALE OF TWO WORLDS: REGIONAL STRENGTHS AND CONCERNS IN MAKING USE OF PRE-EMERGING AND EMERGING TECHNOLOGY AND INNOVATION CLUSTERS

The survey examining the relationship between clusters of the pre-emerging and emerging technologies and innovations, alongside the regional advantages or disadvantages in leveraging these clusters, reveals a complex and concerning global landscape (Table 5). While some regions, particularly those dominated by high-income countries (HICs) or emerging economies with a history of investing in science, are positioned as leaders, others struggled significantly to harness these pre-emerging and emerging technologies and innovations. These findings align with recent WIPO reports (WIPO, 2024a, 2024b), on the world in two speeds in technologies (beyond agrifood systems), according to which the "vast majority of innovation outcomes are in the hands of a few national innovation ecosystems" in the Global North, China and Republic of Korea, further concentrated in clusters in few cities.

North America stands out as the undisputed champion, consistently leading in every cluster. This dominance likely stems from favourable macroeconomic conditions, high investments in science, a strong network of research institutions, vibrant innovation ecosystems, a culture that fosters innovation and advanced infrastructure. The region leads in advanced geospatial technologies, digital technologies and biotechnologies, as well as nanotechnologies. While food manufacturing, nutrition technologies and innovations in renewable energy and transportation are viewed as less prominent, North America still outpaces other regions in these areas.

Europe and Central Asia showcase a notable perceived advantage across most clusters excel in geospatial technologies, digital technologies and renewable energy. This is likely due to a combination of factors, including a strong tradition of agricultural research, existing innovation capacities, supportive policies and well-developed infrastructure. However, despite these strengths, the region – once the cradle of modern plant biotechnology – has lagged behind not only North America, but Latin America and Asia capitalizing on many biotechnological benefits. In digital technologies, the region is also perceived to lag behind North America and Asia. This trend may reflect a stabilization phase in innovation development (see chapter 10) or indicate a pathway to a less technology-driven paradigm (see chapter 10).

Table 5. Regional relative advantage/disadvantage in the ability to potentially make use of clusters

Cluster of pre-emerging and emerging technologies	REGIONAL ADVANTAGE/DISADVANTAGE Region's relative advantage/disadvantage (compared to other regions) in the ability to potentially make use of a given PETIAS cluster. Scale from -5 to 5, where -5: prohibitive disadvantage, 5: overwhelming advantage					
	Europe and Central Asia	Asia and Pacific	Northern Africa and Near East	Sub-Saharan Africa	Latin America	North America
Cutting-edge (emerging) biotechnologies	0.91	1.32	-0.59	-1.09	1.36	2.82
Cutting-edge (emerging) digital technologies	2.15	2.40	-0.20	-1.50	0.50	2.95
Cutting-edge (emerging) geospatial technologies	2.50	1.67	-0.50	-1.78	0.56	3.17
Food manufacturing technologies & nutrition	1.58	1.53	-1.89	-2.37	-0.63	2.21
Nanotechnology & nanobiotech	1.90	1.60	-0.60	-1.45	0.15	2.70
New renewable energy & transportation	2.05	1.32	-1.63	-2.58	-1.16	2.21
Average	**1.89**	**1.66**	**-0.96**	**-1.82**	**0.16**	**2.66**

**Scores were calculated based on a question in which respondents were asked to select the top five drivers they believe are crucial for the development and introduction of pre-emerging and emerging technologies and innovations for each region, ranked by order of importance. The values were normalized, with 1 representing the drivers considered most important by the respondents and 0 representing the least important.*

Asia and the Pacific exhibit remarkable advancements in biotechnologies and digital technologies, at times even surpassing Europe. This suggests a rapid modernization and readiness to tackle pressing agrifood challenges through the use of these technologies. However, despite this progress, clusters that could address intensive population dynamics and inequalities – such as food manufacturing, nutrition, renewable energy and transportation – are not as prominent, raising concerns about their role in managing the increasing urbanization.

However, a closer look reveals a worrisome views in **Latin America. Despite ranking second in biotechnologies,** the region appears to be underutilizing its potential in this and other clusters. This gap between research and practical application highlights worries about Latin America's capacity to harness technological advancements effectively within its agrifood systems. The region also faces disadvantages in clusters that could help address issues related to population dynamics, food security and nutrition, as well as energy supplies.

Northern Africa and the Near East are perceived as disadvantaged across all clusters, even though strong technology hubs are emerging in countries like Egypt and other countries beyond the agrifood systems (WIPO, 2024a). This weak signal suggests that advancements have not yet significantly influenced agrifood systems in the region.

Sub-Saharan Africa presents a particularly troubling picture. The region experiences substantial disadvantages across all clusters, especially in renewable energy, transportation and food manufacturing. These challenges are particularly alarming given the pressure of population growth and urbanisation. If not addressed, securing a sustainable and secure food supply for the future will be exceedingly difficult.

Looking towards the future, the data offers valuable insights for regional leaders and stakeholders. Recognizing these disparities is the first step. Collaboration and knowledge sharing can bridge the gap between leading regions and those lagging behind. North America and Europe and Central Asia, with their robust foundations, can play a pivotal role in supporting research and development initiatives and enhancing national agrifood innovation. ecosystems in other regions, ensuring a more equitable distribution and dialogue of knowledge. Across regions, fostering future-oriented thinking and shaping scenarios of desirable and undesirable futures at regional scale is essential. This approach focuses on the role and functions of new technologies and innovations in agrifood systems, enabling stakeholders to anticipate necessary changes, challenge prevailing mindsets that do not favour desirable futures, and create new pathways towards favourable futures.

In conclusion, the insights regarding pre-emerging information and and emerging clusters, though just one source of inspiration, reveal a world with two distinct faces. While some regions are on the brink of innovation, others face significant obstacles. By recognizing disparities in regional technological and innovation capabilities, fostering international collaboration in research and innovation, promoting regionalized solutions and implementing targeted policy and financial innovations and initiatives, we can pave the way for a future where all regions can leverage pre-emerging and emerging technologies and innovations in agrifood systems, ensuring sustainable, resilient and equitable agrifood systems.

8.3 THE STI GLOBAL DIVIDE: REGIONAL TIME MACHINES FOR IMPACT

The survey done in 2024, focusing on the earliest timeframe for pre-emerging and emerging technologies and innovations to make a significant impact across the six regions, confirms a pronounced perception of spacio-temporal displacement, often quite notable. This time we delved into each of the 20 technologies and innovations to gain insights on possible cross-regional or interregional cooperation in science, technology and innovation (Figure 22-Figure 28). Here there are some observations:

- **Aerial robotics and drones are expected to make an impact the soonest across all regions.** North America and Europe and Central Asia are anticipated to achieve this by 2030, while Sub-Saharan Africa is projected to follow by 2040.
- **North America and Europe and Central Asia are believed to capitalize** on the impact of pre-emerging and emerging technologies and innovations by 2035, with the exceptions being nature-based and ecosystem innovations, synthetic biology and quantum computing respectively.
- **North Africa and the Near East, along with Sub-Saharan Africa, are not perceived to be able to capitalize significantly on the 20 PETIAS 2040, and in some cases until 2045.** An exception is aerial robotics and drones in North Africa and the Near East, anticipated to achieve impact by 2035. Given the income status of some Near East countries, this insight may highlight a potential investment niche for accelerating progress.

- **The Asia and Pacific region present a mixed outlook, with the potential for capitalizing on pre-emerging and emerging technologies and innovations by 2035 and 2040.** Notably, the survey respondents indicated the longest time to impact for technologies and innovations requiring strategic decisions and policy interventions for incentivization and regulation, such as quantum computing, synthetic biology, renewable energy carbon credits and nature-based and ecosystem innovations.

- **Europe and Central Asia are perceived as leaders in socially driven open-source, information on sustainability matters, territorial value chains and the food-to consumer economy.** In contrast, North America is primarily recognized as a technological hub for geospatial and digital innovations, particularly the Internet of Food. Countries in these regions possess the knowledge and capacities to share with those perceived as lagging behind. By doing so, the latter may accelerate their time to impact by five to ten years, creating a win-win situation on a global scale.

Figure 22. Estimated timeframe for significant impact – Overview

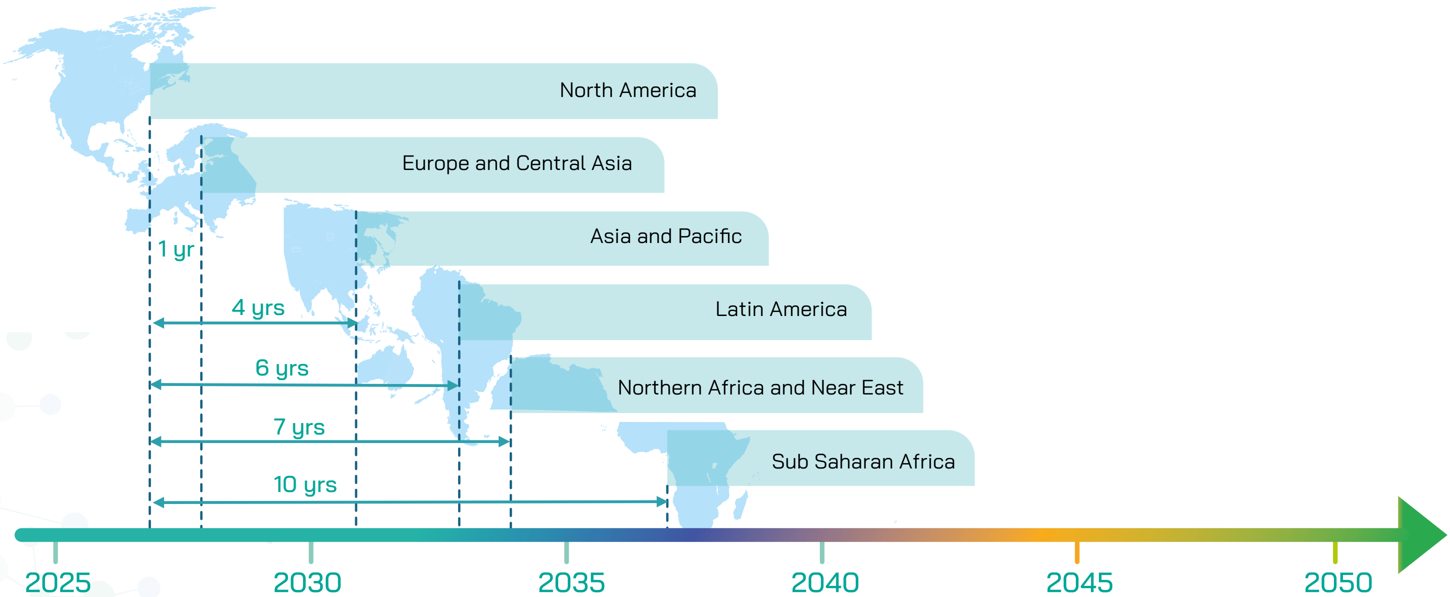


Figure 23. Estimated timeframe for significant impact – Asia and Pacific

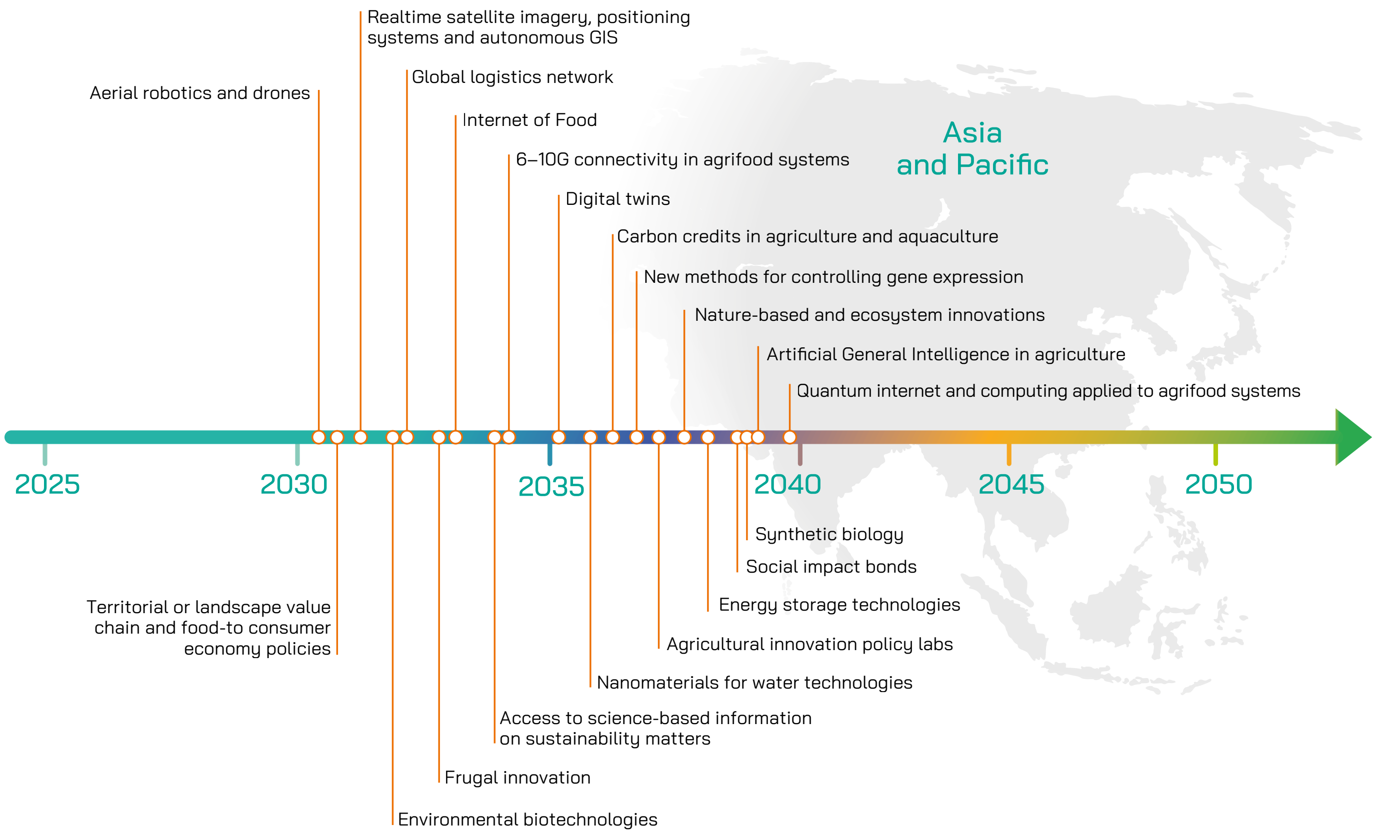


Figure 24. Estimated timeframe for significant impact – Europe and Central Asia

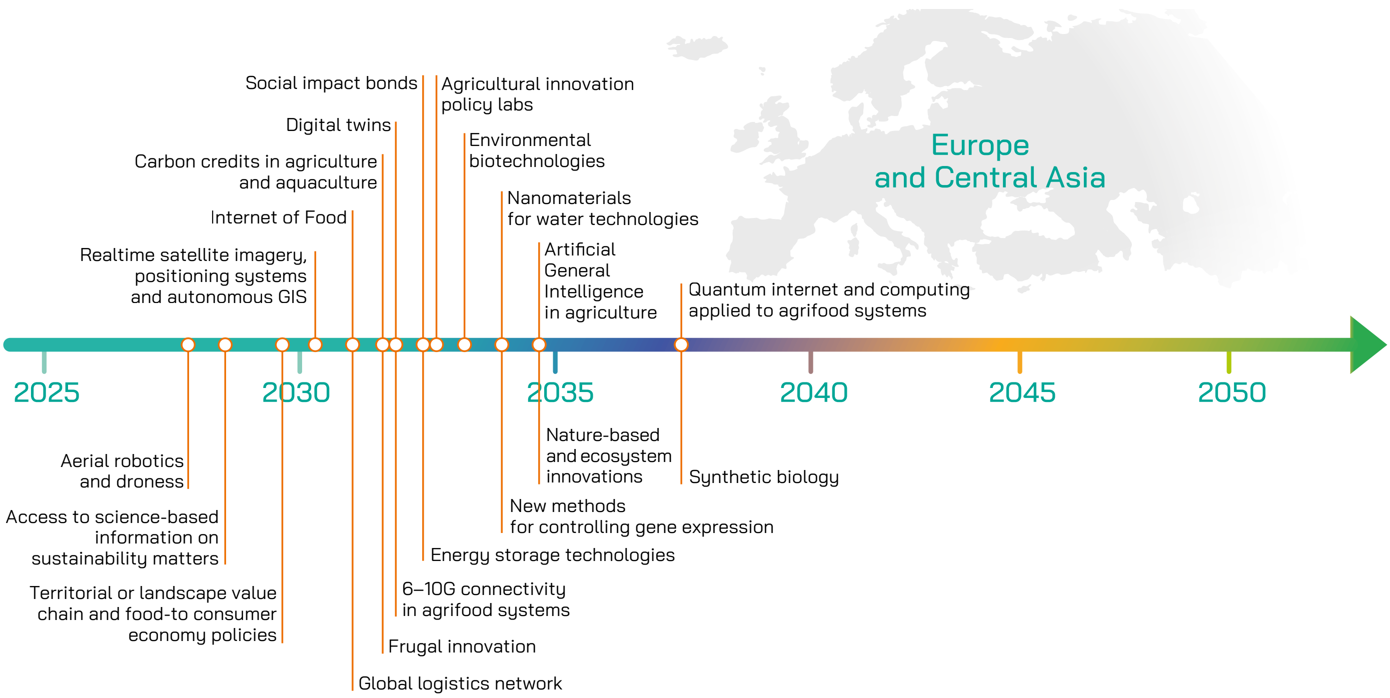


Figure 25. Estimated timeframe for significant impact – Latin America

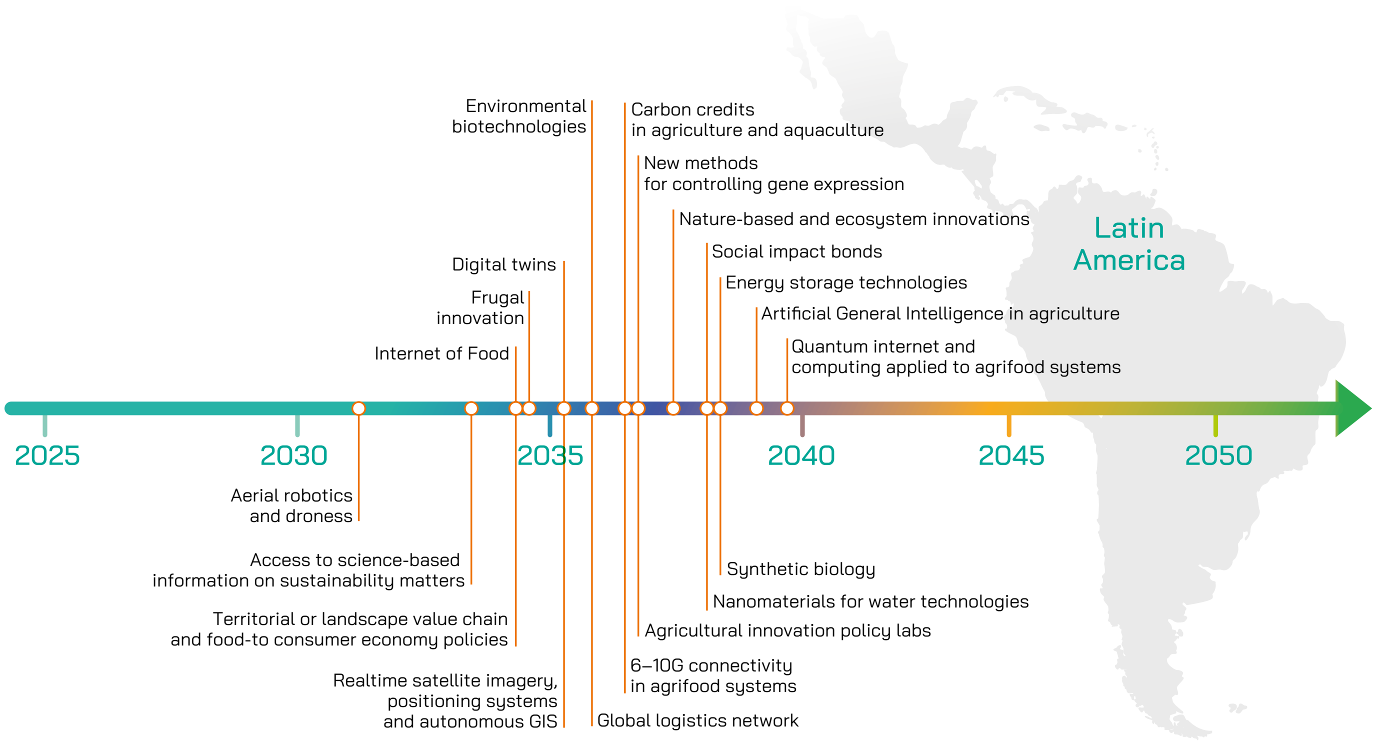


Figure 26. Estimated timeframe for significant impact – North America

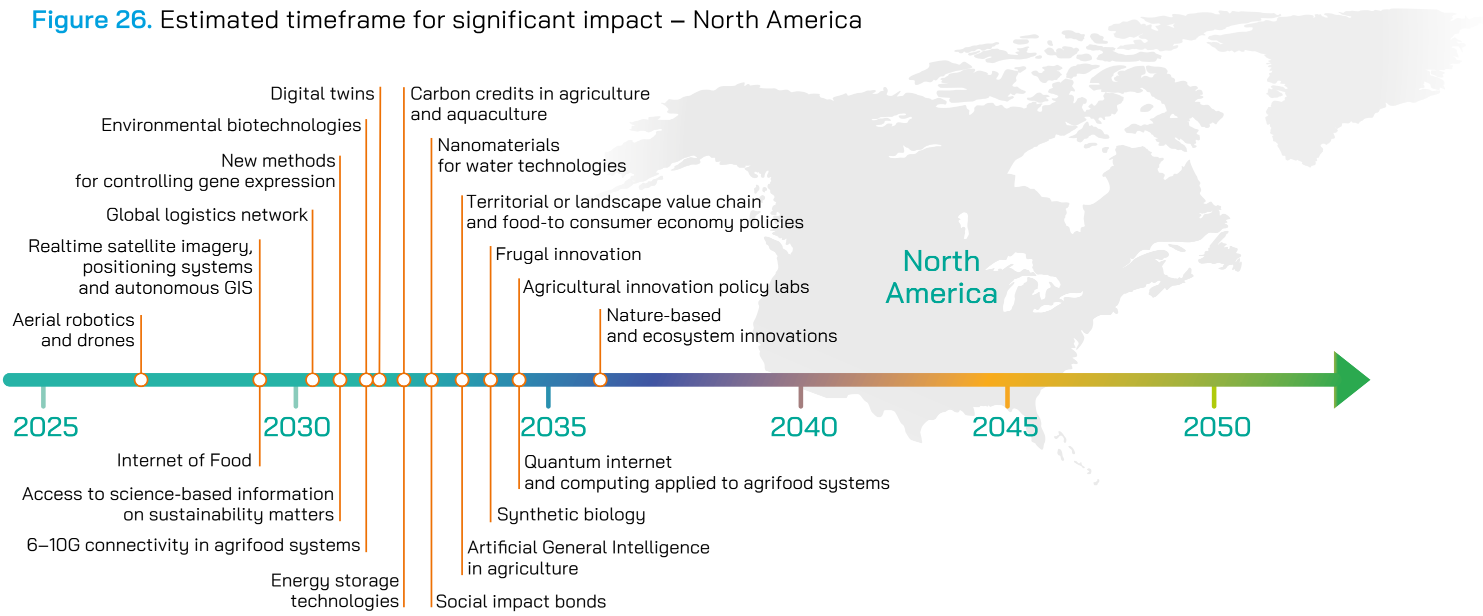


Figure 27. Estimated timeframe for significant impact – Sub Saharan Africa

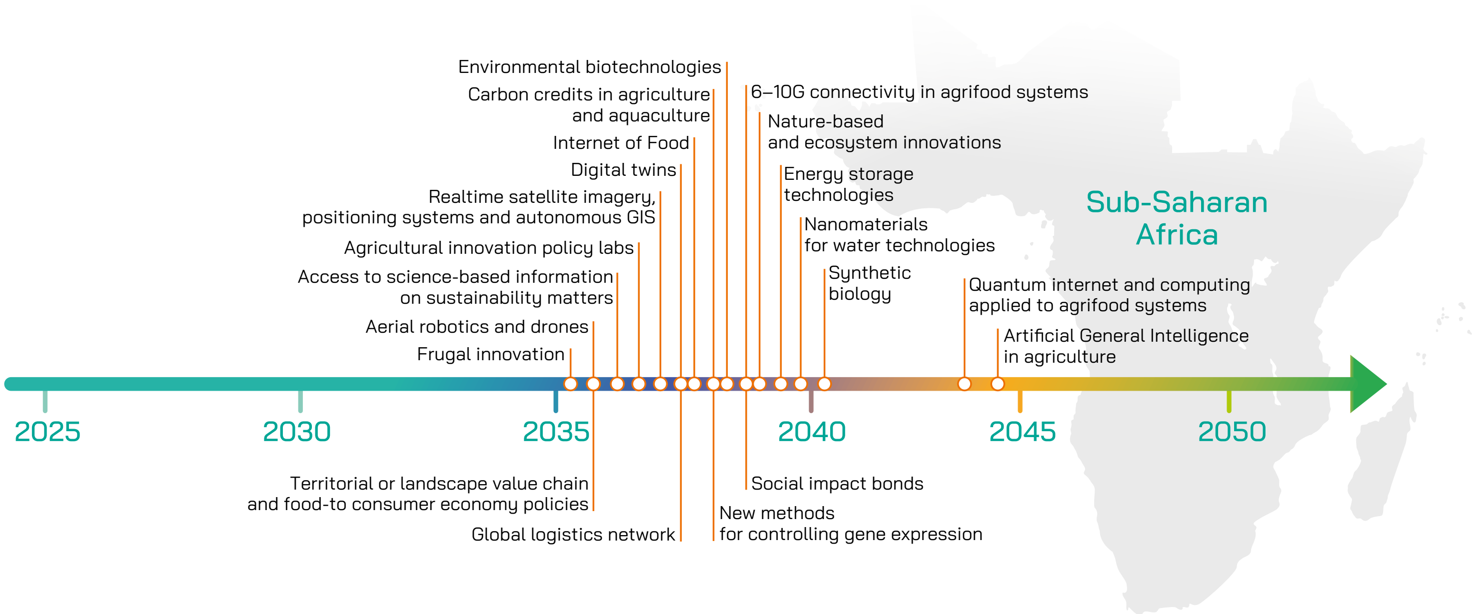
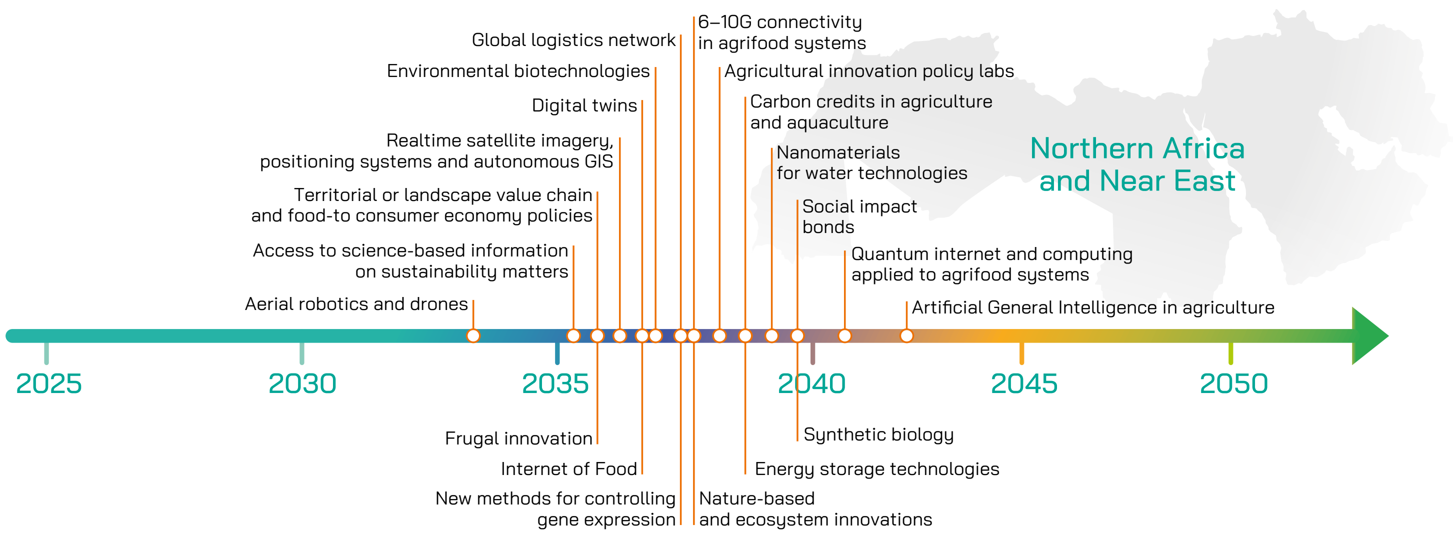


Figure 28. Estimated timeframe for significant impact – Northern Africa and Near East



8.4 FORESIGHTING REGIONALIZED PATHWAYS OF CHANGE

From the five scenarios for pre-emerging and emerging technologies and innovations in agrifood systems, some may develop more easily (with less disruptive or systemic changes within the agrifood systems) or at a faster pace, due to enabling or hindering regional features. These regional characteristics will influence stakeholders' decisions to develop a set of PETIAS (or not) and shape dedicated technology and innovations policies (or not). These regional features correspond to the drivers listed earlier in this report, which exert varying levels of influence depending on the region. They encompass biophysical, socio-economic or geopolitics domains. However, regional features alone will not drive the future of technologies and innovations in a given area. Combined with stakeholder behaviour, proactive responses and the **missions explicitly asssigned to technologies and innovations within agrifood systems**, distinct pathways of change may emerge.

For instance, in regions where **vulnerability to climate change** is pronounced, such as Sub-Saharan Africa (IPCC 2022), monitoring and addressing climatic disasters and crises could drive agricultural governance and science and innovation policies. Consequently, scenario E ("*Technologies and innovations – our best last chance*"), may unfold more rapidly if bold decisions are implemented at policy level, aiming at funding organizations capable of developing new solutions under pressing time constraints. However, in this scenario, due to the urgency of the situation, and local agreements to fast-track new technology and innovation developments, no time for co-innovation is allocated, or sound impact evaluation and time to build societal consensus.

Another pathway of change may occur if no bold policy decisions are taken: a more inequitable scenario, such as **scenario B** ("*Mess and muddle in technologies and innovations*"), which account for a weak technology and innovation governance or policy regulation. New technologies and innovations may develop for those (farmers, food-processors) who can afford them, which means in the context of a climate or sanitary disaster, those who can, will pay for establishing protected areas and hard sanitation controls.

In regions experiencing high **levels of population dynamics and urbanization, such as in Asia, scenario D** ("*AI in charge of agrifood systems and beyond*"), may happen at a faster pace, as a response to increased demand for transformed food products and the decreased availability of agricultural land. However, in this scenario, governance is weak and lacks dedicated policies. Consequently, AI may determine the best land allocation for crop, livestock production, forest or energy products, optimizing logistics aspects for crop transportation or food processing and minimizing natural resources consumptions. AI design and monitoring is developed by the private sector and, in areas where land and agricultural data (crop production, yields, soils parameters, etc.) are available for ensuring relevant learning models and precision mapping, which will discard some parts of Africa or Asia where data are poorly available yet.

Another pathway is possible, accounting for proactive policy decisions, ensuring that AI and technologies and innovations are well-managed, under societal and citizen deliberation mechanisms. Sustainability and inclusion may thus become the preferred criteria AI algorithms will prioritize, along with nutrition and circular economy, which leads to **scenario C** ("*Sustainable prosperity of technologies and innovation*"), possibly through a transitional phase like **scenario A** ("*Struggling between technological illusions and sustainability*").

In regions marked by high **geopolitical instability and conflict,** policy decisions favoring national isolationism or regional political alliances may strongly impact how agrifood systems will perform. To mitigate food insecurity risks, local management of agrifood systems (at national, sub-regional levels) will be preferred. Hence, in such social and political context of crises, it is unlikely that multistakeholders or collaborative policy mechanisms will occur, but rather a centralized and military governance. Consequently, scenario B ("*Mess and muddle in technologies and innovations*") will more likely develop if a monopolistic ownership of technologies and innovations is transferred to some big companies.

Regions with **high levels of food insecurity or low levels of public investment in agrifood systems** face two potential pathways. If bold policy decisions are made, scenarios like scenario A ("*Struggling between technological illusions and sustainability*") can emerge, under the assumptions that specific national technology and innovation strategies are built, particularly towards public investments aiming at bridging the gap of inequalities allowing structural transformation of national economy. If no bold policy decisions are taken, social inequalities may become even stronger and lead to **scenario B** ("*Mess and Muddle in technologies and innovations*").

Regional and country foresights for impact

To gain further insights into regional specificities and translate this analysis into impactful local action, FAO conducted regional and national foresight exercises in Latin America (in partnership with RELASER, the regional network of agricultural extension and advisory services) and in Central Asia and Caucasus (in partnership with CACFRAS, the counterpart network in this region). It involved:

- Regional surveys: Identifying the most relevant PETIAS for the region, rank regional drivers, triggers and wildcards derived through the Delphi survey (2023), while also identifying additional ones.
- Multistakeholder regional workshops: Raising awareness about foresight and collaboratively constructing the most plausible and/or desirable scenarios.
- Multistakeholder national workshops: Influencing ongoing policy processes, tailoring scenarios to specific country contexts, and co-creating advocacy/action plans to achieve the desirable future, with the roles and responsibilities of relevant stakeholders assigned (using preferred futures and backcasting approaches).

While the drivers, trends, triggers and wildcards identified in the synthesis report have been confirmed, several additional factors emerged. Based on these elements, regional and national stakeholders formulated more tailored scenarios to guide concrete policy actions.

The workshops highlighted differences in the most desirable scenarios selected by participants, reflecting local preferences shaped by structural differences, perceptions of the current local situation within agrifood systems, and stakeholder priorities. While the global findings and scenarios remained relevant, the magnitude of drivers varied across regions and countries. Additional drivers and wildcards enabled the development of localized scenarios that better fit specific contexts.

These initiatives provided insights for regional transformations of innovation ecosystems, empowered by research, extension and advisory services (EAS) institutions, and facilitated strategic planning for national EAS forums and policies for Agricultural Knowledge and Innovation Systems (AKIS). The partner organizations committed to advocating for the translation of these results into impactful policies. For example, in the Plurinational State of Bolivia and Paraguay, action plans were devised for national extension forums, while the processes in Uzbekistan and Kazakhstan supporting implementation of Presidential and Ministerial decrees. Moreover, these initiatives equipped regional and national actors with foresight methodologies and raised awareness of their significance, leading to commitments to extend foresight efforts to other countries within the region.

9

A multistakeholder lens

The intricate dance of technology and innovation within agrifood systems is not solely a matter of scientific advancement or a genial peasant's lifehack but a complex interplay of diverse stakeholders. Innovation, after all, is made by people and for people. To navigate this landscape effectively and ensure a sustainable, equitable, and resilient future, it is imperative to anticipate and understand the perspectives, motivations, and potential collaborations of these key players. By foresighting stakeholder dynamics, we can identify opportunities for synergy, mitigate potential conflicts, and collectively steer innovation development towards desired outcomes. This chapter delves into the critical task of mapping stakeholders, analyzing their diverse interests and concerns, and envisioning collaborative frameworks that foster shared responsibility and accelerate progress towards a preferred agrifood future.

9.1 STARTING FROM THE PRESENT DAY: MAPPING INNOVATION SYSTEM STAKEHOLDERS AND THEIR PERSPECTIVES AND CHALLENGES

While foresighting the innovation stakeholders of the future, we used the present day stakes as an anchor, as presented below:

Research and academia

Research and academia play a pivotal role in advancing knowledge, technology and innovation in the agrifood systems. They emphasize evidence-based decision-making, interdisciplinary collaboration, and capacity development. Ethical and social considerations are increasingly integrated into their work. Challenges include working in silos, securing funding, bridging the gap between research and practice, addressing knowledge gaps, promoting open access, and navigating ethical and regulatory complexities. Active participation of research in interactive and open innovation presents a future opportunity for them.

Farmers and farmer organizations

Farmers are a heterogenous group, concerned about economic viability, access to technology and innovation, market access, climate resilience, and rarely participate in decision-making. They face challenges in adopting and adapting new technologies and innovations, managing risks, competing with large-scale producers, building collective power, and accessing finance. Their increasing role as innovators, coupled with skills in place, as well as more active engagement in advocacy for fit-for-purpose innovation can present an opportunity.

Private sector agrifood processors, retailers and transport, agrifood supply companies

The private sector plays a pivotal role in agrifood innovation, driving technological advancements, developing new products and services, and investing in research and development. They are motivated by profit and market opportunities, but also increasingly recognize the importance of sustainability, ethical practices, and social responsibility.

Challenges for the private sector include managing risks, balancing profit with social and environmental concerns, collaborating with diverse stakeholders, and addressing regulatory hurdles.

Extension, innovation and advisory services

Extension and innovation advisory services play a crucial role in knowledge sharing, developing capacity, facilitating innovation, collaboration, and adapting solutions to local contexts. They are increasingly committed to supporting inclusive and interactive innovation.

Challenges include staying abreast of technological advancements, reaching remote communities, building trust, securing adequate funding, and promoting frugal innovation. By addressing these challenges, extension, innovation and advisory services provided by various actors can contribute significantly to the transformation of agrifood systems.

NGOs and civil society organizations

NGOs and CSOs are key actors in driving sustainable use of innovation. They advocate for policies, empower communities, and ensure social justice. Challenges include securing funding, navigating complex political landscapes, developing capacity, collaborating with stakeholders, and measuring impact.

Policy and decision-makers

Ideally, policymakers recognize the need for a systemic approach to innovation, addressing interconnected challenges like climate change, food security, and social equity. They acknowledge the importance of innovation but emphasize responsible and inclusive practices. Balancing competing interests of various stakeholders is crucial. Building resilience and promoting international collaboration are also priorities.

Challenges for policymakers include keeping pace with technology and innovation advancements, addressing social and ethical concerns, securing funding, and promoting collaboration. Measuring and evaluating policy impacts is essential to ensure effectiveness. Foresight participants have perceived this group as the most powerful to drive a sustainable change, but this power may not be exercised often due to lack of skills or other power dynamics. Therefore, removing barriers to policy and decision makers is essential.

Financial institutions

Financial institutions are increasingly interested in investing in innovative projects, driven by factors like risk and return considerations, the potential of pre-emerging and emerging technologies, and growing market demand for sustainable products. However, challenges remain in assessing and managing risks, measuring impact, developing innovative financial products, developing capacity, and promoting transparency.

Consumers

Consumers are increasingly demanding sustainable, healthy, ethical, transparent, and affordable food products. They face challenges in accessing information, affording sustainable options, navigating conflicting information, and influencing the market. By making informed choices and advocating for change, consumers can act as powerful innovators, driving the agrifood industry towards more sustainable, equitable, and resilient practices. Their preferences and demands can influence product development, market trends, and policy decisions, ultimately shaping the future of the agrifood systems.

9.2 AGRIFOOD INNOVATION SYSTEM (AIS) STAKEHOLDERS: EVOLVING CONCEPTS AND EMERGING TRENDS

Our foresight research has identified several weak signals indicating significant shifts in the dynamics, the role and nature of AIS stakeholders. They are:

Blurring of stakeholder groups boundaries

We observe a transition from siloed institutional frameworks towards a rise of multistakeholder innovation initiatives like living labs, innovation hubs, accelerators and policy labs. Often one person is wearing several stakeholder hats: a researcher, farmer and consumer as an example.

Emergence of new stakeholder types

Those include innovation managers and brokers, and innovation support systems. They serve at navigating an increased complexity of actors and bridge the gap between research, the field, business and society.

The rise of Artificial Intelligence

Our foresight analysis has highlighted the rapid advancement of artificial intelligence (AI) and its potential to disrupt innovation systems. AI is progressing from narrow AI (ANI), which performs specific tasks, to general AI (AGI), which aims to replicate human cognitive abilities. The potential for super AI (ASI), surpassing human intelligence, raises both exciting possibilities and ethical concerns.

As AI continues to evolve, it has the potential to become a powerful stakeholder in the innovation system. AI can be used to analyze vast amounts of data, identify patterns, and generate new insights. It can also automate tasks, improve efficiency, and create new products and services, or potentially take decisions autonomously, thus becoming an influential actor depending on the role assigned to it and its management system. Indeed, frameworks commonly used in socio-technical systems approaches, include non-human entities to better emphasize relationships and interdependencies, dominance or competition among them.

Changing governance models

The governance of innovation systems is evolving, with a shift towards more participatory and inclusive models. We have detected weak signals suggesting a growing demand for stakeholder involvement in decision-making and a need for more transparent and accountable governance structures.

9.3 STAKEHOLDER DYNAMICS: A PLENTIFUL ARRAY OF FUTURE POSSIBILITIES

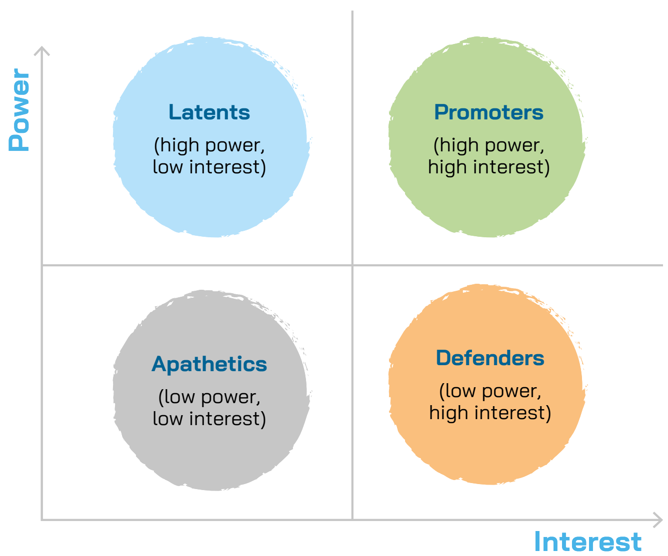
To navigate the stakeholder dynamic in future and influence todays' decisions on institutional frameworks and capacities, we preferred to use flexible stakeholder notions based on their functions in the AIS. We added, whereas relevant an emerging stakeholder - AI (in particular AGI and ASI) that is currently "hidden". AI is poised to become a significant and potentially autonomous player in the coming years. While it is currently viewed primarily as a tool for tasks such as decision-making, content creation, and report generation, its future role may evolve based on the frameworks governing its deployment and management. Socio-technical systems approaches highlight the importance of including non-human entities to illustrate the relationships, interdependencies, and dynamics of dominance or competition among them.

Accounting for this multistakeholder lens, we created a preliminary analysis of the possible interests, roles and potential impacts of each category of stakeholders per scenario. Such analysis sustains the assumption that each pathway of change enclosed in the scenario may generate changes among the network of stakeholders (i.e. enhanced or weakened power to act, or, on the contrary, more collaboration and inclusive share of power and decisions). While each category of stakeholders entails a substantial heterogeneity – all the more when considering the different regions of the world – such pre-analysis brings out possible future shortcomings and draws attention to multistakeholders' possible opportunities for collaboration, as well as trade-offs that should be avoided or anticipated in a strategic planning perspective.

Different categories of stakeholders concerning their levels of interest and influence

Based on their level of interest and their power to influence the innovation systems' governance and functioning, stakeholders can be clustered into four main categories. The four categories include: (i) actors with high power and high interest; (ii) actors with low power and high interest; (iii) actors with low power and low interest; and (iv) actors with high power and low interest (Figure 29, adapted from Mendelow, 1991). In the framework of this research, we termed the four categories Promoters, Latents, Defenders and Apathetics.

Figure 29. Stakeholders power and interest grid



Source: adapted from Mendelow 1991

Promoters. The promoters are category gathering actors who are very involved in defining the orientation of the systems. Still, they are also the group of actors who are happy to see the system remaining as it is as they are yielding benefits may not want it to change. For example, in Scenario B (*Mess and muddle in innovations and technologies*), large private companies may see opportunities in this state of the innovation system. Promoters and Latents are the leading players who need to be mobilized if the system evolves in one direction or another. They would have a higher priority than Latents, as they have a more significant stake and could be directly affected by the system's direction.

Defenders. This group includes actors who are highly concerned or affected by the performances and outcomes of the agrifood innovation systems but have little or no capacity or power to influence them because of the governance and operational settings of the system. Moreover, the Defenders are generally those who need the technologies and innovations or will be impacted by them. Their low capacity to influence the system accentuates the issues of access, relevance, participation and, finally, the low uptake and outcomes of those technologies and innovations. Consumers, farmers and farmers' organizations are examples of Defenders in Scenario B (*Mess and muddle in innovations and technologies*). Consequently, one key lever to improve the quality and uptake of emerging technologies and innovations is to create conditions that will give opportunities to the defenders to share their feedback and, most importantly, to be part of the decision-making processes.

Latents. The Latents are actors who have high power to influence the structure, functioning and maybe even the performance of the innovation systems but show or have low interest. They do not take part directly, but their decision may change the settings, outputs and outcomes. In some scenarios like Scenario B (*Mess and muddle in technologies and innovations*), being in the position of Latents doesn't automatically mean that the actors initially have no interest. It may imply that the actors have somehow withdrawn and show little interest in the events because of low capacity or failure to play their roles. This is, for instance, the case of decision-makers in Scenario E (*Technologies and innovations – our best last chance*). It is important to keep latent actors happy or satisfied because of their power to contribute to scaling emerging technologies and innovations, for instance, by creating an adequate enabling environment.

Apathetics. This category includes players who cannot influence the system for generating and valorizing emerging technologies and innovations. These actors are also characterized by the fact that they have little interest in or impact on, the system's operation and performance. For these reasons, they may appear to be outside the system or of little interest in the context of an intervention to improve the system. However, ignoring them could be a mistake, as their current position is not necessarily definitive. On the other hand, the apathetic can quickly change category as the situation evolves. In Scenario E (*Technologies and innovations: our best last chance*), for example, where politicians and decision-makers are in a bankrupt position, they find themselves in the apathetic category. They can quickly move into the Latent or even Promoter category if they regain their regalian role and effectively mobilize resources to facilitate the emergence of technologies and innovations.

It's important to note that a player's position in a given category is not a fixed and definitive situation. Positions may evolve in response to external or internal factors affecting individual players or elements affecting the agrifood innovation system's structure and functioning. Internal dynamics of a category of actors can help change its positioning. For example, better organization and the development of advocacy and strategic dialogue skills can help producers and their organizations move from the frequent position of Defenders to that of Promoters.

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9.4 POSSIBLE OPPORTUNITIES FOR COLLABORATION AND TRADE-OFFS AMONG STAKEHOLDERS WITHIN THE DIFFERENT SCENARIOS

In **Scenario A**, the Promoters position is occupied by three major players: (i) Research and academia, (ii) Private sector agrifood processors, retailers and transport, agrifood supply companies (iii) NGOs and civil society organizations. Research is still heavily mobilized to supply innovations and knowledge that are not always fit-for-purpose, to the existing productivity-driven system which finances it. The place of research in the category of Promoters is all the more important as it is also expected to play a part in the growing sustainability debate. However, linked to macroeconomic characteristics, the research and academia may also be Defenders in this scenario with little power due to insufficient funding, low societal trust in science and floating misperceptions on research outcomes. The private sector continues to benefit from the system and would have much to lose if the switch to sustainability were to take place rapidly before it has had time to adapt. AI may transit from an influential tool towards an independent actor- Promoter due to the fast pace of its adoption in different domains, including decision-making. AI hallucinations may still not be resolved that translates to more illusions and not clear sustainability gains. This could link to Scenario D if no robust regulations and human control are adopted.

Furthermore, the position of NGOs and CSOs in the Promoters category is linked to their decisive role in raising awareness among stakeholders and lobbying decision-makers, in particular, to integrate sustainability issues better. These NGOs and CSOs support niche innovations around sustainability issues. The private sector, with its strong focus on productivity and profitability, is still dominant and influences the whole system despite the growing discourse around sustainability. Producers and their organizations, consumers and extension services fall into the category of Defenders. Indeed, although they are very much involved in the sustainability and product debate, the current system's configuration – still highly centralized, top-down and dominated by the logic of productivity – does not allow them to exert any real influence in preserving their interests. Research and innovation agendas become disconnected from development agendas, as research and innovation activities mainly target farm productivity issues, with increasing but still inadequate attention given to sustainability issues. In this scenario, The Latents category includes policy, decision-makers and financial institutions.

In **Scenario B** (*Mess and muddle in technologies and innovations*), public authorities and decision-makers are in the Apathetics category, along with civil society organizations. Indeed, in this scenario, policy and decision-makers have little influence on how the system works and have resigned their specific role. The positioning of civil society organizations in the Apathetics category results from their powerlessness and withdrawal in the face of the general climate of disorder. The position of financial institutions as Promoters stems from the fact they finance the large corporations that drive the systems. These institutions are, in turn, impacted by the results of the private sector, which drives innovation. Also in this scenario, the AI could become a Promoter with unsolved reliability and data ownership issues that translate into deepening divide and sustainability failures, as in the context of this scenario robust regulations are unlikely and the risk of biases is very high. Consumers, extension services, producers and organizations find themselves in the Defenders position. They need technologies and innovations adapted to their needs, but this is impossible due to a lack of power to influence the other players, notably the promoters who drive the system. These promoters are practically freewheeling, as no other players have the necessary capacity to influence them. Indeed, in this scenario, no actors are in the Latent category. In this situation, the change that could enable the Defenders to find themselves in a position of influence could come from two evolutions. On the one hand, a better structuring of Defender players would give them a more audible voice to advocate and mobilize Latent players. On the other hand, better structuring would also enable Defenders to pressure Promoters; better capacity for self-identification and expression of priority demands would also contribute to this result.30

Figure 30. Stakeholders positions in the Scenario A: struggling between technological illusions and sustainability

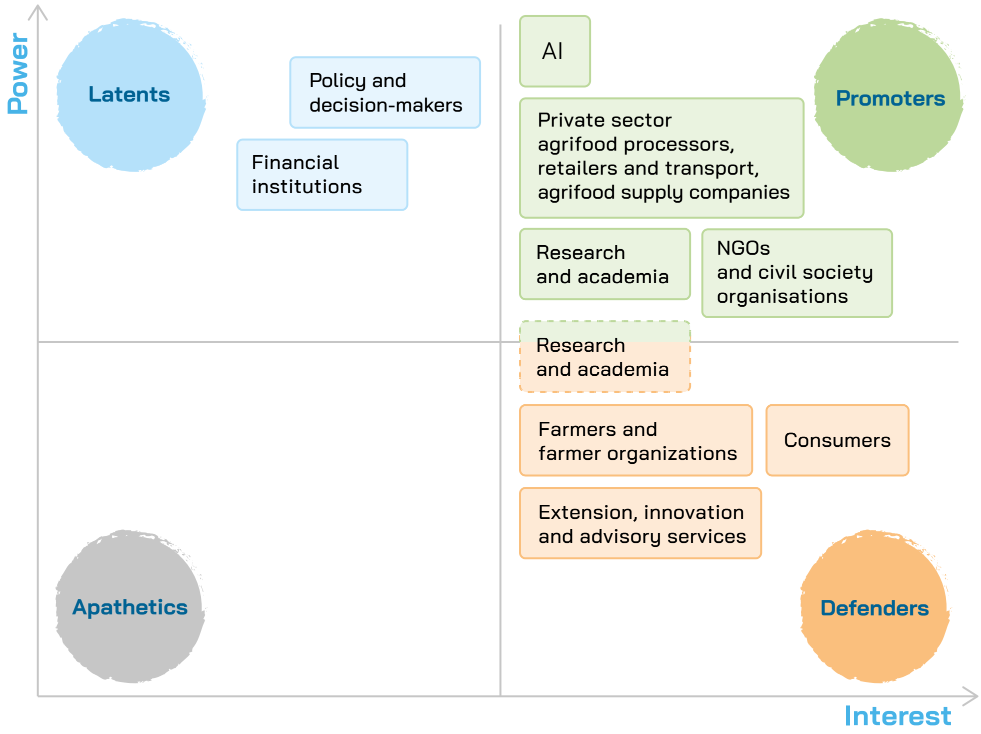
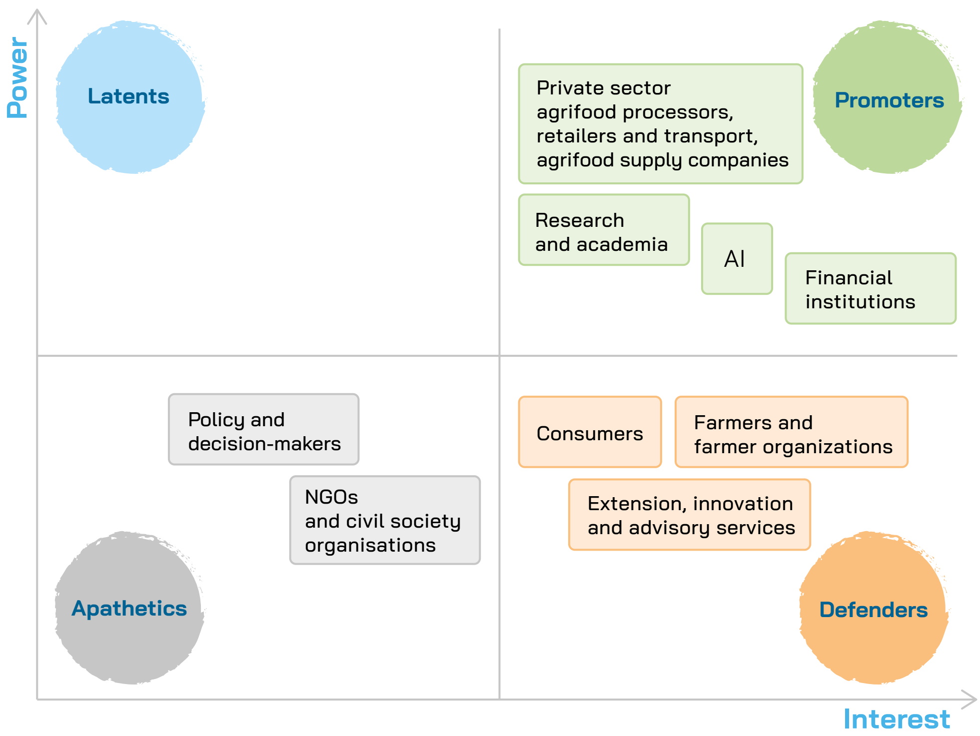
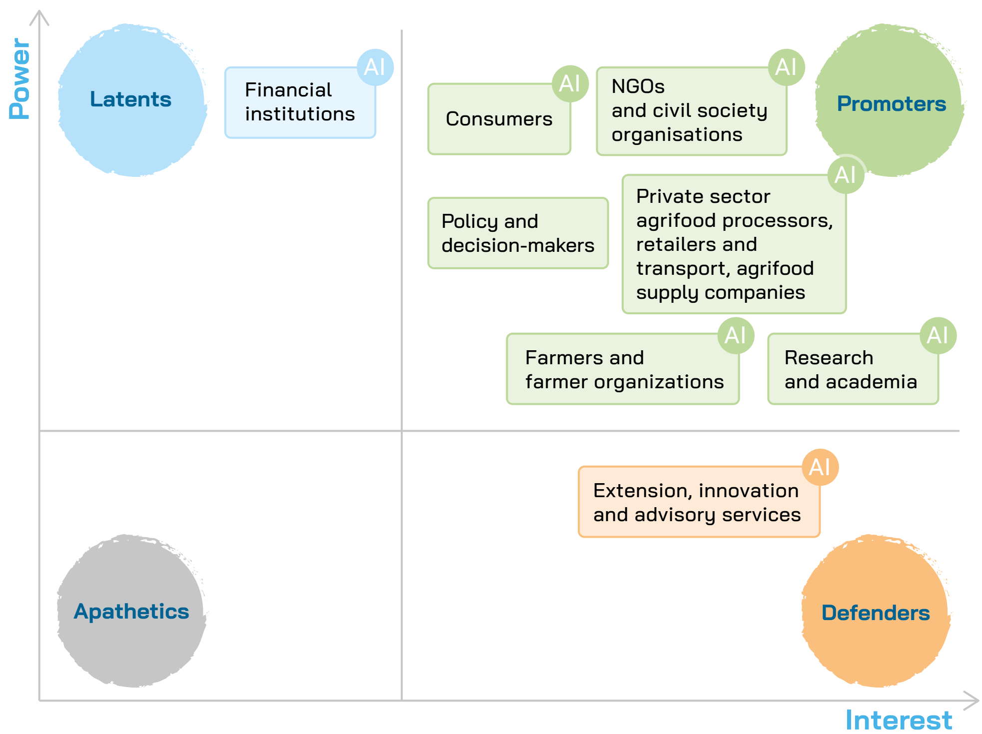


Figure 31. Stakeholders positions in the Scenario B: mess and muddle in technologies and innovations



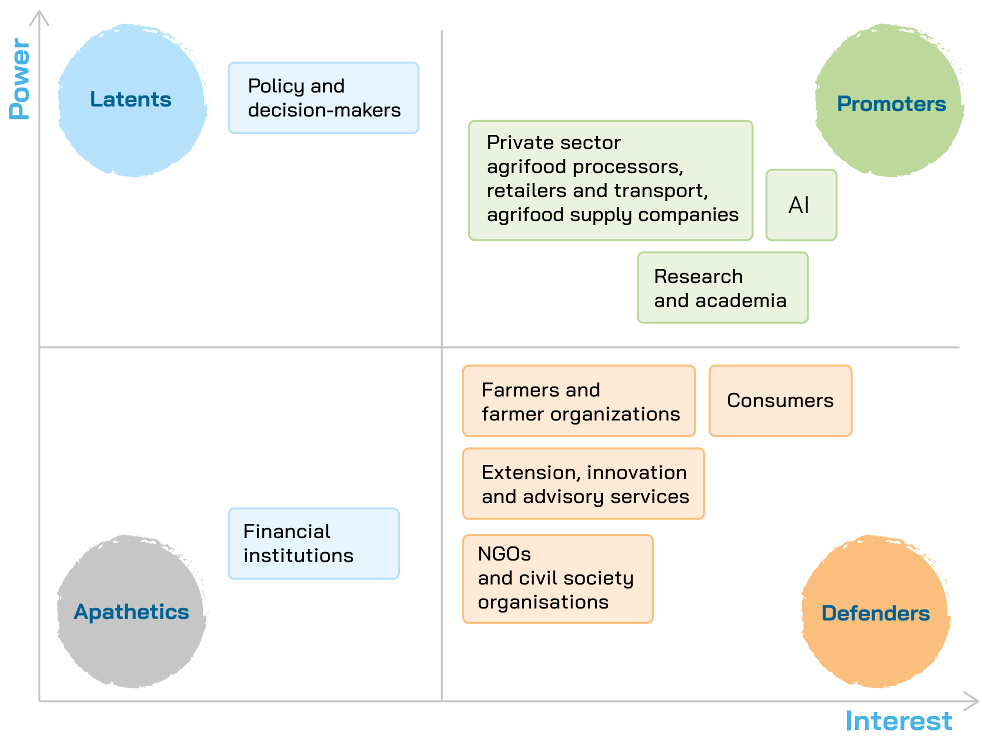
In Scenario C (Sustainable prosperity of technologies and innovations), all stakeholders are in a position to play a major role and have very high levels of interest and power. This situation is very unusual compared with the other scenarios, where the differences between players are more marked. It is linked to the objectives of sustainability and resilience, which are the main drivers of this scenario. Indeed, sustainability and global health require a systemic approach in which the need for different categories of players to contribute is recognized and valued. All types of stakeholders are a true part of the policy-making process, supporting decision-making and experimentation through multi-actors and localized partnerships. Often marginalized categories of stakeholders, such as consumers, smallholders and citizens, are better recognized and become the main decision-makers. Financial institutions are in a Latent position, as financial stakes do not drive the system. However, these institutions have a strong capacity for influence as they finance the development of the technologies and innovations needed to achieve sustainability goals. The position of the AI in this scenario is quite ambiguous: while it may play an important role to support decision-making and efficient planning and use of resources, augmenting the capacities of all actors, the strong position of the other stakeholders would ensure equitable regulations with regards to the AI and human oversight, thus preventing AI from becoming an independent actor (high power, no interest).

Figure 32. Stakeholders positions in the Scenario C: Sustainable prosperity of technologies and innovation



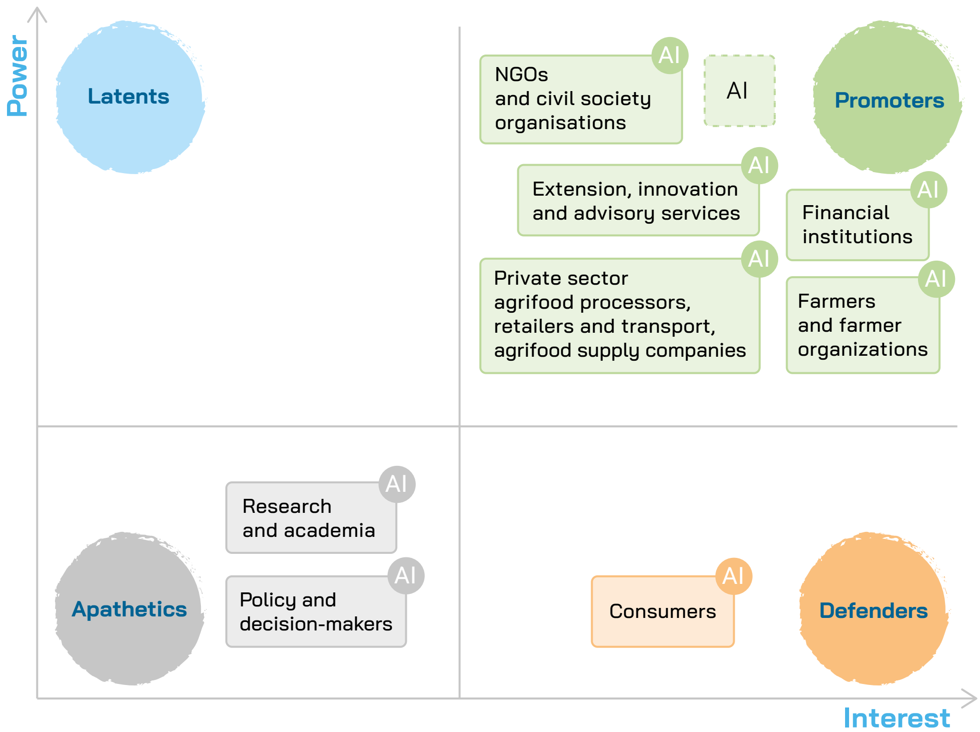
In Scenario D (*AI in charge of agrifood systems and beyond*), the AI is the Promoter, guiding the whole system. In addition, the private sector, the research and academia that helped set up and ensure the data supply and the related technology also occupy the position of Promoters. They are influential because they control the production and sorting of data available to artificial intelligence. Policy and decision-makers are in the position of Latents because they have decided to set up a mode of governance based primarily on AI. They don't directly influence AI's behaviour, but they can review AI's areas of competence. Apart from financial institutions in the Apathetics position, almost all other players are in the Defenders category. The system strongly impacts them, but they can't influence it directly unless they find ways to lobby and dialogue with the research and academia that feeds AI. Farmers and other vulnerable groups could be particularly impacted regarding access. Still, if their knowledge, experience and needs are not reflected in the AI-dominated system, they could be subject to biases. The other way would be to organize themselves to conduct advocacy at the policy level so that the management mode based on artificial intelligence is reviewed. Financial institutions are in Apathetics' position. They have little influence but are at the same time little directly impacted by the AI-based governance system.

Figure 33. Stakeholders positions in the Scenario D: AI in charge of agrifood systems and beyond



In Scenario E (*Technologies and innovations – our best last chance*), the dynamic is driven by civil society organizations, producers and private-sector players, who organize themselves to compensate for the deficits of government and research, whose traditional mission is to develop technologies and innovations in line with the challenges faced by producers and their organizations. Policy and decision-makers, research and academia find themselves in the position of Apathetics, as they are overwhelmed by the issues at stake. They no longer have any real influence. Although powerless, they could play an essential role in the medium term. For policy and decision-makers, it could mean creating a favorable environment for the scaling-up of frugal technologies and innovations developed by civil society and producers and positively influencing the research and investment agendas to address the most pressing crises. For research, it could mean documenting and refining the technologies and frugal innovations urgently developed by civil society organizations and finding solutions to deepen and amplify these innovations. Consumers also find themselves in the position of Defenders, as the crisis strongly impacts them and have a strong demand for technologies and innovations. In principle, they would be the final beneficiaries of the effects and impacts of the technologies and innovations developed in the prevailing crisis. Still, the disorganization of governance means they are not the main beneficiaries. Also, here, the position of the AI could take different turns according to the specific contexts: due to its potential, it may be rapidly adopted to address the crisis, but with the policymakers as Apathetics and little time for adoption, robust regulations are unlikely. On the other hand, with their strong position in this scenario, the civil society and the producers could also be influential in ensuring AI's equitable and sustainable use.

Figure 34. Stakeholders positions in the Scenario E: Technologies and innovations –our best last chance



9.5 TAKEAWAYS FROM THE STAKEHOLDER ANALYSIS BY SCENARIOS

To achieve a strong, functioning, and mission-oriented Agrifood Innovation System (AIS) capable of accelerating agrifood systems' transformation and achieving the preferred future, it is crucial to create the right conditions to empower all stakeholders and motivate their interest to contribute, elevating them as promoters.

Here are the main takeaways from the stakeholder analysis by scenarios:

1. **Empowering stakeholders as Promoters**
   For a robust and mission-driven AIS, it is essential to establish proper conditions that empower all stakeholders. Motivating stakeholders to contribute actively will help elevate them to the role of Promoters, which is vital for accelerating agrifood systems' transformation.

2. **Roles of Latents and Apathetics**
   Stakeholders in positions other than Promoters, such as Latents and Apathetics, are still expected to take action. These stakeholders should utilize their margins of power to influence the innovation process, demonstrating that their roles are significant despite not being in the Promoter category.

3. **Opportunities for stakeholders**
   The analysis highlights clear opportunities for policy and decision-makers to step in and exercise their powerful regulatory roles in a balanced manner. Consumers and civil societies are encouraged to drive innovation, while farmers are positioned as key innovators and essential parts of the innovation ecosystem.

4. **Managing AI as a stakeholder**
   In the coming years, AI may evolve as an independent and powerful stakeholder with its own interests. Effective management of AI as a stakeholder will be crucial to ensure it aligns with the overall goals of the AIS and contributes positively to the innovation process.

9.6 FROM A FEW TO MANY: THE NEED FOR AN INCLUSIVE GOVERNANCE

The FAO and CIRAD foresight report (Alexandrova-Stefanova N., *et al.*, 2023) has concluded that harnessing technology and innovation for agrifood system transformation is not a job for a sole stakeholder group and the analysis presented above provides a deeper understanding of the stakeholder dynamics, opportunities and trade-offs concluding on the need of leveraging the potential of all stakeholders to provide meaningful contribution to AIS. This implies excelling on AIS multilateral governance.

The governance models translate in a supportive policy, financial and collaboration incentives, and management of the innovation process and leveraging the voices of stakeholders to reach their full capacity as Promoters.

This does not necessarily imply that everyone needs to participate in the same way at every step. Still, all stakeholders' needs, demands and concerns must be articulated, heard and jointly addressed. Applying participatory multilateral governance, as encouraged in the UN Pact of the Future, 2024, the research and investments agenda be aligned with societal needs, minimize trade-offs while maximizing benefits and leverage technologies and innovations to transform agrifood systems sustainably and inclusively.

However, a truly participatory and transparent governance does not come without challenges. The previous chapter on unbalanced and changing power and interest dynamics illustrates it well. In addition, as multiple experiences show, it is quite a lengthy process (that may discourage participants), requiring a mindset change (from imposition to mutual trust and collaboration), new mechanisms (like consultations, fora, etc. that may also be costly), new organization (e.g. accommodating time and location of various stakeholders) and last but not least new capacities and skilled facilitators.

In particular, functional capacities are key still lacking. They include deep listening, dialoguing instead of monologuing, openness to new knowledge and experiences, inclusive communication, innovation capacities (TAPipedia, 2017). These capacities are also essential for the facilitator(s) of the process, in addition to balancing existing power dynamics, including vulnerable groups, conflict resolution and consensus-building skills. The latter also implies the need for careful choice of who the facilitator will be (institution or individual).

Political will is vital to enact collective decisions and maintain open communication channels ensuring stakeholders' ownership of the results. It would allow for participatory governance to be impactful and to avoid ''fake democracy'' and ''participation fatigue''.

In the frame of the work for this report, we conducted three role-play exercises on the participatory governance of the innovation process (FAO foresight workshop and the IFSA Conference 2024). They were all based on the Samoa circle methodology. They consisted of simulating multistakeholder consultations on the introduction of selected technologies and innovations: i) one social innovation with a low level of trade-offs; ii) one high-tech solution with a medium level of trade-offs; and iii) one "futuristic" technology with a high level of trade-offs. It is important to note that on these three occasions, the play participants were assigned roles different from their real-life "hats". Each context implied a sense of urgency (food crisis), while the goal was to elaborate jointly a win-win and viable action plan for a sustainable introduction of the given technology or innovation.

These role plays shed some interesting light on the challenges of multilateral governance. In all three occasions, despite limitations such as time constraints and simulation sensation, the players failed to reach the multilateral governance output (joint action plan or project proposal) driven by siloed interests, lack of capacity to engage in multilateral governance and unwillingness to assume responsibility in a joint action. Participants, who were representing different stakeholder group from their own, acted driven by the prevailing mindsets and perceptions of the stakeholder' role, showing little ability to adapt the roles to the demands of the scenarioscenario, and exit the current paradigm. For instance, despite the supportive role of private sector and strong collaboration with NGOs in scenario D, the private sector was usually depicted asless collaborative, and farmers quite vocal and not always acting in support of sustainable practices. These findings were supported by other FAO foresight exercises, related to regional aspects and UNDP-FAO board game (in a process of publishing).

This signals a need to develop capacity to adapt to contexts and exercise participatory governance.

To conclude, despite challenges, this foresight experience and FAO's work on the mission-oriented AIS show unambiguously that multilateral, inclusive and transparent governance at different levels is a must for inclusive, resilient and sustainable AIS and broader agrifood systems. Innovative approaches (like Innovation Policy Labs, e-governance, incentives, etc.) must be promoted to facilitate implementation of such governance models, foster political will and develop capacities for meaningful and empowered participation. Chapter 11 provides some further insights into actionable strategies in this regard.

9.7 MULTILATERAL GOVERNANCE COMES WITH RESPONSIBILITIES: ROLES OF STAKEHOLDERS

Participation in governance comes with responsibilities that must be conscious and effective. At the same time, meaningful involvement empowers stakeholders to act: to articulate their demands and concerns, collaborate with others on equal footing, implement actions and take ownership of the process and its results.

While concrete roles of various stakeholders may vary between different social, political and cultural contexts, the authors summarized some main recommendations, coming both from their reflection, experience and participatory components of this foresight (such as from the FSN Forum):

Policy and decision-makers:

- Develop inclusive, sustainable and tailored-to-regional needs policies that enable innovation and technology development.
- Create preparedness to maximize benefits and minimize drawbacks of innovation disruptions.
- Create a supportive environment for co-creating and adopting advanced technologies and innovations, especially green ones (including subsidies, tax breaks, etc.).
- Establish frameworks for participatory governance, ensuring that all stakeholders, including vulnerable groups, are involved in decision-making processes around the STI.
- Enhance robust and smooth regulatory mechanisms to ensure that technological advancements are accessible, equitable, ethically and environmentally sound.
- Facilitate the provision of extension services to enable access to technologies and relevant skills.
- Facilitate knowledge exchange between different stakeholders and provide easily accessible information for the society.
- Promote partnerships with public and private organizations at national and international levels.
- Secure funding for further research and development, and consider pull funding mechanisms.
- Invest in digital and physical infrastructure to support the implementation of new technologies, especially in rural areas.
- Conduct extensive needs and cost-benefit analyses to optimize the benefits of adopted innovations and technologies.

Researchers and academia:

- Align research agendas with societal needs and local challenges and integrate social sciences in the innovation process.
- Engage in the context-specific participatory and applied research to ensure relevance and impact.
- Engage in co-creation by collaborating with diverse stakeholders to assess needs, co-create solutions and evaluate performance and impact, ensuring that innovations are practical and widely accepted.
- Facilitate knowledge dialogue and excel on science communication: work closely with farmers, local communities and consumers.
- Support frugal innovation efforts.
- Conduct extensive needs and cost-benefit analyses to optimize the benefits of adopted innovations and technologies.

NGOs and civil society organizations:

- Invest in evidence-based knowledge to bridge the research and practical use gap by facilitating skills and capacity development.

- Raise awareness about sustainable agriculture, the potential of advanced technologies and innovations and sustainable behaviours and mobilize communities.
- Advocate for inclusive and sustainable development of technologies and innovations for just integration of scientific and traditional knowledge for greater relevance and impact.
- Facilitate participation by ensuring that marginalized groups have a voice in developing and implementing new technologies and innovations, as well as broader innovation governance processes.
- Promote participatory approaches to assessing various environmental, social and economic impacts of policies or actions.
- Participate in and influence the design, implementation and assessment of relevant policies and actions.
- Facilitate access to innovations for communities and marginalized people.

Private sector agrifood processors, retailers and transport, agrifood supply companies:

- Invest in developing and implementing advanced technologies and innovations in agriculture, including precision farming and hydroponics.
- Balance profitability with social and environmental responsibility by, for example, incorporating renewable energies and organic practices in their solutions.
- Participate in the innovation governance processes.
- Provide technical support and maintenance services with innovative business models to avoid creating clients' dependency.
- Engage in collaboration and partnerships with the public sector and civil society.
- Invest in grassroots innovation and integration of traditional knowledge in the proposed solutions while avoiding extractivism.

Extension, innovation and advisory services:

- Act as facilitators of inclusive co-creation of knowledge, technologies and innovations.
- Act as a bridge between other stakeholders, ensuring that information "from the ground" reaches research and policy institutions.
- Invest in developing their own new technical and functional capacities, from the skills related to high-tech and nature-based solutions to innovation and facilitation capacities.
- Participate actively in the innovation governance processes and advocate for inclusive and sustainable development of technologies and innovations that sustainably integrate scientific and traditional knowledge for greater relevance and impact.
- Raise awareness about sustainable agriculture, the potential of advanced technologies and innovations and sustainable behaviours, and mobilize communities.
- Ensure a smooth and inclusive coordination of the pluralistic EAS systems and collaborate and partner with the public sector and civil society.

Financial institutions

- Provide innovative and equitable funding modalities for investment in development and access to technologies and innovations (e.g. digital infrastructure in rural areas).
- Rethink investments in technology and innovation to prioritize policy and organisational innovations including nature-based and frugal innovations proven to bring an impact.
- Participate actively in the innovation governance processes to align investment agenda with societal needs.

Consumers

- Participate actively in the innovation governance processes.
- Be informed about agrifood systems dynamics to make informed, healthy and socially informed (e.g. the actual cost of food) and environmentally (locally produced) sustainable consumer choices.
- Promote and engage in community-based initiatives such as direct purchases from farmers, participatory guarantee schemes, etc.

Farmers and farmer organizations:

- Engage in co-creation, adoption and implementation of technologies and innovations.
- Engage in training programmes to learn about new technologies and sustainable farming practices.
- Participate more effectively in and influence the design, implementation and assessment of policies and actions around AIS governance to ensure their concerns and interests are addressed.
- Work with research institutions, extensionists and NGOs to pilot and adapt technologies to local contexts.
- Actively contribute to data collection, monitoring and evaluation efforts by providing information on needs and feedback on the performance and impact of new technologies and innovations.
- Share experiences and best practices with peers, fostering a collaborative and knowledge-sharing community.

For smallholder producers, female and youth farmers, Indigenous peoples, consumers and other usually vulnerable groups, implementing the actions recommended for them requires accomplishing all the different responsibilities of other stakeholders, like empowerment, facilitating access, training, investing in infrastructure, etc.

Furthermore, coordination and collaboration were mentioned several times. This confirms the need for multilateral governance and implies that there are also overlaps between the roles of different groups.

10

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Anticipatory strategic planning

FAO recognizes the critical role of foresight in the transformation of agrifood systems. Through initiatives like the "Harvesting Change" report, the FAO and CIRAD are championing a proactive approach to innovation. They provide stakeholders with valuable insights into pre-emerging and emerging technologies and innovations and the mechanisms that fulfil the promise and make impact where they are most needed. By understanding the trajectory of technological advancements, stakeholders can identify opportunities, mitigate risks and shape desirable futures for their communities and industries. They can also reconsider assumptions about the future of the sectors and markets they invest in.

This proactive stance is crucial in a world where change is the only constant. By embracing strategic foresight, stakeholders can move beyond reacting to crises and become active participants in shaping the future of agrifood systems. FAO's commitment to fostering foresight capabilities among stakeholders is a testament to the importance of anticipatory planning in building a more sustainable, resilient and equitable agrifood future. The chapter below proposes strategic planning based on theoretical insights to better understand the mechanisms to innovate to reach transformative outcomes and practice-related actions that must be taken.

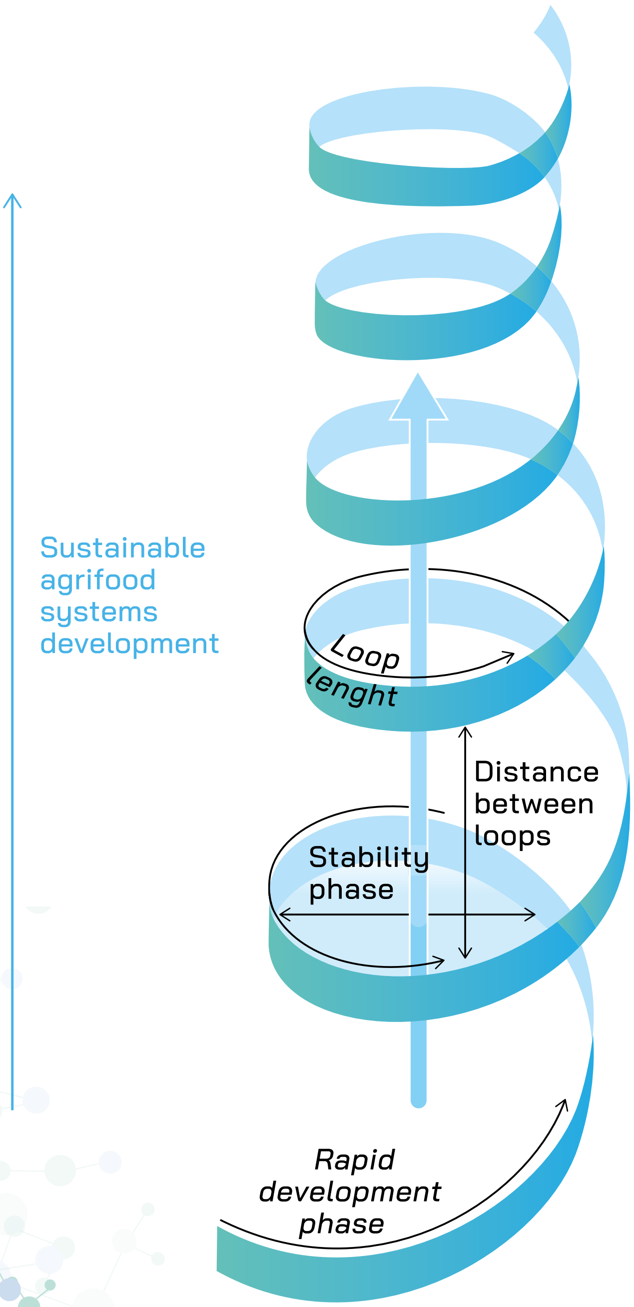
10.1 MOVING THE THEORETICAL TARGET

10.1.1 A helix innovation model: better theory for better impact

The conventional understanding of technology generation and adoption often simplifies the innovation process as a linear trajectory: a scientific advancement triggers the development of a technology, which is subsequently refined, its effectiveness (fit-for-purpose) and cost efficiency are improved, marketed, commercialized and scaled up. The linearity implies that push funding at the start, followed by incentives along the line, is sufficient to drive massive adoption and lead to impact. However, this linear model fails to capture innovation's complex and iterative nature as a product, process or form of organization used for the first time in a particular context, especially related to sustainable agrifood systems. It proves inadequate for many innovations, particularly those that are disruptive, community-driven or applied in new contexts.

We propose a hypothetical helical model as an attempt to get a more nuanced understanding of the relationship between innovation and transformation of sustainable agrifood systems. Although this is not the first time that innovation has been linked to a helical structure, in other models, the academia, business, government and society are siloed (quadruple innovation helix (Carayannis and Campbell, 2009)) or refer to capacity development processes for agrifood innovation systems (TAP, 2016). Our model posits that innovation processes are cyclical, alternating between periods of rapid technological advancement and phases of deceleration or stabilization, after which systemic changes translated to new leaps are made possible. The model is presented in Figure 35.

Figure 35. Innovation for agrifood system transformation - a helix model



Key elements of the hypothetical helical model include:

i. Phases of rapid development.

Technological convergence, synergistic innovation ecosystems, supportive policies and financial mechanisms drive rapid innovation during these phases. Consensus among value chain actors, including farmers and consumers, is essential for accelerating progress. However, this phase is often followed by:

ii. Phases of deceleration and adjustment.

Periods of deceleration allow for policy adjustments, institutional changes and skill acquisition. These adjustments ensure that innovations align with evolving challenges and opportunities. Resolving trade-offs between competing interests is essential for sustainable progress. These phases ensure that innovations contribute to sustainable development goals rather than inadvertently creating new challenges. In this phase, the needs of stakeholders are assessed and then translated into technology or innovation solutions.

iii. Loop length and (iv) the distance between loops (a leap).

The loop length determines the time the innovation system needs to adapt to rapid developments, and the distance between loops denotes the time between two stability states, hence the ability of the system to cope with changes and disruption, also called resilience. Successfully managing the innovation process and avoiding system stress and negative disruption would imply decreasing the loop length and the distance between loops.

Our research highlights the importance of understanding this helical dynamic in guiding sustainable agrifood systems transformation. By identifying periods of acceleration and deceleration, decision-makers can proactively shape the innovation landscape to maximize positive outcomes. For instance, investments in research and infrastructure can support innovation during rapid technology and innovation development. Conversely, during stabilization periods policy interventions, education and enhanced capacities can address emerging challenges and ensure that innovations are aligned with sustainability goals.

Furthermore, policy and decision-makers (innovation managers) can manage the innovation process by distributing the potential system tension (between the rapid innovation pace and the socio-economic conditions for its use in practice) more equally and frequently along the process through taking actions that introduce more and more frequent helix steps (rapid and stabilization chains) with shorter loops.

While technologies and innovations are undoubtedly important, our research also underscores the crucial role of policy, social and organizational innovations now: all our sources of information demonstrate the critical demand for policy and other non-technological innovations, depicting a possible stabilization phase for many of the studied technologies and innovations. They are essential for creating the enabling conditions for their upscaling and ensuring that innovations contribute to equitable and sustainable outcomes. Hence, a shift in the way of incentivization – from push funding for research and development to policy, social and organizational innovations may be required.

The helical model for different technologies and innovations and their clusters may differ. Hence, a rapid phase for one pre-emerging or emerging technology and innovation may coincide with a stability phase of another. Furthermore, there is undoubtedly more than one innovation pathway or an innovation pathway may evolve in different directions (see scenario evolution in Chapter 6). The foresight research provides insights into the timelines of pre-emerging and emerging technologies and innovations that need to be refined and contextualized further. Bold actions from policy, decision-makers, multilateral stakeholders and the international community are to be taken in all cases, and our research contributes to this.

Beyond a general comprehension of the complex interplay between the accelerating agrifood systems transformation and pre-emerging and emerging technologies and innovations, this foresight research offered a comprehensive toolkit for navigating the innovation process. This toolkit included a deep dive into the driving forces, internal trends, triggers and key transformations shaping the agrifood landscape. Additionally, it presented a range of potential scenarios and preferred future outcomes, enabling stakeholders to anticipate and plan for the impacts of these innovations.

10.1.2 Prime directive: acknowledge and support diverse innovation pathways and paradigms

Before we present the specific recommended actions, it is crucial to emphasize that agrifood stakeholders should recognize and support diverse innovation pathways, including those that challenge established knowledge and technology transfer patterns. Since the Neolithic Revolution, agrifood innovation has been grassroots, vernacular, local and frugal, leading to productive and safe indigenous farming and husbandry practices. It is crucial to avoid overemphasizing technology transfer or co-innovation models that solely focus on high-tech solutions. Instead, stakeholders should embrace a broader approach that values frugal, social and policy innovations, recognizing their potential to contribute to sustainable and equitable agrifood systems. Yet, new technologies and innovations are generated to help solve new or old challenges more effectively. Having the technology at hand and not taking advantage of it implies a weakness in capitalizing on its benefits. It can lead to missed opportunities for sustainability, resilience and inclusion, an economic loss in a highly competitive environment and slow global growth (IMF, 2024).

The choice of innovation pathway or paradigm shift will depend on various factors, including the specific local context, stakeholder engagement and a supportive enabling environment. To foster a more inclusive and dynamic innovation landscape, it is imperative to invest in participatory research and development, promote indigenous and traditional knowledge and support grassroots innovation. This may be, presumptuously, seen as a duplication of effort or even a diversion from the mainstream technology transfer efforts. However, this perception is mistaken, as a multi-faceted approach supporting various innovation pathways is crucial for sustainable and inclusive agrifood systems transformation. Creating enabling environments through supportive policies, infrastructure and access to finance and markets is vital. Developing capacity through education and training programmes will further equip stakeholders with the skills and knowledge needed to participate in and benefit from innovation. By acknowledging and supporting diverse innovation pathways, we can create a more resilient, sustainable and equitable agrifood systems that benefits all stakeholders and contributes to a better future for both people and the planet.

10.1.3 Monitoring and evaluation framework to steer the development and uptake of responsible innovation framework

Given the high attention given to impacts, primarily environmental, economic and social impacts resulting from new technologies and innovations, we advocate considering the different dimensions related to responsible use and conceptualization of innovation as an additional recommendation. The term has been widely developed for industrialized countries in the Global North. Still, its implementation has also been recently questioned in the Global South (Vasen *et al.,* 2017) and for ecological transformation, including frugal innovations (Aggeri, 2023). Whereas most agricultural innovations are considered "responsible" as long as they address SDGs challenges (Macnaghten *et al.,* 2014), we instead advocate for specific attention and for developing appropriate and regionalized, locally sensitive and socially smart frameworks to ensure that new technologies and innovations developed remain genuinely "responsible".

Literature provides a combined foresight and monitoring and evaluation frameworks. We suggested using the four-dimensions framework developed by (Stilgoe *et al.,* 2013): 'anticipation, inclusion, reflectivity, responsiveness' framework.

- **Anticipation dimension:** relates to improved foresight approach for steering more responsible ideation and use of innovations, which provides possible early warnings of future effects and anticipative transformative changes, such as this report intends to deliver.
- **Inclusion dimension:** relates to the inclusion of new voices in the governance of AIS through the mobilization of deliberative processes, co-design approaches, cognitive justice, public dialogue and inclusive policymaking.
- **Reflectivity dimension:** relates to the capacity of stakeholders to develop reflexive thinking and significantly to develop institutional reflexivity in science, technology and innovation governance. Reflexive entails challenging assumptions of scientific amorality and agnosticism, such as each stakeholder's role and moral responsibilities.
- **Responsiveness dimension:** relates to the extent to which the technologies and innovations may respond to global, societal, environmental or agrifood systems-related challenges and how they respond to the need for new knowledge and actions as emerging perspectives, views and norms.

The 'anticipation, inclusion, reflectivity, responsiveness' framework (Stilgoe *et al.,* 2013) suggests that responsible innovations should be implemented while developing institutional capacities. For instance, this framework will help track progress – or deviations – towards achieving desired outcomes based on regional and stakeholder priorities. Such a framework is valuable for steering to develop forward and transformative thinking, in line with the need to go beyond compliance with established regulations, in ways that challenge conventional roles and institutional responsibilities (Stilgoes *et al.,* 2013).

Finally, developing a relevant monitoring, evaluation and learning framework will help steer future literacy among stakeholders and enhance capacities. It is also worth noting that implementing such a framework through a multistakeholder and regionalized approach is a valuable means to avoid potential bias attributed to foresight frames, which have been criticized for causing longsightedness (i.e. detachment from the present), reify promises and visions and/or reproduce misperceptions of control and determinism (Boenink, 2013). Hence, questioning the responsible dimension of technologies and innovations also calls for attention to how foresight has been conducted, how anticipatory development is progressively constituted and how future scenarios are also "subjects of" responsibility (Urueña *et al.,* 2021).

10.2 PUTTING KNOWLEDGE INTO PRACTICE

10.2.1 Foresight-informed typology: guiding strategic planning to accelerate positive impacts of pre-emerging and emerging technologies and innovations

The typology developed through our research and elaborated in Chapter 3 provides a valuable framework for understanding and analyzing the landscape of pre-emerging and emerging agricultural technologies and innovations and guides processes listed below in a participatory setting through a broader evidence base and multistakeholder consultation. It can be used in several ways:

- **Technology or innovation assessment and prioritization:** by categorizing technologies and innovations according to their stage of development, the earliest time to mature, the earliest time to make a significant impact, and segregated impact on resilience, inclusivity and sustainability, this typology helps researchers, policymakers and investors to identify promising areas for investment and support. It can also be used to assess the risks and challenges associated with different technologies and innovations and to develop strategies for mitigating them.

- **Innovation ecosystem development:** the typology can be used to identify gaps and opportunities in the innovation ecosystem for agricultural technologies and innovations. By understanding the relationships between different categories of technologies and innovations, policymakers and stakeholders can develop targeted interventions to support the development and diffusion of pre-emerging and emerging technologies and innovations.

- **Policy development:** this typology can inform the development of policies and regulations related to new technologies and innovations in agrifood systems. By understanding the unique characteristics of different categories of technologies and innovations, including their developmental stage, purpose, pace of advancement, expected impact, interrelations with other technologies and innovations and potential for transformative and disruptive effects, policymakers can better tailor their policies to address the specific needs and challenges taking a system perspective. For instance, policies for pre-emerging and emerging technologies and innovations, which are still in development and may have uncertain outcomes, might focus on fostering research and development not at a single technology level but at an emerging field level, promoting collaboration and managing risks. Policies for well-established clusters might prioritize facilitating synergies and supporting inclusive upscaling. By considering the entire lifecycle of technologies and innovations and exploring system approaches, policymakers can create more effective and targeted policies that accelerate sustainable, resilient and inclusive agrifood systems.

The proposed framework consists of several steps, as elaborated below and shown in Figure 36.

Step 1: Identify **the problem to be solved**

Guiding question: Which agrifood system challenge should be addressed with the support of pre-emerging and emerging technologies and innovations?

- Clearly define the purpose:
  - address a specific challenge of the agrifood systems (Annex 1) or a holistic agrifood systems' transformation.
  - at a global or a regional (or country levels if data is available)

Step 2: Analyze **pre-emerging and emerging technologies and innovations against the purpose**

Guiding question: which technologies and innovations have the highest potential to address a given challenge?

Figure 36. Foresight-informed typology guiding – strategic decisions on pre-emerging and emerging technologies and innovations for impact

1	**Identify the problem to be solved** What agrifood system challenge do I need to address with the support of pre-emerging and emerging technologies and innovations?	• *Clearly define the purpose*
2	**Analyse pre-emerging or emerging technologies and innovations in relation to the purpose** Which technologies and innovations have the highest potential to address this specific challenge?	• *Identify relevant technologies and innovations* • *Assess their key characteristics*
3	**Analyse clusters** Which cluster do these technologies and innovations belong to? Are there additional technologies or innovations from the same cluster that can effectively address the challenge and share similar innovation ecosystems to strengthen ecosystem specialization?	• *Identify relevant technologies and innovations* • *Assess their key characteristics*
4	**Analyse emerging innovation fields** Are the identified technologies and innovations part of an emerging innovation field? If so, should additional mechanisms be established to address uncertainties? What combination of technologies and innovations can drive greater sustainability, resilience and inclusivity?	• *Determine cluster membership* • *Consider synergies* • *Evaluate ecosystem potential* • *Assess the innovation ecosystems*
5	**Analyse areas of application** What application areas does this technology or innovation cover, including unintended areas? Can this present a new market and niche innovation opportunities?	• *Identify emerging fields* • *Consider interdisciplinary aspects*
6	**Develop a strategic approach and act** How can we maximize opportunities and minimize challenges in facilitating innovation and value addition in a specific country, regional or stakeholder context? Are there regulatory or ethical implications, and what is the appropriate level to be address them?	• *Prioritize technologies* • *Invest in clusters and emerging fields* • *Foster interdisciplinary collaboration* • *Develop appropriate policies and regulations* • *Monitor and evaluate* • *Adapt as needed* • *Consider ethical implications*

- Identify relevant **technologies and innovations:** Use the typology to identify technologies and innovations that could potentially address the challenge.
- Assess their potential characteristics:
  - Use the foresight report to obtain experts'-based insights on:
    - Global relative advantage (overall or by challenge);
    - Earliest time to mature;
    - Earliest time to make a significant impact;
    - Trade-offs level;
    - Possible impacts on sustainability;
    - Possible impacts on resilience;
    - Possible impacts on inclusivity.
  - Use other sources to evaluate the potential impact of each technology on the challenge, considering factors like scalability and cost-effectiveness.

Step 3: Analyze **clusters**

Guiding questions: From which cluster are those technologies and innovations? Can more technologies and innovations from the same cluster successfully address the challenge? They would share one or similar innovation ecosystems. Hence, investments can be optimized, and ecosystem specialization can be strengthened.

- Determine cluster membership: Identify the clusters to which the selected technologies and innovations belong.
- Consider synergies: Explore how these technologies and innovations might interact and create synergies with others.
- Evaluate ecosystem potential: Assess the strength and potential of the innovation ecosystem within each cluster.
- Evaluate ecosystem potential: Assess the strength and potential of the innovation ecosystems within the emerging field.

Step 4: Analyze the **emerging innovation fields**

Guiding questions: are the identified technologies and innovations part of an emerging innovation field? If so, shall additional mechanisms be implemented to overcome uncertainties, such as monitoring and evaluation, regulation, multilateral governance and communications? What combination of technologies and innovations can boost a more significant change towards sustainability, resilience and inclusivity?

- Identify emerging fields: Determine if any technologies and innovations are part of emerging fields.
- Consider interdisciplinary aspects: Explore the potential for interdisciplinary collaboration and research to enhance the impact of the technologies and innovations.

Step 5: Analyze **areas of application**

Guiding questions: What application areas does this technology or innovation cover, including areas not intended primarily? Can this present a new market and innovation niche opportunities?

- Identify primary application areas: Determine the primary areas where the technologies and innovations can be applied to address the challenge.
- Consider secondary applications: Explore potential secondary applications and opportunities for diversified use of these technologies and innovations.
- Identify opportunities to optimize the innovation ecosystem readiness: Assess the readiness of the ecosystem to support the application of these technologies and innovations.

Step 6: Develop a **strategic approach and act**

Guiding question: How to maximize opportunities and minimize challenges in facilitating innovation and value addition in a specific country, region or stakeholder context? Are there regulatory or ethical implications, and what is the appropriate level to address them?

- Prioritize technologies and innovations: Based on the analysis, prioritize the technologies and innovations with the highest potential to address the challenge.
- Invest in clusters and emerging fields: Allocate resources to support developing and upscaling technologies and innovations within promising clusters and emerging fields.
- Foster interdisciplinary collaboration: Encourage collaboration between researchers and practitioners from different disciplines to maximize the impact of the technologies and innovations.
- Develop appropriate policies and regulations: Implement policies and regulations that support the responsible development and deployment of the technologies and innovations, considering ethical implications and potential risks.

- Monitor and evaluate: Continuously monitor the progress and impact of the selected technologies and innovations.
- Adapt as needed: Be prepared to adjust the strategy based on emerging trends, challenges, or opportunities.
- Consider ethical implications: Ensure that the development and deployment of the technologies and innovations are aligned with ethical principles and values.

In conclusion, we would like to highlight that current strategies often focus on developing and promoting individual technologies and innovations, with regulatory frameworks implemented reactively to address uncertainties or disruptions. This approach can be limiting, as technologies and innovations rarely emerge in isolation. The foresight-informed typology highlights the interconnectedness of technologies and innovations within clusters and emerging fields. By understanding these relationships, policymakers can shift their focus from supporting individual technologies and innovations to nurturing entire ecosystems. This involves allocating financial and policy resources not only to specific technologies and innovations but also to the broader clusters and emerging fields they belong to, fostering synergies and accelerating the development of transformative solutions.

10.2.2 Key transformations for key actions for shaping desirable futures in agrifood innovation

The report's insights and, in particular, the key transformations can serve as a valuable guide in shaping desirable futures for technologies and innovations in agrifood systems, helping stakeholders navigate the complexities of technological and innovation change and build a more sustainable, resilient and inclusive agrifood system.

This section provides additional insights to close the STI divide by leaving no one behind at the national level to operationalize the typology framework provided by the participants in our foresight exercises, collected through backcasting. The interplay between key transformations and key actions should naturally occur after the analyses suggested in the typology framework are completed and sufficient clarity and consensus on the strategic plan are achieved. The list of actions is, therefore, not exhaustive and contextual.

Key transformation:

- Ensure inclusive and participatory governance in agrifood innovation.

Key actions:

- Ensure evidence-based approach in decision-making.
- Balance between strategies for diversification and specialization in technologies and innovations (after analysis of the innovation ecosystems).
- Promote inclusive and interactive innovation by supporting participatory processes, experimentation, community-led initiatives and startups from marginalized communities.
- Facilitate partnerships between research institutions, civil society organizations, farmers, consumers, private sector businesses and local or indigenous communities.
- Engage and empower consumers, farmers and others interested in innovating but disempowered stakeholders through educational campaigns, transparent and fair labelling, skills and governance participation.

Key transformation:

- Address ethical and social dimensions of agrifood systems.

Key actions:

- Prioritize initiatives that emphasize social equity, inclusivity and the empowerment of marginalized communities.
- Encourage innovations that promote social justice and sustainable food production.
- Develop binding and/or non-binding instruments - guidelines, policies and regulations allow

innovation to be used by all shortly after it emerges while safeguarding social and environmental standards.

- Foster consensus through inclusive dialogues, including foresight.

Key transformation:

- Foster evidence-based, integrated, fit-for-purpose knowledge for agrifood system innovation.

Key actions:

- Diversify investment portfolios to include (according to the typology analysis) research on grassroots innovations, citizen science and Indigenous innovations.
- Promote interdisciplinary and interactive innovation that integrates multiple disciplines and stakeholder perspectives, including traditional knowledge with modern scientific approaches.
- Align investment priorities with the specific needs and challenges of different regions.

Key transformation:

- Create enabling environments through incentives and funding mechanisms.

Key actions:

- Rebalance investment priorities to address present and future societal needs.
- Establish funding mechanisms that support participatory processes, experimentation and inclusive innovation.
- Provide tax incentives or subsidies for citizens, farmers and businesses investing in pre-emerging and emerging technologies and innovations or sustainable practices.
- Create public-private partnerships to share risks, accountability and rewards.
- Explore crowdfunding for sustainability outcomes, including frugal innovation.

Key transformation

- Foster systemic change in agrifood systems.

Key actions:

- Develop massive capacity for change, including through UN2.0 capabilities.
- Create supportive and transformative policies and regulations, including decentralized decision-making, which is feasible and appropriate.
- Promote knowledge sharing and international and national collaboration.
- Embrace a long-term and adaptive approach.

10.2.3 How do we start? Recommendations for stakeholders of the global and local agrifood innovation systems

As implied above, stakeholders' attitudes and institutional frameworks that support them depend on the current innovation paradigm and the innovation process and development phases. However, to kick off meaningful changes, we need to engage in action that would bring us close to the desired outcome. This section provides a lens on explorative actions that would allow us to do things better for impact from the viewpoint of the current innovation paradigm dominated by a traditional institutional setup. Yet, new actors are emerging and, if proven impactful, may confiscate some of these functions, for example, public-private incubators and accelerators, innovation hubs, innovation support services and local multistakeholder approaches such as innovation policy labs, living labs, etc. We elaborate on national governmental actors as they are seen as the stakeholder group with the highest potential to drive innovation but too often choose not to exercise this power (FAO regional foresight exercises, FSN forum).

Representatives of different sectors of national institutions:

- **Align research agendas:** Conduct a comprehensive review of existing research and innovation agendas within their respective sectors (agriculture, livestock, fisheries, etc.). Identify areas where research priorities can better align with the agrifood systems' challenges outlined in the report, such as climate change, food security, gender equality and resource scarcity (see the typology-based framework above).

- **Strengthen technical and functional capacity:** Assess their departments' current technical and functional capacities (soft skills). Identify gaps in knowledge and skills related to pre-emerging and emerging technologies and innovations like AI, biotechnology and nanotechnology, nature-based innovations, functional capacities, such as facilitation, innovation management and brokerage, etc. Develop targeted training programmes or partnerships with research institutions to bridge these gaps.

- **Foster cross-sectoral collaboration:** Initiate dialogues and establish collaborative platforms with other national public and private institutions involved in food-related issues. This could include creating inter-ministerial working groups or task forces to address complex challenges that require a multi-sectoral approach.

Representatives of different sectors of subnational (national regions') institutions:

- **Contextualize technologies and innovations:** Identify in a participatory way pre-emerging and emerging technologies and innovations that are most relevant to the specific needs and challenges of their local communities. Consider factors like local resources, infrastructure and cultural practices when evaluating the suitability of different technologies and innovations.

- **Engage in pilot projects:** Co-create projects and initiatives with local farmers, businesses, or research institutions to implement pilot projects that test the feasibility and effectiveness of selected technologies and innovations in the local context. This could involve experimenting with digital tools, sustainable farming practices, or innovative food processing methods.

- **Develop local capacity:** Invest in training and education programmes for local farmers, entrepreneurs and community members to enhance their understanding, co-creation and adoption of new technologies and innovations. This could involve workshops, living labs, farmer field schools, innovation platforms/hubs, (and other hands-on and participatory solutions, demonstrations, or mentorship programmes that provide practical skills and knowledge.

High-level political representatives:

- **Champion innovation:** Advocate for policies and investments that promote innovation in the agrifood systems. This could involve allocating public funds to research and development, creating incentives for private-sector investment, or establishing regulatory frameworks supporting responsible design, development, testing and adaptation of pre-emerging and emerging technologies and innovations.

- **Promote public-private partnerships:** Encourage collaboration between the public and private sectors to accelerate the development and deployment of innovative solutions. This could involve creating platforms for dialogue, establishing joint research initiatives, or providing financial support for collaborative projects.

- **Raise awareness:** Communicate the importance of innovation in addressing agrifood challenges to the public and other stakeholders. This could involve public speeches, multilateral dialogue platforms, media campaigns, or educational initiatives highlighting the potential benefits or risks of pre-emerging and emerging technologies and innovations for food security, sustainability and economic growth. Such communication should not be unilateral but should trigger an open and transparent societal debate involving all the stakeholders about innovation needs, risks and potential impacts.

Cross-ministerial coordination structures:

- **Facilitate information sharing:** Establish mechanisms for regular information sharing and coordination among different ministries and departments involved in food-related issues. This could include creating shared databases, organizing inter-ministerial meetings, or developing communication protocols to ensure that relevant information is disseminated effectively.

- **Harmonize policies and regulations:** Identify and address inconsistencies or conflicts in policies and regulations across different sectors that may hinder the safe and responsible use of pre-emerging and emerging technologies and innovations. This could involve reviewing existing regulations, developing harmonized standards guidelines, or creating new policies that specifically address the unique challenges and opportunities of technologies and innovations in the agrifood systems.

- Review institutional structure that could create unnecessary duplications or gaps in mandates or trigger barriers to collaboration or resource competition.

- **Coordinate Resource Allocation:** Develop a coordinated approach to resource allocation for research, development and implementation of pre-emerging and emerging technologies and innovations. This could involve pooling resources from different ministries, prioritizing investments based on shared goals, or establishing joint funding mechanisms to support collaborative projects.

Statistical and other public knowledge/data-producing entities:

- **Enhance data collection:** Expand data collection efforts to include relevant indicators for monitoring the innovation processes, adoption and impacting pre-emerging and emerging technologies and innovations in the agrifood systems. This could involve collecting gender and age-disaggregated data on technology usage, productivity gains, environmental impacts and social outcomes.

- **Ensure data accessibility:** Make agrifood-related data accessible to researchers, policymakers and other stakeholders. This could involve creating open data platforms, developing user-friendly interfaces, or establishing data-sharing agreements to facilitate collaboration and informed decision-making.

- **Invest in data analysis:** Develop the capacity for advanced data analysis and modelling to derive insights from collected data. This could involve training staff in data science techniques, partnering with research institutions, or utilizing artificial intelligence and machine learning tools to identify trends, patterns and potential risks.

- Ensure effective data protection regulations and capacities of different stakeholders: In this sense including farmers.

Food-related technical units:

- **Monitor technological and innovation developments:** Stay informed about the latest advancements in pre-emerging and emerging technologies and innovations relevant to their areas of expertise (food safety, veterinary services, agricultural extension, etc.). This could involve attending conferences, workshops, collaborations, study tours, or subscribing to relevant publications and online resources.

- **Adapt technical services:** Update technical services and extension programmes to incorporate new technologies, innovations and best practices. This could involve developing training materials on precision agriculture techniques, providing guidance on the safe use of nanotechnology in food production, or offering support for implementing digital traceability systems. Equally important are capacities for participatory research, co-innovation approaches, etc.

- **Collaborate with research institutions and other relevant stakeholders:** Partner with research institutions and farmers to conduct field trials and pilot projects that evaluate the effectiveness of pre-emerging and emerging technologies and innovations in real-world settings. This could involve testing new crop varieties, evaluating the impact of precision irrigation systems, or assessing the safety of novel food processing methods.

Farmers and farmer organizations

- **Embrace innovation development and adoption:** proactively explore, co-create e and adopt non-technological innovations and pre-emerging and emerging technologies that align with their specific needs and local context. This could involve investing in precision agriculture tools, adopting sustainable farming practices, utilizing digital platforms for market access and knowledge sharing, and being receptive to agricultural extension services and other sources of knowledge.
- **Participate in capacity development programmes:** engage in training and education programmes offered by government agencies, extension services, civil society or private sector entities to enhance their skills and knowledge in utilizing new technologies and innovations effectively.
- **Collaborate and network:** actively participate in farmer organizations, cooperatives, or other collaborative networks to share experiences, exchange knowledge and collectively address challenges related to technology and non-technological innovation development and adoption.

For farmers to implement these actions, other stakeholders need to accomplish theirs.

Academia, extension and advisory services and research

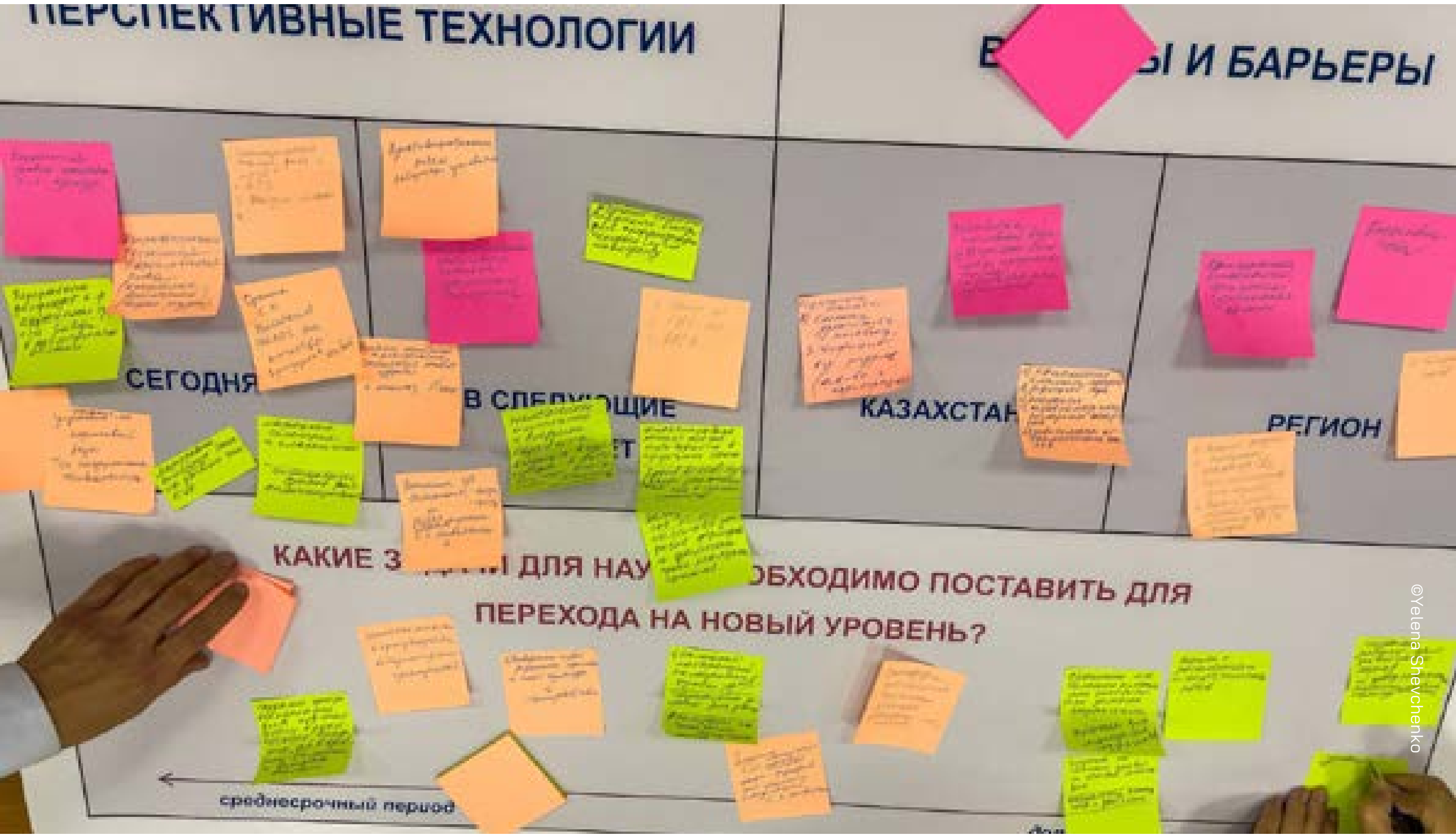
- **Align research with societal needs:** conduct research that directly addresses the pressing challenges agricultural producers and communities face, such as climate change adaptation, food security and sustainable resource management. Embrace future-oriented research goals and uncertainty about future hypotheses.
- **Bridge the knowledge gap:** develop and disseminate user-friendly, accessible information and training materials on pre-emerging and emerging technologies and innovations. This could involve creating online courses, conducting workshops, or establishing demonstration farms to showcase the practical applications of new technologies and innovations. At the same time, be open to the public debate and questions about the STI.
- **Foster collaboration:** establish strong partnerships with farmers, industry stakeholders and policymakers to ensure that research findings are translated into actionable solutions and policies that support innovation and sustainable agriculture.

Non-governmental and civil society organizations

- **Advocate for inclusive innovation:** promote policies and initiatives focusing on relevant and sustainable STI for smallholders and ensure equitable access to pre-emerging and emerging technologies and innovations for small-scale farmers, marginalized communities and vulnerable groups.
- **Empower communities:** implement capacity development programmes and awareness campaigns to educate communities about new technologies and innovations' potential benefits and risks. This enables them to make informed decisions and participate actively in the innovation processes and transformation of agrifood systems.
- **Monitor and evaluate impact:** conduct independent assessments of pre-emerging and emerging technologies and innovations' social, economic and environmental impacts, ensuring that they contribute to sustainable development and do not exacerbate inequalities or harm vulnerable populations.

Private sector companies

- **Invest in responsible use of innovations:** prioritize research and development investments in technologies and innovations that promote sustainability, resource efficiency and social inclusivity in the agri-food systems.
- **Collaborate with stakeholders:** engage in partnerships with farmers, research institutions and other stakeholders to co-create and test innovative solutions that address real-world challenges and meet the needs of diverse communities.



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- **Ensure ethical and transparent practices:** adopt ethical business practices and transparent communication regarding the development, technology ownership (including maintenance, data, etc.), deployment and potential impacts of new technologies and innovations, fostering trust and accountability among consumers and stakeholders.

Consumers

- **Make informed choices:** seek out and support products and brands that demonstrate a commitment to sustainability, ethical practices and the responsible use of technologies and innovations in the agri-food systems.
- **Demand transparency:** advocate for clear labelling and information about the production methods, environmental impact and social implications of food products, enabling consumers to make conscious choices that align with their values.
- **Engage in dialogue:** participate in public consultations, community-based initiatives like solidarity purchases and participatory guarantee schemes, surveys and feedback mechanisms to voice their concerns and preferences regarding the future of agrifood systems, contributing to a more inclusive and responsive decision-making process.

11

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Beyond strategic planning: striving transformative outcomes with new technologies and innovations in agrifood system. Recommendations

This foresight report illuminated a landscape rich with potential and brimming with challenges. We have explored the tapestry of pre-emerging and emerging technologies and innovations, emerging innovation fields, regional innovation pathways and paradigm shifts and planful of innovation actors, weaving a narrative of promise and potential. The collective wisdom of experts and stakeholders has identified a set of twenty technological and non-technological innovations poised to revolutionize the agrifood systems, making them more sustainable, resilient, and inclusive.

While perceptions may fluctuate influenced by various factors, the trends that emerged from this in-depth foresight process are undeniable.

Blended functions are required. To have a chance to keep its promise, the pre-emerging and emerging technologies or innovations must be efficient, democratic and sustainable at a time.

Need to prioritize non-technological solutions. Policy and organizational innovations, such as innovation policy labs, nature-based and frugal innovations, territorial value chains and consumer-to-food economies, stand out as fundamental tools for addressing the multifaceted challenges confronting the agrifood systems. These innovations not only optimize inputs but also catalyze transformative agendas, making them indispensable components of any challenge-oriented strategy.

Frugal and nature-based innovations, as well as emerging fields like grassroot innovations require closer look and ongoing observation. They are perceived as the best positioned to advance on resilience, sustainability and inclusivity but also are believed to have impact long after their maturity. More data and informed decisions on strategies to nurture them are to be considered.

Wise selection of technologies to start with. Among the technological innovations, geospatial technologies, and aerial robots and drones have emerged as frontrunners, offering significant potential with minimal trade-offs. The critical role of infrastructure and logistics in ensuring resilience, sustainability, and inclusivity has also been clearly highlighted, albeit with associated higher trade-offs.

Demand to capitalize on disruptive technologies struggles with innovation averse mindsets and delayed effective governance to minimize the tradeoffs: Artificial General Intelligence (AGI) and its potential evolution to Artificial Super Intelligence (ASI), quantum computing, synthetic biology, and environmental biotechnologies, while holding a disruptive potential, present higher trade-offs and may take longer to deliver on their promises. In addition to their potential to address challenges and drive paradigm shifts, these technologies, which often feature prominently in the top five solutions to global issues, are not perceived to fulfill their potential in the short term yet. Our foresight community of experts and stakeholders has signaled a concern that some regions and countries might miss important opportunities to capitalize on advanced biotechnologies.

The solution is not one and impact requires synergies. To achieve transformative outcomes, relying on a singular technology or top innovations does not suffice, despite their possible outperformance in addressing one or several challenges. Addressing challenges and advancing specific areas of application is a complex endeavor that demands an ecosystem approach. No single technology can serve as a silver bullet. Instead, the synergistic potential of technology and innovation clusters and emerging innovation fields, grouping PETIAS of the same nature or with higher interdisciplinary respectively, and that are adapted to specific contexts, holds the key to unlocking effective, sustainable, and inclusive transformation. While diversification can foster more relevant and resilient innovation products, specialization can also enhance excellence. However, the pace of technological and innovation emergence varies, and the time required to make an impact differs. The challenge lies in aligning technologies and innovations to achieve synergistic impacts, which necessitates careful consideration of trade-offs, while bringing them to a similar speed.

Innovation is a collective endeavor at all levels. Co-innovation is crucial for putting the innovation in a context and scaling up with broader and often sooner impacts. Inclusive partnerships and financing mechanisms involving the public sector, industry, consumers, farmer groups, and agencies are necessary, empowering local actors to co-innovate and co-create adapted solutions is key. This necessitates a thorough assessment of local, national and regional specificities, opportunities, and challenges. We have dived into regional perspectives in this report and found that:

- **the world is evolving at different speeds with respect to agrifood technologies and innovations** with regions like Europe and North America poised to realize the potential of pre—emerging and emerging technologies and innovations sooner. International and interregional cooperation is imperative, not merely for making technologies and innovations available, but developing local capacities, and ensuring mobility in science, technology and innovation;

- **enhanced international and multistakeholder collaboration,** especially with the Global South, is vital. Many technologies and innovations have originated elsewhere but may not be readily available in the Global South. Similarly, southern technologies and innovations can benefit from partnerships with other regions. Transformative partnerships, new governance and business models, repurposed investments, refocused research programs, and development support are essential.

Innovation is made by people, for people and with people. Innovation is inherently human-centered, involving the active participation of stakeholders. Their perspectives, challenges, and motivations, which we foresighted and projected in our scenarios are essential for driving the emergence and impact of innovations. We shall strive to equitably empower and motivate all stakeholder groups to actively be promoters of innovation – technological, social, policy, financial and institutional, avoiding "innovation fatigue" or innovation aversity.

In future, a non-human innovation stakeholder (AGI/ASI) may arise and play influential role. Future strategies may need to understand and manage its perspectives. This report elaborated future scenarios, where AI is an independent stakeholder or AI augments other stakeholders' capabilities.

Aligning research and innovation agendas with societal development challenges is crucial to ensure that new technologies and innovations fulfill their roles and expectations. Strengthening technical and functional capacities is essential for understanding, anticipating, and managing the increasing complexity and uncertainties within the agrifood systems. Democratizing access to science, technology, and innovation ensures that all, including vulnerable groups, can benefit from proposed solutions.

Innovation pathways are not linear. A helical model reflects the dialectical interplay between periods of rapid growth and periods of consolidation, leading to an innovation leap. During the rapid phase, new knowledge is accumulated, and the progress of research and innovation is incentivized with pull mechanisms.
A deep science-policy-society interface happen during the stabilization phase. Purposely altering rapid and stable phases more frequently may accelerate achieving maturity and impact and achieve transformative outcomes. This is the essence of co-innovation that approximates innovation space and time in a participatory manner. It calls to strategic actions.

Supporting innovation with foresight-informed strategies is paramount to bridge stakeholder, regional, and income-related divides. A key element of any strategy is to bridge the divide between technology and innovation maturity and impact by strengthening local human and social capital, at all levels and everywhere. Prioritizing the most impactful ones, while ensuring conducive conditions for others to mature and ensuring preparedness are essential steps. Understanding the drivers, triggers, trends, and wildcards, which this report offered, is a powerful tool to shape the emergence and uptake of these technologies and innovation. Managing rapid and stable phases of innovation is key. Monitoring the performance, outcomes, and impacts of pre-emerging and emerging technologies and innovations, along with other factors, is essential for informing decisions regarding economic, agronomic, environmental, social, and cultural results or potential risks.

Creating conducive environments is crucial for reducing the emergence phase of technologies and innovations and ensuring a reorientation towards more sustainable, resilient, and inclusive patterns. This includes policy incentives, intellectual property rights, repurposed investments, and refocused research programs. Efficient governance and coordination mechanisms are also necessary.

A joint vision of our preferred future for emergence and impact of technologies and innovations, centered on sustainability, resilience and equity, mission oriented-AISs and closing the STI gap has been developed to set up the goals and strive achievement. Despite our preferred vision, uncertainties persist, necessitating a consideration of different scenarios for resilience. Strategic actions, considering alternative plausible futures are needed throughout the whole process of innovation, starting from its inception to create preparedness and mitigate trade-offs.

We must strive for transformative outcomes that address the deep-rooted challenges of the agrifood systems innovation that would imply exceeding from the current paradigm in which STI gap persists. Five key transformation areas have emerged: governance and participation, ethics and social considerations, fit-for-purpose knowledge, incentives and funding, and fostering systemic changes and a pivotal for paradigm shifts. New research and innovation paradigm shifts (RIPS) arose that propose diverse pathways to address the transformation.

We focused on the following RIPS: converging technologies, AI and quantum computing, biomimicry, open innovation, citizen science, geoengineering, on-farm agrifood system, and pandemics.

Finally, in this report, we would like to stress on two transversal themes that emerged in most of the studies and are discussed horizontally across chapters: **multilateral governance** and the **rise of the AI.**

Effective and multilateral innovation governance is crucial for maximizing benefits and minimizing trade-offs for all stakeholders at a time. Participatory and multilateral governance models are on the rise but require skills, time, and shared responsibility. Such models are essential for maximizing benefits and minimizing trade-offs, empowering and motivating stakeholders. This domain itself calls for innovation.

Artificial Intelligence (AI) stands as a pivotal force in the agrifood systems landscape, emerging as a top-tier technology for addressing a multitude of challenges. Its potential is immense, spanning from optimizing resource allocation and enhancing production efficiency to improving food safety and reducing waste. AI's capabilities extend across various emerging innovation fields, making it a key player in driving transformative paradigm shifts. As a prominent stakeholder in numerous future scenarios, AI poses the imperative to address drawbacks and concerns about false promises and drive the use of the technology for impact in agrifood systems. However, the successful integration of AI requires robust data infrastructure, effective governance mechanisms, and a deep understanding of social and behavioral sciences.

In conclusion, this foresight report offers a roadmap for navigating the complex landscape of pre-emerging and emerging technologies and innovations in the agrifood systems. By fostering collaboration, embracing diverse approaches, and addressing the challenges and opportunities head-on, we can harness the transformative potential of these innovations to create a more sustainable, resilient, and inclusive future for all.

12

Ways forward: a call to action for shaping the future of technology and innovation in agrifood systems

12.1 FROM INTELLECTUAL EXERCISE TO TRANSFORMATIVE ACTION

In the age of polycrisis, navigating the complex challenges and exciting opportunities facing agrifood systems requires a forward-looking approach. This foresight report is more than just an intellectual exercise; it is a call to action. To truly shape the future of agrifood systems, we must move beyond analysis and towards implementation. This report provides insights, practical tools, and frameworks that can inspire further integration of foresight in our visions and planning. Foresight is not a standalone exercise and must rest on and be complemented with a solid data and evidence foundation.

The next steps are integrating foresight into our strategies, reorienting research agendas, repurposing funding, and reimagining institutions and policies, we can harness the power of pre-emerging and emerging technologies and innovations to drive transformative change.

12.2 RETHINKING RESEARCH AGENDAS: A FOCUS ON PRE-EMERGING AND EMERGING TECHNOLOGIES AND INNOVATIONS

As the landscape of agrifood systems continues to evolve, it is imperative that our research agendas reflect the latest trends in pre-emerging and emerging technologies and innovations. We must ensure that the research efforts are aligned with the most pressing challenges and opportunities and are oriented towards achieving tangible impact on resilience, sustainability and inclusion in the agrifood systems.

12.3 REPURPOSING FUNDING: INVESTING IN THE FUTURE

To effectively drive innovation towards sustainable, inclusive and resilient outcomes, we must strategically allocate resources. We need to repurpose funding towards pre-emerging and emerging technologies and innovations and innovation ecosystems that can effectively address agrifood challenges, facilitate system gains within the agrifood systems, and help integrate social and behavioural sciences into the entire innovation processes with focus on the stabilization phases. Investing in policy innovation is a niche to be explored. This requires a shift in mindset, away from reactive decision-making, towards anticipatory actions benefiting both present and future generations.

12.4 REIMAGINING INSTITUTIONS AND CAPACITIES: BUILDING FOR THE FUTURE

The institutions and capacities within the agrifood systems must be reimagined to meet the challenges emerging from transiting institutional silos to interactive and open multi-actor innovation. Foresight shall become the key approach in this endeavor. By investing in human and social capital, fostering collaboration, and promoting innovation mindsets, we can create a more agile and responsive agrifood systems that are capable of adapting to change.

12.5 RESHAPING POLICY SPACES: CREATING AN ENABLING ENVIRONMENT

Policy plays a critical role in shaping the future of technology and innovation in agrifood systems. Enabling environment must be created in support of both the rapid and stable innovation phases, implementing paradigm shifts and key transformations. This will require innovative approaches that are both dynamic and predictable. The emerging trend of democratizing science, technology and innovation[2] would require specific policy action and may imply tangible and innovative multistakeholder participation in policy making. Reviewing and reorienting existing policies, we can create an enabling environment that supports co-innovation, targeted investment, and sustainable development. This requires a proactive approach that anticipates future trends and addresses emerging challenges.

12.6 HARNESSING UN2.0 CAPABILITIES: A POWERFUL TOOL FOR CHANGE

UN2.0 capabilities offer a powerful tool for driving innovation and transformation within the agrifood systems. By leveraging data, digital technologies, innovation, foresight and behavioral science, UN2.0 can help remove barriers to innovation, engage stakeholders, and create more inclusive and equitable agrifood systems.

12.7 A CALL TO ACTION

The future of agrifood systems is in our hands. By integrating foresight into our strategies, reorienting research agendas, repurposing funding, reimagining institutions and policies, and harnessing UN2.0 capabilities, we can create more sustainable, resilient, and inclusive agrifood systems for generations to come.

FAO has embraced foresight in its Strategic Framework 2022-31 and its global innovation model by incorporating FutureFood-I Labs that use foresight to observe trends and zoom on specific innovation domains such as reimagining extension and advisory services, agroecological transitions, gender, and regional innovation dimensions. The labs develop foresight capacities, create partnerships and make tangible impact in countries through Innovation Policy Labs.

Let us embrace the foresight opportunity and take bold action to shape the future we want.

This theme will be further elaborated in the FAO publication Agrifood systems Technology and Innovation Outlook (ATIO) in 2025.

ANNEX 1.
EIGHT AGRIFOOD SYSTEMS CHALLENGES

Challenges	Description
A1. Population and development dynamics, food and nutrition security, sustainable diets	• World population is expected to increase to 9.6 billion by 2050 and 75 percent to live in the urban areas. • Agriculture underpins the livelihoods of over 2.5 billion people – most of them in LMICs and remains a key driver of development. • Between 702 and 828 million people were affected by hunger in 2021. The number has grown by about 150 million since the outbreak of the COVID-19 pandemic – 103 million more people between 2019 and 2020 and 46 million more in 2021. • Nearly 670 million people will still be facing hunger in 2030 – 8 percent of the world population, which is the same as in 2015 when the 2030 Agenda was launched. • To feed 9.7 billion people in 2050, crop production would need to be 50 percent higher compared to a 2013 baseline, while demand for animal-based foods, coupled with the rapid urbanization in sub-Saharan Africa and South Asia and the income growth in low and mid-income countries, is projected to increase by nearly 70 percent.
A2. Climate change and disaster risks	• Climate change is already affecting agriculture and food security through rising temperatures, changing precipitation patterns and a greater frequency of extreme weather and climate events. 21–37 percent of total greenhouse gas emissions are attributable to the agrifood systems. 82 percent of all damage and loss caused by drought was absorbed by agriculture in low- and lower-middle income countries.
A3. Erosion of natural resource base, loss of biodiversity	• Deforestation, mainly driven by agricultural land expansion, is linked to outbreaks of zoonotic and vector-borne diseases; increasing water scarcity, land degradation and desertification. • Globally, species extinction risk has worsened by about 10 percent over the last three decades. Nearly a third of fish stocks are overfished and a third of freshwater fish species assessed are considered threatened.
A4. Food loss and waste	• Approximately 14 percent of the world's food is lost on an annual basis between harvest and the retail market and an estimated 17 percent of food is wasted at the retail and consumer levels.
A5. Energy demand and use in agrifood systems	• 70 percent of the energy consumed by agrifood systems occurs after food leaves farms, in transportation, processing, packaging, shipping, storage and marketing, and is unsustainable. The challenge is to decouple the development of efficient and inclusive food chains from the use of fossil energy, without hampering food security.
A6. Inclusion of the most vulnerable	• Food insecurity, poverty, income inequalities and the lack of employment opportunities reinforce each other in a vicious cycle by eroding human capital and decreasing labour productivity, thereby perpetuating poverty and social inequalities across generations. In sub-Saharan Africa and South Asia, the youth population is rising fast but has poor access to land and productive resources and lacks decent work opportunities, causing internal and international migration. Fair income earning opportunities and the realization of the right to decent work are therefore key. • Gender inequality in agriculture stifles productivity growth and threatens food security. Feminization of agriculture due to adoption of labour-saving technologies and better opportunities for men to join other sectors, continues to grow and is particularly high in Near East and North Africa. • Digital technologies are slowly spreading in agrifood systems globally. But their adoption is hampered by the digital divide, particularly sharp in rural areas and affecting women. Availability, affordability and access to technologies is also a major challenge. • It is vital to address the root causes of distress migration from rural areas. • Smallholders and indigenous populations must be empowered and their rights to resources and food protected.
A7. Transboundary and emerging agrifood systems threats	• With globalization and climate change, the risks to crops and livestock are increasing and jeopardize food safety. • Zoonotic diseases and antimicrobial resistance pose a growing threat to human health. More than 70 percent of infectious diseases that have emerged in humans since the 1940s can be traced back to animals, including wildlife.
A8. National and international governance	• There should be fair international commercial agreements that prevent food dumping in developing countries' markets and natural resources extraction, while incentivize local food production and processing. • There must be fair and transparent governance of digital technologies and data, including privacy. It is key to protect the rights of the most vulnerable populations. • Effective, coherent and implementable agricultural and rural development policies are needed. • Responsible investments principles and fair contract farming conditions must be met. • Strengthened agricultural innovation systems and innovation capacities should be developed.

**Adapted from FOFA (FAO, 2017)*

ANNEX 2.
20 PETIAS: GLOBAL RELATIVE ADVANTAGE AND TRADE-OFFS LEVELS

The list below includes the top 20 most promising agrifood pre-emerging and emerging technologies and innovations, based on their relative advantage assessed in the Real-time Delphi, also presenting an additional qualitative indication on the level of trade-offs that need to be acknowledged should this technology be prioritized. Trade-off levels depend on the externalities of maturing a given technology or innovation. A lower trade-off level is better, meaning lesser negative externalities can be identified.

Table 6. Global relative advantage score of pre-emerging and emerging technologies and innovations

Pre-emerging and emerging technology/innovation	Global Relative Advantage score	Trade-off level
Nature-based and ecosystem innovations	6.76	Low
Artificial General Intelligence in agriculture	6.54	Medium
Agricultural innovation policy labs	6.48	Low
Energy storage technologies	6.46	Medium
Social impact bonds	6.26	Low
Realtime satellite imagery, positioning systems and autonomous GIS	6.20	Medium
6–10G connectivity in agrifood systems	6.17	High
Environmental biotechnologies	6.11	Medium
Synthetic biology	6.09	Medium
Ensuring access to science-based information on sustainability matters	5.99	Low
Internet of Food	5.97	Medium
Frugal innovation	5.95	Low
Digital twins	5.92	High
Quantum internet and computing applied to agrifood systems	5.91	Medium
Aerial robotics and drones	5.89	High
New methods for controlling gene expression	5.87	Medium
Global logistics network	5.82	Medium
Territorial or landscape value chain and food-to consumer economy policies	5.66	Low
Carbon credits in agriculture and aquaculture	5.56	Medium
Nanomaterials for water technologies	5.41	Medium

ANNEX 3. OVERVIEW OF PETIAS, CLUSTERS, CHALLENGES AND AREAS OF APPLICATIONS

					Estimated timeframe to significant impact											
Each of the 32 pre-emerging and emerging technologies and innovations	Cluster that it belongs	Global	Relative advantage	Trade-off level	Asia and Pacific	Europe and Central Asia	Latin America	North America	Northern Africa and Near East	Sub Saharan Africa	Asia and Pacific	Europe and Central Asia	Latin America	North America	Northern Africa and Near East	Sub Saharan Africa
Nature-based and ecosystem innovations	Policy innovation	2036	6.76	Low	3.86	3.41	3.91	3.90	4.14	4.44	2037	2035	2037	2038	2038	2040
Artificial General Intelligence in agriculture	Advanced digital technologies	2035	6.54	Medium	4.09	3.39	4.36	3.18	4.91	5.00	2038	2034	2039	2034	2042	2043
Agricultural innovation policy labs	Policy innovation	2035	6.48	Low	3.83	3.13	3.82	3.52	4.23	4.00	2037	2033	2037	2035	2039	2038
Energy storage technologies	New energy & transportation	2038	6.46	Medium	3.87	3.09	4.00	3.00	4.32	4.52	2037	2033	2038	2033	2039	2041
Social impact bonds	Financial and social innovations	2036	6.26	Low	4.09	3.09	3.95	3.14	4.59	4.42	2039	2033	2038	2034	2041	2040
Real-time satellite imagery, positioning systems and autonomous GIS	Advanced geospatial technologies	2036	6.20	Medium	3.29	2.61	3.64	2.48	3.86	4.06	2034	2031	2036	2030	2037	2038
6–10G connectivity in agrifood systems	Advanced digital technologies	2043	6.17	High	3.43	3.04	3.77	2.77	4.14	4.39	2035	2033	2036	2031	2038	2040
Environmental biotechnologies	Advanced biotechnologies	2043	6.11	Medium	3.35	3.17	3.68	2.77	4.05	4.33	2035	2034	2036	2032	2038	2039
Synthetic biology	Advanced biotechnologies	2046	6.09	Medium	4.09	3.83	4.05	3.41	4.59	4.69	2039	2037	2038	2035	2041	2041
Access to science-based information on sustainability matters	Policy innovation	2040	5.99	Low	3.43	2.35	3.41	2.73	3.73	3.88	2035	2030	2035	2032	2036	2037
Internet of Food	Advanced digital technologies	2042	5.97	Medium	3.39	2.65	3.45	2.50	4.00	4.23	2035	2031	2035	2030	2037	2039
Frugal innovation	Policy innovation	2034	5.95	Low	3.39	2.96	3.50	3.41	3.82	3.72	2035	2033	2035	2035	2037	2037
Digital twins	Advanced digital technologies	2045	5.92	High	3.57	3.00	3.59	2.82	3.95	4.19	2036	2033	2036	2032	2037	2039
Quantum Internet and computing applied to agrifood systems	Advanced digital technologies	2047	5.91	Medium	4.22	3.78	4.55	3.59	4.64	4.91	2039	2037	2041	2036	2041	2043
Aerial robotics and drones	Advanced digital technologies	2040	5.89	High	2.70	2.17	3.09	1.82	3.23	3.81	2031	2028	2033	2027	2034	2037
New methods for controlling gene expression	Advanced biotechnologies	2046	5.87	Medium	3.70	3.35	3.77	2.68	4.14	4.28	2036	2034	2036	2031	2038	2039
Global Logistics Network	New energy & transportation	2042	5.82	Medium	3.36	2.68	3.71	2.62	4.10	4.19	2035	2031	2036	2031	2038	2039
Territorial or landscape value chain and food-to-consumer economy policies	Policy innovation	2034	5.66	Low	2.96	2.48	3.50	3.18	3.82	3.84	2033	2030	2035	2034	2037	2037
Carbon credits in agriculture and aquaculture	Financial and social innovations	2034	5.56	Medium	3.65	2.95	3.77	3.00	4.27	4.26	2036	2033	2037	2033	2039	2039
Nanomaterials for water technologies	Micro-, nanotechnology & nanobiotech	2042	5.41	Medium	3.65	3.30	3.95	3.09	4.41	4.59	2036	2034	2038	2033	2040	2041

* already achieved=1, before 2030=2, before 2035=3, before 2040=4, before 2045=5, before 2050=6, beyond 2050=7. Calculate the average.

* already achieved=2024, before 2030=2027, before 2035=2032.5, before 2040=2037.5, before 2045=2042.5, before 2050=2047.5, beyond 2050=2055. Calculate the average.

Novel biomass energy	New energy & transportation	2035	5.40	
RNA interference	Advanced biotechnologies	2045	5.24	
Artificial neurons	Advanced digital technologies	2051	5.19	
Metaverse, virtual reality and augmented reality	Advanced digital technologies	2046	4.90	
Novel pesticides, fertilizers, antibiotics incl. nanotechnology substances	Micro-, nanotechnology & nanobiotech	2042	4.82	
Nanomaterials for food packaging	Micro-, nanotechnology & nanobiotech	2041	4.76	
Nanorobotics	Micro-, nanotechnology & nanobiotech	2047	4.72	
Nuclear fusion	New energy & transportation	2052	4.49	
Personalized nutrition	Food manufacturing technologies and nutrition	2047	4.42	
Teleportation of complex molecules	New energy & transportation	2063	4.17	
4D nanoscale printing	Food manufacturing technologies and nutrition	2053	3.54	
3D printing of food and liquids	Food manufacturing technologies and nutrition	2052	3.30	

ANNEX 4. TABLE OF PETIAS ADDRESSING AGRIFOOD SYSTEMS' CHALLENGES

max RA/challenge (the highest improvement in the ablility to addresss the challenge out of all the analysed PETIAS)

Most impactful technology or innovation per challenge

Technologies and innovations addressing the challenge (relative advantage)

cluster (average relative advantage)

Agrifood systems challenges				cluster		Emerging fields
Inclusion of the most vulnerable	Nature-based and ecosystem innovations	7,32	4,98	Advanced biotechnologies	5.17	• Circular agriculture; Web 3.0; • Grassroot Innovation in agrifood systems; • Nature-positive agriculture; • Metaverse in agriculture (agriverse)
				Advanced digital technologies	4.65	
				Advanced geospatial technologies	4.95	
				Policy innovation	5.75	
				New energy & transportation	3.11	
				Financial and social innovations	4.25	
				Food manufacturing technologies and nutrition	4.98	
				Micro-, nanotechnology & nanobiotech	6.77	
Transboundary and emerging agrifood systems threats	Artificial General Intelligence in agriculture	6,84	5,37	Advanced biotechnologies	5.84	• Metaverse in agriculture (agriculture); • Omics-based tailored solutions; • Next-gen gene editing; Web 3.0; • Precision Agrifood Systems; • Molecular computers in agrifood systems
				Advanced digital technologies	5.89	
				Advanced geospatial technologies	6.45	
				Policy innovation	5.32	
				New energy & transportation	3.52	
				Financial and social innovations	5.05	
				Food manufacturing technologies and nutrition	5.04	
				Micro-, nanotechnology & nanobiotech	5.69	
National and international governance	Agricultural innovation policy labs	7,71	4,81	Advanced biotechnologies	4.22	• Web 3.0; Grassroot Innovation in agrifood systems; • Molecular computers in agrifood systems
				Advanced digital technologies	5.13	
				Advanced geospatial technologies	5.32	
				Policy innovation	5.97	
				New energy & transportation	3.36	
				Financial and social innovations	3.89	
				Food manufacturing technologies and nutrition	4.78	
				Micro-, nanotechnology & nanobiotech	5.85	

Areas of application related to the challenge	RIPS
• Production systems; • Processing systems; • Value chains and services; • Energy and transportation; • Food waste; • Governance and trade; • One health and nutrition; • Inclusion of the most vulnerable	• Convergence; • Geoengineering, modification of weather and climate; • The development of quantum computers and the emergence of AGI; • The agrifood farm
• Production systems; • Processing systems; • Value chains and services; • Energy and transportation; • Governance and trade; • New materials, new proteins and circular economy; • One health and nutrition; • Blue economy; Inclusion of the most vulnerable	• Convergence; Geoengineering, modification of weather and climate; • The development of quantum computers and the emergence of AGI; • The agrifood farm
• Production systems; • Processing systems; • Value chains and services; • Energy and transportation; • Food waste; • Governance and trade; • New materials, new proteins and circular economy; • One health and nutrition; • Blue economy; • Inclusion of the most vulnerable	• Convergence; Geoengineering, modification of weather and climate; • The development of quantum computers and the emergence of AGI; • The agrifood farm

ANNEX 5. TABLE OF AREAS OF APPLICATION

max RA/challenge (the highest improvement in the ablility to addresss the challenge out of all the analysed PETIAS)

Most impactful technology or innovation per challenge

Technologies and innovations addressing the challenge (relative advantage)

cluster (average relative advantage)

Agrifood systems challenges				cluster		Emerging fields
Population and development dynamics, food and nutrition security, sustainable diets	Synthetic biology	7.59	6.18	Advanced biotechnologies	7.01	• Omics-based tailored solutions; • Vertical farming; Circular agriculture; Molecular Computers in Agrifood Systems; • Next-gen gene editing; Web 3.0; • Nature-positive agriculture
				Advanced digital technologies	6.25	
				Advanced geospatial technologies	7.09	
				Policy innovation	6.09	
				New energy & transportation	4.78	
				Financial and social innovations	6.11	
				Food manufacturing technologies and nutrition	5.56	
				Micro-, nanotechnology & nanobiotech	6.78	
Climate change and disaster risks	Nature-based and ecosystem innovations	7.68	5.98	Advanced biotechnologies	6.51	• Molecular Computers in Agrifood Systems; • Omics-based tailored solutions; • Vertical farming; • Circular agriculture; • Next-gen gene editing; • Web 3.0; • Nature-positive agriculture
				Advanced digital technologies	6.49	
				Advanced geospatial technologies	7.68	
				Policy innovation	6.60	
				New energy & transportation	3.54	
				Financial and social innovations	5.11	
				Food manufacturing technologies and nutrition	6.02	
				Micro-, nanotechnology & nanobiotech	6.29	
Erosion of natural resource base, loss of biodiversity	Nature-based and ecosystem innovations	7.74	5.51	Advanced biotechnologies	6.04	• Omics-based tailored solutions; • Vertical farming; • Circular agriculture; • Molecular Computers in Agrifood Systems; • Next-gen gene editing; • Nature-positive agriculture
				Advanced digital technologies	6.10	
				Advanced geospatial technologies	7.64	
				Policy innovation	6.34	
				New energy & transportation	3.52	
				Financial and social innovations	4.80	
				Food manufacturing technologies and nutrition	4.32	
				Micro-, nanotechnology & nanobiotech	6.32	
Food loss and waste	Artificial General Intelligence in agriculture	7.13	5.57	Advanced biotechnologies	5.84	• Omics-based tailored solutions; • Circular agriculture; • Nature-positive agriculture
				Advanced digital technologies	6.01	
				Advanced geospatial technologies	4.68	
				Policy innovation	5.03	
				New energy & transportation	4.84	
				Financial and social innovations	5.48	
				Food manufacturing technologies and nutrition	5.12	
				Micro-, nanotechnology & nanobiotech	6.01	
Energy demand and use in agrifood systems	Energy storage technologies	8.25	5.59	Advanced biotechnologies	6.00	• Vertical farming; • Circular agriculture; • Nature-positive agriculture;
				Advanced digital technologies	5.98	
				Advanced geospatial technologies	5.82	
				Policy innovation	6.19	
				New energy & transportation	3.32	
				Financial and social innovations	4.75	
				Food manufacturing technologies and nutrition	6.30	
				Micro-, nanotechnology & nanobiotech	5.65	

Areas of application related to the challenge	RIPS
• Production systems; • Processing systems; • Value chains and services; • Energy and transportation; • Food waste; • Governance and trade; • New materials, new proteins and circular economy; • One health and nutrition; • Blue economy; • Inclusion of the most vulnerable	• Convergence; • Biomimicry; • Open- and open-source innovation; • Citizen science; • The development of quantum computers and the emergence of AGI; • Onset of recurrent plant or veterinary disease pandemic on key species; • The agrifood farm
• Production systems; • Processing systems; • Value chains and services; • Energy and transportation; • Food waste; • Governance and trade; • New materials, new proteins and circular economy; • One health and nutrition; • Blue economy; Inclusion of the most vulnerable	• Convergence; Biomimicry; • Open- and open-source innovation; • Citizen science; • Geoengineering, modification of weather and climate; • The development of quantum computers and the emergence of AGI; • The agrifood farm
• Production systems; • Processing systems; • Value chains and services; • Food waste; • Governance and trade; • New materials, new proteins and circular economy; • One health and nutrition; • Blue economy	• Convergence; Biomimicry; Open- and open-source innovation; Citizen science; Geoengineering, modification of weather and climate; The development of quantum computers and the emergence of AGI; Onset of recurrent plant or veterinary disease pandemic on key species
• Production systems; Processing systems; • Value chains and services; • Energy and transportation; • Food waste; Governance and trade; • New materials, new proteins and circular economy; • One health and nutrition; Blue economy; • Inclusion of the most vulnerable	• Convergence; Biomimicry; • Open- and open-source innovation; • Citizen science; • The development of quantum computers and the emergence of AGI; • Onset of recurrent plant or veterinary disease pandemic on key species; • The agrifood farm
• Production systems; • Processing systems; • Value chains and services; • Energy and transportation; • Food waste; Governance and trade; • New materials, new proteins and circular economy; • One health and nutrition; • Blue economy; • Inclusion of the most vulnerable	• Convergence; Geoengineering, modification of weather and climate; • The development of quantum computers and the emergence of AGI; • The agrifood farm

Areas of application	Cluster	PETIAS
Production systems	Advanced biotechnologies	Synthetic biology; RNA interference; new methods for controlling gene expression; Environmental biotechnologies
	Advanced digital technologies	6–10G connectivity in agrifood systems; aerial robotics and drones; Artificial General Intelligence in agriculture; digital twins; Internet of Food; quantum internet and computing applied to agrifood systems; artificial neurons
	Advanced geospatial technologies	Real-time satellite imagery, positioning systems and autonomous GIS
	Policy innovation	Agricultural innovation policy labs; territorial or landscape value chain and food-to-consumer economy policies; access to science-based information on sustainability matters; nature-based and ecosystem innovations; frugal innovation
	New energy & transportation	Novel biomass energy; energy storage technologies; teleportation of complex molecules
	Financial and social innovations	Carbon credits in agriculture and aquaculture; social impact bonds
	Food manufacturing technologies and nutrition	4D nanoscale printing; personalized nutrition
	Micro-, nanotechnology & nanobiotech	Nanorobotics; nanomaterials for water technologies; novel pesticides, fertilizers, antibiotics incl. nanotechnology substances
Processing systems	Advanced biotechnologies	Synthetic biology
	Advanced digital technologies	6–10G connectivity in agrifood systems; aerial robotics and drones; Artificial General Intelligence in agriculture; digital twins; quantum internet and computing applied to agrifood systems; artificial neurons
	Advanced geospatial technologies	/
	Policy innovation	Nature-based and ecosystem innovations; agricultural innovation policy labs; access to science-based information on sustainability matters; frugal innovation; territorial or landscape value chain and food-to-consumer economy policie
	New energy & transportation	Novel biomass energy; energy storage technologies
	Financial and social innovations	Carbon credits in agriculture and aquaculture
	Food manufacturing technologies and nutrition	3D printing of food and liquids; 4D nanoscale printing; personalized nutrition
	Micro-, nanotechnology & nanobiotech	Nanorobotics; nanomaterials for food packaging
Value chains and services	Advanced biotechnologies	/
	Advanced digital technologies	6–10G connectivity in agrifood systems; aerial robotics and drones; Artificial General Intelligence in agriculture; digital twins; internet of food; quantum Internet and computing applied to agrifood systems
	Advanced geospatial technologies	Real-time satellite imagery, positioning systems and autonomous GIS
	Policy innovation	Agricultural innovation policy labs; territorial or landscape value chain and food-to-consumer economy policies; access to science-based information on sustainability matters; Nature-based and ecosystem innovations; frugal innovation
	New energy & transportation	Global logistics network; energy storage technologies
	Financial and social innovations	Carbon credits in agriculture and aquaculture; social impact bonds
	Food manufacturing technologies and nutrition	Personalized nutrition
	Micro-, nanotechnology & nanobiotech	Nanomaterials for food packaging
Energy and transportation	Advanced biotechnologies	Environmental biotechnologies; synthetic biology; new methods for controlling gene expression; RNA interference
	Advanced digital technologies	Artificial General Intelligence in agriculture; 6–10G connectivity in agrifood systems; Internet of Food; digital twins; quantum internet and computing applied to agrifood systems; aerial robotics and drones
	Advanced geospatial technologies	Real-time satellite imagery, positioning systems and autonomous GIS
	Policy innovation	Nature-based and ecosystem innovations; agricultural innovation policy labs; access to science-based information on sustainability matters; territorial or landscape value chain and food-to-consumer economy policies
	New energy & transportation	Energy storage technologies; global logistics network; novel biomass energy; nuclear fusion; teleportation of complex molecules
	Financial and social innovations	Social impact bonds; carbon credits in agriculture and aquaculture
	Food manufacturing technologies and nutrition	3D printing of food and liquids
	Micro-, nanotechnology & nanobiotech	/

		Estimated timeframe to significant impact					
Relative advantage	Earliest time to mature	Asia and Pacific	Europe and Central Asia	Latin America	North America	Northern Africa and Near East	Sub Saharan Africa
5.66	14 PETIAS mature in 2040s, 10 PETIAS mature in 2030s, 2 PETIAS mature in 2050s, 1 PETIAS mature in 2060s.	before 2035/2040	before 2035/2040	before 2035/2040	mostly before 2035	mostly before 2040	way in the future (before 2045/2040)
5.54	9 PETIAS mature in 2040s, 8 PETIAS mature in 2030s, 3 PETIAS mature in 2050s.	before 2035/2040	before 2035/2040	before 2035/2040	mostly before 2035	mostly before 2040	way in the future (before 2045/2040)
5.93	9 PETIAS mature in 2040s, 9 PETIAS mature in 2030s.	before 2035/2040	mostly before 2035	before 2035/2040	mostly before 2035	mostly before 2040	mostly before 2040
5.75	11 PETIAS mature in 2040s, 9 PETIAS mature in 2030s, 2 PETIAS mature in 2050s, 1 PETIAS mature in 2060s.	before 2035/2040	mostly before 2035	mostly before 2040	mostly before 2035	mostly before 2040	way in the future (before 2045/2040)

Areas of application	Cluster	PETIAS
Food waste	Advanced biotechnologies	Environmental biotechnologies; synthetic biology; new methods for controlling gene expression; RNA interference
	Advanced digital technologies	Artificial General Intelligence in agriculture; Internet of Food; digital twins; quantum internet and computing applied to agrifood systems; aerial robotics and drones; artificial neurons
	Advanced geospatial technologies	Real-time satellite imagery, positioning systems and autonomous GIS
	Policy innovation	Nature-based and ecosystem innovations; agricultural innovation policy labs; access to science-based information on sustainability matters; frugal innovation; territorial or landscape value chain and food-to-consumer economy policies
	New energy & transportation	Energy storage technologies; global logistics network; novel biomass energy
	Financial and social innovations	Carbon credits in agriculture and aquaculture
	Food manufacturing technologies and nutrition	Personalized nutrition; 4D nanoscale printing; 3D printing of food and liquids
	Micro-, nanotechnology & nanobiotech	Nanomaterials for food packaging
One health and nutrition	Advanced biotechnologies	Environmental biotechnologies; synthetic biology; new methods for controlling gene expression; RNA interference
	Advanced digital technologies	Artificial General Intelligence in agriculture; Internet of Food; digital twins; quantum internet and computing applied to agrifood systems; aerial robotics and ddrones; artificial neurons
	Advanced geospatial technologies	/
	Policy innovation	Nature-based and ecosystem innovations; agricultural innovation policy labs; access to science-based information on sustainability matters; frugal innovation; territorial or landscape value chain and food-to-consumer economy policies
	New energy & transportation	Global logistics network
	Financial and social innovations	/
	Food manufacturing technologies and nutrition	Personalized nutrition; 4D nanoscale printing; 3D printing of food and liquids
	Micro-, nanotechnology & nanobiotech	Nanomaterials for water technologies; novel pesticides, fertilizers, antibiotics incl. nanotechnology substances; nanomaterials for food packaging; nanorobotics
Governance and trade	Advanced biotechnologies	/
	Advanced digital technologies	Artificial General Intelligence in agriculture; 6–10G connectivity in agrifood systems; Internet of Food; quantum internet and computing applied to agrifood systems; aerial robotics and drones
	Advanced geospatial technologies	Real-time satellite imagery, positioning systems and autonomous GIS
	Policy innovation	Nature-based and ecosystem innovations; agricultural innovation policy labs; access to science-based information on sustainability matters; frugal innovation; territorial or landscape value chain and food-to-consumer economy policies
	New energy & transportation	Energy storage technologies; global logistics network
	Financial and social innovations	Carbon credits in agriculture and aquaculture
	Food manufacturing technologies and nutrition	/
	Micro-, nanotechnology & nanobiotech	Nanorobotics

		Estimated timeframe to significant impact					
Relative advantage	Earliest time to mature	Asia and Pacific	Europe and Central Asia	Latin America	North America	Northern Africa and Near East	Sub Saharan Africa
5.61	12 PETIAS mature in 2040s, 8 PETIAS mature in 2030s, 3 PETIAS mature in 2050s.	before 2035/2040	before 2035/2040	before 2035/2040	mostly before 2035	way in the future (before 2045/2040)	way in the future (before 2045/2040)
E+C	15 PETIAS mature in 2040s, 5 PETIAS mature in 2030s, 3 PETIAS mature in 2050s.	before 2035/2040	before 2035/2030	before 2035/2040	mostly before 2035	mostly before 2040	mostly before 2040
6.01	8 PETIAS mature in 2030s, 7 PETIAS mature in 2040s.	before 2035/2040	before 2035/2030	before 2035/2040	before 2035/2030	mostly before 2040	mostly before 2040

Areas of application	Cluster	PETIAS
New materials, new proteins and circular economy	Advanced biotechnologies	Environmental biotechnologies; synthetic biology; new methods for controlling gene expression; RNA interference
	Advanced digital technologies	Artificial General Intelligence in agriculture; Internet of Food; digital twins; quantum internet and computing applied to agrifood systems; aerial robotics and drones; artificial neurons
	Advanced geospatial technologies	/
	Policy innovation	Nature-based and ecosystem innovations; agricultural innovation policy labs; access to science-based information on sustainability matters; frugal innovation; territorial or landscape value chain and food-to-consumer economy policies
	New energy & transportation	Global logistics network; teleportation of complex molecules
	Financial and social innovations	Carbon credits in agriculture and aquaculture
	Food manufacturing technologies and nutrition	/
	Micro-, nanotechnology & nanobiotech	Nanomaterials for water technologies; nanomaterials for food packaging; nanorobotics
Blue economy	Advanced biotechnologies	Environmental biotechnologies; Synthetic biology; new methods for controlling gene expression; RNA interference
	Advanced digital technologies	Artificial General Intelligence in agriculture; 6–10G connectivity in agrifood systems; Internet of Food; digital twins; quantum internet and computing applied to agrifood systems; aerial robotics and drones
	Advanced geospatial technologies	Real-time satellite imagery, positioning systems and autonomous GIS
	Policy innovation	Nature-based and ecosystem innovations; agricultural innovation policy labs; access to science-based information on sustainability matters; frugal innovation; territorial or landscape value chain and food-to-consumer economy policies
	New energy & transportation	Global logistics network; novel biomass energy
	Financial and social innovations	Social impact bonds; carbon credits in agriculture and aquaculture
	Food manufacturing technologies and nutrition	Personalized nutrition; 3D printing of food and liquids
	Micro-, nanotechnology & nanobiotech	Nanomaterials for water technologies; novel pesticides, fertilizers, antibiotics incl. nanotechnology substances; nanomaterials for food packaging; nanorobotics
Inclusion of the most vulnerable	Advanced biotechnologies	/
	Advanced digital technologies	Artificial General Intelligence in agriculture; 6–10G connectivity in agrifood systems; digital twins; metaverse, virtual reality and augmented reality
	Advanced geospatial technologies	Real-time satellite imagery, positioning systems and autonomous GIS
	Policy innovation	Nature-based and ecosystem innovations; agricultural innovation policy labs; access to science-based information on sustainability matters; frugal innovation; territorial or landscape value chain and food-to-consumer economy policies
	New energy & transportation	Energy storage technologies; global logistics network
	Financial and social innovations	Social impact bonds; carbon credits in agriculture and aquaculture
	Food manufacturing technologies and nutrition	/
	Micro-, nanotechnology & nanobiotech	Nanomaterials for water technologies

		Estimated timeframe to significant impact					
Relative advantage	Earliest time to mature	Asia and Pacific	Europe and Central Asia	Latin America	North America	Northern Africa and Near East	Sub Saharan Africa
5.71	12 PETIAS mature in 2040s, 6 PETIAS mature in 2030s, 1 PETIAS mature in 2050s, 1 PETIAS mature in 2060s.	before 2035/2040	mostly before 2035	before 2035/2040	mostly before 2035	mostly before 2040	way in the future (before 2045/2040)
5.66	16 PETIAS mature in 2040s, 9 PETIAS mature in 2030s, 1 PETIAS mature in 2050s.	before 2035/2040	before 2035/2030	before 2035/2040	before 2035/2030	mostly before 2040	way in the future (before 2045/2040)
6.01	9 PETIAS mature in 2030s, 6 PETIAS mature in 2040s.	before 2035/2040	mostly before 2035	before 2040/2035	mostly before 2035	mostly before 2040	mostly before 2040

ANNEX 6. PETIAS AND CLUSTERS ADDRESSING [AREAS OF APPLICATIONS]

1. Production systems

Advanced biotechnologies

- Synthetic biology: Innovations in synthetic biology are leading to microbes that can provide nitrogen directly to crops, reducing the need for synthetic fertilizers. This not only cuts costs for farmers but also minimizes environmental harm from fertilizer runoff (Brownell, 2024).
- RNA interference: Enhances crop traits like drought and salinity (Chaudhary *et al.,* 2024) and pest resistance (Verma and Modgil, 2024) thus reducing demand for pesticides, optimizing vertical farming, and aid reforestation efforts to preserve soil moisture and carbon sinks (Joga *et al.,* 2021).
- New methods for controlling gene expression: Enhance precision agriculture, optimize vertical farming, and support regenerative practices.
- Environmental biotechnology: Microbiome engineering enhances soil health and consequently plant growth and pest control (Arif *et al.,* 2020). Bioremediation cleans contaminated water for irrigation (Ravelo *et al.,* 2017).

Advanced digital technologies

- 6G-10G connectivity for agriculture: Optimizes irrigation, fertilization, and pest control through real-time data, even in remote locations.
- Aerial robotics and drones: Monitor crop health, optimize irrigation and fertilizer use, survey land, managing livestock, and support reforestation efforts.
- Artificial General Intelligence in agriculture: Optimizes precision agriculture, land management, vertical farming, and regeneration.
- Digital twins: Optimize irrigation, fertilizer use, and pest control for more than one weather scenario. Monitor crop health, soil quality, and equipment performance (Pylianidis *et al.,* 2021).
- Internet of Food: Optimizes irrigation, fertilizer use, and pest control in precision agriculture, monitors soil and crop health for better decision-making, and enables automated systems for vertical and regenerative farming (Holden *et al.,* 2018).
- Quantum computing: Optimizes resource allocation, crop yields, and environmental impact in precision, vertical, and regenerative farming beyond the present level of complexity.
- Artificial neurons: Help in analyzing vast amounts of data from various sources, such as soil moisture levels, weather patterns, and crop health; can be trained for yield predictions. This data-driven approach allows for precise resource allocation, optimizing inputs like water and fertilizers, which leads to increased crop yields and reduced waste (Cesco *et al.,* 2023).

Advanced geospatial technologies

- Realtime satellite imagery, Autonomous GIS, Positioning systems: Optimize irrigation, fertilizer use, pest control, and crop health monitoring. Enable efficient land management and supports regenerative agriculture practices.

Policy innovation

- Innovation policy labs: Based both on evidence (data, digital) and collective intelligence (foresight, behavioural insights), multistakeholder groups remove policy barriers to innovate by supporting system shifts towards more sustainable, equitable and resilient agricultural production models in a community, institution or nationally.
- Territorial food-to-consumer economy: supports sustainable land management, connects farmers to local consumers, and fosters regenerative practices.
- Access to information on sustainability matters: Farmers can access reliable information and predict the effect on innovative practices associated with sustainability, thus reducing the risk to innovate and improve land management, optimize irrigation, and implement regenerative practices.

- Nature-based and ecosystem innovations: Agroforestry, integrated pest management, pollinator habitats, cover cropping, and crop rotation in precision, vertical, and regenerative farming.
- Frugal innovation: Low-cost sensors for precision agriculture, mobile apps for farm management, DIY hydroponics, and soil restoration techniques.
- New renewable energy and transportation
- Novel biomass: Optimizes resource management and enhances soil health in various farming systems.
- Novel energy storage technologies: Support energy-intensive processes like hydroponics and aquaponics to produce nutritious food.
- Teleportation of complex molecules: Instantaneous transfer of microelements, water molecules and pesticide molecules could revolutionize the input supply industry when the technology becomes feasible, accessible, efficient and safe.

Market and financial innovation

- Carbon credits in agriculture and aquaculture: Reward reduced emissions and carbon sequestration in soil through practices like sustainable land management, vertical farming, and reforestation.
- Social impact bonds: Fund sustainable land management, urban farming, regenerative practices, as well as paradigmatic shifts related to new ways of producing food (see Chapter 3).

Food manufacturing technologies and nutrition

- 4D nanoscale printing: Smart nano-sensors for real-time monitoring, self-repairing vertical farming structures, and scaffolds for soil health.
- Personalized nutrition: Create crops that are customized based on genetic, metabolomic and lifestyle factors, such as producing biofortified crops with specific vitamins or minerals that a particular demographic lacks (Ofori *et al.*, 2022).

Macro- and nanotechnology and nanobiotech

- Nanorobotics: Monitor plant health, soil conditions, and optimize resource use in various farming systems.
- Nanomaterials for water technologies: Nanofiltration membranes purify and recycle water, offering energy-efficient desalination solutions, providing freshwater for agriculture in arid regions, reducing consumption and waste.
- Nano pesticides, fertilizers and antibiotics: Targeted pesticides, fertilizers, and potential soil remediation.

2. Processing systems

Advanced biotechnologies

- Synthetic biology: Designs cell factories for bio-based production and bioremediation (Rylott and Bruce, 2020).
- Artificial neurons: Enhance quality and optimize processes like fermentation.

Advanced digital technologies

- 6G-10G connectivity for agriculture: Improves quality control and integrates processing processes.
- Aerial robotics and drones: Monitor and optimize operations in food processing plants.
- Artificial General Intelligence in agriculture: Enhances quality control and optimizes processes.
- Digital twins: Optimize processes and equipment maintenance schedules for improved efficiency and reduced downtime, ensuring continuous improvement.
- Quantum computing: Designing efficient algorithms for sorting, grading, and processing of food products.

Policy innovation

- Innovation policy labs: Develop policy, institutional and operational innovations to reduce post-harvest losses, improve nutritional content, and diversify product offerings.
- Territorial food-to-consumer economy: Promotes local, smaller-scale processing and value-added products.
- Access to information on sustainability matters: Businesses can access data on sustainable sourcing and processing methods, reducing waste and promoting circularity.
- Nature-based and ecosystem innovations: Utilize natural processes like fermentation, composting, and anaerobic digestion for food processing and waste management, reducing reliance on synthetic chemicals and enhancing sustainability.
- Frugal innovation: Energy-efficient tools, local resources, and traditional knowledge for small-scale processing operations.

New renewable energy & transportation

- Novel biomass: Sources ingredients for food and bio-based packaging materials, while utilizing biorefineries to create biofuels and bioplastics (Kumar and Verma, 2021).
- Novel energy storage technologies: Reduce energy costs and ensure uninterrupted operation of food processing facilities during grid fluctuations or outages.

Market and financial innovation

- Carbon credits in agriculture and aquaculture: Promote energy-efficient technologies, sustainable sourcing, and transparent labeling.

Food manufacturing technologies and nutrition

- 3D printing of food and liquids: Precise portioning and on-demand production.
- 4D nanoscale printing: Intelligent packaging, self-assembling bioreactors for sustainable protein production, with adaptive and self-healing materials, enhancing the efficiency and sustainability of processing systems.
- Personalized nutrition: biofermentation in bioreactors of personalized food products with specific nutrient profiles to address individual deficiencies.

Macro- and nanotechnology and nanobiotech

- Nanorobotics: Enhances food safety, nutrient delivery, and shelf life.
- Nanomaterials for food packaging: Nanocomposites enhance barrier properties of packaging, extending shelf life and preserving nutritional value (Adeyeye and Ashaolu, 2021).

3. Value chains and services

Advanced digital technologies

- 6G-10G connectivity for agriculture: Enables traceability, supply chain optimization, and e-commerce for farmers.
- Aerial robotics and drones: Tracking shipments, delivering products, and providing crop insurance services.
- Artificial General Intelligence in agriculture: Improves supply chain management and financial services.
- Digital twins: Track products, optimize logistics, and ensure food safety.
- Internet of Food: Tracks food from farm to table, ensures authenticity, manages inventory, and engages consumers with information (Ranganathan *et al.,* 2022).
- Quantum computing: Enhances supply chains, logistics, and financial risk modeling.

Advanced geospatial technologies

- Realtime satellite imagery, Autonomous GIS, Positioning systems: Ensure traceability, supply chain optimization, and crop insurance.

Policy innovation

- Innovation Policy labs: Remove policy and operational barriers to transparent value chains, new farmer business models, and support small-scale farmers.
- Territorial food-to-consumer economy: Shortens supply chains, increases transparency, and supports fair prices for farmers.
- Access to information on sustainability matters: Stakeholders can track products, verify certifications, and make informed purchasing decisions.
- Nature-based and ecosystem innovations: Develop sustainable packaging, eco-labels, and fair-trade certifications.
- Frugal innovation: Mobile platforms connecting farmers and consumers, shared transportation for small farmers.

New renewable energy & transportation

- Global logistics network: Tracks products, ensures quality, and facilitates access to financial services.
- Novel energy storage technologies: Enable refrigerated storage and transportation, and extending shelf life.

Market and financial innovation

- Carbon credits in agriculture and aquaculture: Promote energy-efficient technologies, sustainable sourcing, and transparent labeling.
- Social impact bonds: Incentivize fair trade and ethical sourcing, fund traceability technologies.

Food manufacturing technologies & nutrition

- Personalized nutrition: Matches production to consumer demand based on personalized nutrition profiles.

Macro- and nanotechnology and nanobiotech

- Nanomaterials for food packaging: Nanoparticles enable tracking and traceability, ensuring food safety and authenticity throughout the supply chain.

4. Energy and Transportation

Advanced biotechnologies

- Synthetic biology, RNA interference, New methods for controlling gene expression, Environmental biotechnology: Engineer advanced biofuels and sustainable materials.

Advanced digital technologies

- 6G-10G connectivity for agriculture: Optimizes energy management for farms and potentially reduces carbon footprint.
- Aerial robotics and drones: Inspect infrastructure, deliver goods, and monitor transportation routes.
- Artificial General Intelligence in agriculture: Optimizess renewable energy use and transportation efficiency, explores new energy sources (Ukoba *et al.*, 2024).
- Digital twins: Model energy use across the agrifood systems and optimize transportation.
- Internet of Food: Monitors cold chains and optimizes logistics for sustainability.
- Quantum computing: Optimizes biofuel production and transportation routes.

Advanced geospatial technologies

Realtime satellite imagery, Autonomous GIS, Positioning systems: Optimize energy consumption on farms and monitor renewable energy sources.

Policy innovation

- Innovation policy labs: Co-create new policy and operational frameworks for sustainable energy and transportation in a participatory and inclusive manner.
- Territorial food-to-consumer economy: Reduces emissions by minimizing transportation distances and promoting local energy sources.
- Access to information on sustainability matters: Information on renewable energy sources and efficient logistics can reduce the environmental impact of agriculture.
- Nature-based and ecosystem innovations: Integrate renewable energy sources like wind and solar, and bioenergy from agricultural waste.

New renewable energy & transportation

- Nuclear energy in agriculture: Nuclear power plants could provide a reliable, low-carbon energy source for powering some aspects of agriculture, especially in vertical farming or desalination for irrigation in water-scarce regions (FAO, 2021a).
- Global logistics network: Efficiently transports biofuel feedstocks and distributes finished products. Preserves perishable goods during transportation, reducing food waste.
- Teleportation of complex molecules: Teleportation could reduce reliance on traditional transportation methods, lowering emissions and energy consumption.
- Novel biomass: Produce biofuels for transportation and bioenergy for heating and electricity.
- Novel energy storage technologies: Electrifying agricultural vehicles and providing charging infrastructure to reduce reliance on fossil fuels.

Market and financial innovation

- Carbon credits in agriculture and aquaculture: Encourage biofuels, electric vehicles, and renewable energy use.
- Social impact bonds: Finance renewable energy projects and low-carbon transportation.

Food manufacturing technologies & nutrition

- 3D printing of food and liquids: Reduced transportation needs and efficient packaging.

5. Food waste

Advanced biotechnologies

- Synthetic biology, RNA interference, New methods for controlling gene expression: Reduce waste through enzyme and microbial engineering. Extend crop shelf life.
- Environmental biotechnology: Composting and anaerobic digestion valorize waste into animal feed or fertilizers.

Advanced digital technologies

- Artificial General Intelligence in agriculture: Predicts spoilage and develops new preservation techniques.
- Digital twins: Predict spoilage and identify waste reduction.
- Internet of Food: Tracks food waste, monitors freshness, and connects surplus food with organizations in need.
- Quantum computing: Predicts spoilage and develops preservation techniques.
- Artificial neurons: Predict spoilage and optimize waste management processes.

Advanced geospatial technologies

- Realtime satellite imagery, Autonomous GIS: monitor waste throughout the supply chain.
- Positioning systems: Monitor shipments and optimizes waste collection.

Policy innovation

- Innovation policy labs: Design innovative solutions, incentivize waste reduction, and empower consumers.
- Territorial food-to-consumer economy: Improves coordination between producers and consumers, reducing waste and facilitating local use of surplus food.
- Access to information on sustainability matters: Data on food waste can inform targeted interventions and raise consumer awareness.
- Nature-based and ecosystem innovations: Compost organic waste for fertilizer, where feasible create biogas for energy, and promote circular systems.
- Frugal innovation: Simple storage solutions and community-based food sharing.

New renewable energy & transportation

- Global logistics network: Connects surplus food with those in need and optimizes logistics to reduce spoilage.
- Novel biomass: Converts food waste into biogas and fertilizer or livestock feed.
- Novel energy storage technologies: Power refrigeration systems and food preservation technologies to extend shelf life and reduce waste.

Market and financial innovation

- Carbon credits in agriculture and aquaculture: Incentivize reduction through better storage and distribution practices.

Food manufacturing technologies and nutrition

- 3D printing of food and liquids: Upcycle and precisely portion for waste reduction (Yu and Wong, 2023).
- 4D nanoscale printing: Nanostructured materials for extended shelf life.
- Personalized nutrition: Produce food that aligns with consumer preferences and nutritional needs, reducing waste due to overproduction or spoilage.

Macro- and nanotechnology and nanobiotech

- Nanomaterials for food packaging: Intelligent packaging with nano-sensors can detect spoilage and extend shelf life, reducing food waste.

6. Governance, and trade

Advanced digital technologies

- 6G-10G connectivity for agriculture: Informs policy decisions with real-time data and promotes fair trade. Transparent and verifiable information about origin and production methods can ensure fair prices for farmers.
- Aerial robotics and drones: Monitor illegal activities, enforce regulations, and facilitate fair trade.
- Artificial General Intelligence in agriculture: AGI could streamline customs procedures, ensure compliance with regulations, and predict market trends.
- Internet of Food: Tracks products to verify ethical sourcing and fair compensation for farmers.
- Quantum computing: Models policy impact and forecasts market trends.

Advanced geospatial technologies

- Realtime satellite imagery, Autonomous GIS, Positioning systems: provide data for policy making, monitor regulatory compliance, and facilitate fair trade. Ensure regulatory compliance and fair trade practices.

Policy innovation

- Innovation policy labs: develop evidence-based anticipatory and behaviourally-informed policies and decisions, create dialogue platforms, and design fair trade policies.
- Territorial food-to-consumer economy: strengthens local agrifood systems and promotes fair trade policies.
- Access to information on sustainability matters: Policymakers can make evidence-based decisions, promote transparency, and incentivize sustainable practices.
- Nature-based and ecosystem innovations: develop policies that support sustainable practices, biodiversity, and equitable access to resources.
- Frugal innovation: accessible platforms/ social media for information and policy dialogue on sustainable solutions in the agrifood systems.

New renewable energy and transportation

- Global logistics network: streamlines international trade and ensures food safety compliance.
- Novel energy storage technologies: Integrate energy storage into smart grids to improve energy management and create new market opportunities for farmers.

Market and financial innovation

- Carbon credits in agriculture and aquaculture: create a market for rewarding sustainability and promote transparency.

Micro-and nanotechnology and nanobiotech

- Nanorobotics: monitoring compliance and preventing disease outbreaks. Detect and prevent the spread of plant and animal diseases across borders to anchor decisions on trade.

7. New materials, new proteins and circular economy

Advanced biotechnologies

- Synthetic biology, RNA interference, New methods for controlling gene expression: design new biomaterials with improved properties, proteins, and recycling processes.
- Environmental biotechnology: bio-based plastics and composites. Novel biopesticide substancies.

Advanced digital technologies

- Artificial General Intelligence in agriculture: Designs bio-based materials and proteins.
- Digital twins: accelerate bio-based materials and protein alternatives.
- Internet of Food: monitors resource use and waste generation to identify opportunities for circularity.
- Artificial neurons: aid in designing bio-based materials and engineering proteins.
- Quantum computing: accelerate the design of sustainable materials and proteins.

Policy innovation

- Innovation policy labs: analyze paradigmatic shifts related to circular economy, cell-based food and other new concepts in a particular country or local context and promote informed and inclusive decision-making.
- Territorial food-to-consumer economy: encourages local circularity.

- Access to information on sustainability matters: information on sustainable materials and bio-based alternatives can drive innovation and reduce resource depletion, while decreasing innovation risks.
- Nature-based and ecosystem innovations: utilize bio-based materials, restore degraded lands, and promote closed-loop systems for nutrients and water.
- Frugal innovation: new sources of protein from traditional practices: insects, algae etc.

New renewable energy and transportation

- Global logistics network: enables movement of bio-based materials and facilitates waste recycling.
- Teleportation of complex molecules: potentially revolutionizes the design and creation of new biomolecules for fertilizers, pesticides, and food products, enabling faster innovation and more sustainable solutions.

Market and financial innovation

- Carbon credits in agriculture and aquaculture: support development of low-carbon bio-based materials.

Micro-and nanotechnology and nanobiotech

- Nanorobotics: convert agricultural waste into valuable products through nanotechnological processes.
- Nanomaterials for water technologies: bio-based nanomaterials replace traditional plastics.
- Nanomaterials for food packaging: bio-based nanomaterials can replace traditional plastics, contributing to a circular economy.

8. One Health and nutrition

Advanced biotechnologies

- Synthetic biology, RNA interference, New methods for controlling gene expression, Environmental biotechnology: develop probiotics, vaccines, and biosensors for disease detection.

Advanced digital technologies

- Artificial neurons: detect diseases early and analyze crop nutrition.
- Aerial robotics and drones: Mmonitor animal health, deliver medical supplies, and map disease outbreaks.
- Artificial General Intelligence in agriculture: monitors diseases and develops personalized nutrition.
- Digital twins: Model disease spread, optimize animal and plant health, and personalize nutrition.
- Internet of Food: IoF devices track food intake and provide personalized nutritional advice.
- Quantum computing: tailors dietary and food safety recommendations based on individual genetic and metabolic profiles, while assessing food safety risks and proposing mitigation strategies.

Policy innovation

- Innovation policy labs: manage food safety and nutrition risks, and promote healthy diets.
- Territorial food-to-consumer economy: improves access to fresh, nutritious food and supports healthy diets.
- Access to information on sustainability matters: farmers and consumers can access information on healthy and sustainable food choices.
- Nature-based and ecosystem innovations: promote diverse diets, integrate livestock and crop production, and improve soil health for nutrient-rich food.

- Frugal innovation: affordable, locally-sourced supplements, promoting traditional diets.

New renewable energy & transportation

- Global logistics network: distributes vaccines and improves access to nutritious food.
- Food manufacturing technologies & nutrition
- 3D printing of food and liquids: tailored meals for specific nutritional requirements or health conditions.
- 4D nanoscale printing: targeted drug delivery, nano-encapsulation of nutrients.
- Personalized nutrition: delivers tailored nutrition interventions for humans, animals and plants to improve health outcomes and prevent chronic diseases.

Macro- and nanotechnology and nanobiotech

- Nanorobotics: diagnose and treat diseases, enhance nutrition.
- Nanomaterials for water technologies: nanomaterials remove harmful microorganisms and toxins from drinking water, improving public and animal health.
- Nanomaterials for food packaging: packaging with antimicrobial nanoparticles can enhance food safety and reduce the risk of foodborne illnesses.
- Nano pesticides, fertilizers and antibiotics: potential for targeted delivery of nutrients or antibiotics to livestock.

9. Blue economy

Advanced biotechnologies

- Synthetic biology: engineers marine organisms for biofuel and plastic production, improves aquaculture efficiency, developsing microorganisms for environmental monitoring and remediation, create sustainable fish feeds, and supports marine conservation efforts (Sankhla *et al.,* 2020).
- RNA interference, New methods for controlling gene expression: improve aquaculture species and seafood production.
- Environmental biotechnology: marine bioremediation and aquaculture disease control.

Advanced digital technologies

- 6G-10G connectivity for agriculture: real-time monitoring of water quality, fish health, and environmental impact.
- Aerial robotics and drones: monitor ocean health, track marine life, and manage fisheries.
- Artificial General Intelligence in agriculture: AGI could optimize fishing quotas and protect marine ecosystems.
- Digital twins: simulate ocean conditions and ecosystems.
- Internet of Food: monitors fish populations, optimizes aquaculture, and ensures seafood safety
- Quantum computing: improves fisheries management and environmental monitoring.

Advanced geospatial technologies

- Realtime satellite imagery, Autonomous GIS, Positioning systems: track marine ecosystems, identify pollution, and monitor fishing activities.

Policy innovation

- Innovation policy labs: promote responsible decision-making for sustainable aquaculture and protect marine ecosystems.
- Territorial food-to-consumer economy: connects coastal communities with local seafood producers and promotes sustainable practices.

- Access to information on sustainability matters: stakeholders can access data on sustainable fishing practices and ocean health.
- Nature-based and ecosystem innovations: restore coastal ecosystems, promote sustainable fishing practices, and develop marine-based products.
- Frugal innovation: sustainable fishing and aquaculture techniques.

New renewable energy and transportation

- Global logistics network: enables global seafood distribution and supports aquaculture.
- Novel biomass: Algae cultivation can be used for biofuels, animal feed, and other products (Lum *et al.*, 2013).

Market and financial innovation

- Carbon credits in agriculture and aquaculture: promote sustainable aquaculture practices like seaweed farming.
- Social impact bonds: finance initiatives that protect marine ecosystems and biodiversity.

Food manufacturing technologies and nutrition

- 3D printing of food and liquids: develop alternative seafood products like plant-based or lab-grown fish.
- Personalized nutrition: create personalized seafood products with tailored nutritional profiles.

Macro- and nanotechnology and nanobiotech

- Nanorobotics: monitor water quality and protect marine ecosystems.
- Nanomaterials for water technologies: improve water quality in aquaculture and monitor marine ecosystems.
- Nanomaterials for food packaging: nanomaterials can improve packaging for seafood products, ensuring freshness and extending shelf life.
- Nano pesticides, fertilizers and antibiotics: Potential use in aquaculture to prevent disease.

10. Inclusion of the most vulnerable

Advanced digital technologies

- 6G-10G connectivity for agriculture: bridge the connectivity divide by providing affordable access to high-speed internet and digital tools for marginalized communities, women, youth and elderly, as well as people with disabilities.
- Artificial General Intelligence in agriculture: AGI could develop user-friendly interfaces and tools for farmers in developing countries.
- VR and AR: virtual training and data-driven insights for farmers.
- Internet of Food: empowers smallholder farmers, women and youth with information and access to markets.

Advanced geospatial technologies

- Realtime satellite imagery: monitors weather patterns and extreme events, helping vulnerable communities prepare and adapt.

Policy innovation

- Innovation policy labs: design and implement policies that promote gender equality in agrifood systems, empower youth and elderly farmers, and support indigenous communities in preserving their traditional agricultural practices.
- Territorial food-to-consumer economy: empowers smallholder farmers, women, youth, elderly, and indigenous peoples by providing them with direct access to markets and increased control over their livelihoods.
- Access to information on sustainability matters: provides accessible information empowers marginalized groups, promotes gender equality, and supports indigenous knowledge systems.

- Nature-based and ecosystem innovations: empower marginalized groups through sustainable practices, promote traditional knowledge, and ensure equitable access to resources.

- Frugal innovation: empower marginalized groups through skills and resources.

New renewable energy and transportation

- Global logistics network: improves market access for smallholder farmers and promotes rural development.

- Novel energy storage technologies: increase energy access and affordability for marginalized communities, enabling them to participate in the agricultural economy.

Market and financial innovation

- Carbon credits in agriculture and aquaculture: provide income for marginalized groups adopting sustainable methods.

- Social impact bonds: empower women farmers through financial and technical support. Create training and employment opportunities for young people in agriculture. Support elderly and indigenous peoples traditional knowledge and practices, ensuring their inclusion in the agrifood systems.

Macro- and nanotechnology and nanobiotech

- Nanomaterials for water technologies: nanomaterials enable decentralized and cost-effective water treatment and purification technologies, accessible to vulnerable communities.

References

Abiri, R., Rizan, N., Balasundram, S.K., Shahbazi, A.B. & Abdul-Hamid, H. 2023. Application of digital technologies for ensuring agricultural productivity. *Heliyon*, 9(12): e22601. https://doi.org/10.1016/j.heliyon.2023.e22601

Adeyeye, S.A.O. & Ashaolu, T.J. 2021. Applications of nano-materials in food packaging: A review. *Journal of Food Process Engineering*, 44(7): e13708. https://doi.org/10.1111/jfpe.13708

Aggeri, F. 2023. Ecological transformation: pathways to frugal and responsible innovation. *Field Actions Science Reports. The journal of field actions* (Special Issue 25): 10–13.

Akbar, S., Wei, Y. & Zhang, M.-Q. 2022. RNA Interference: Promising Approach to Combat Plant Viruses. *International Journal of Molecular Sciences*, 23(10): 5312. https://doi.org/10.3390/ijms23105312

Akpasi, S.O., Anekwe, I.M.S., Tetteh, E.K., Amune, U.O., Shoyiga, H.O., Mahlangu, T.P. & Kiambi, S.L. 2023. Mycoremediation as a Potentially Promising Technology: Current Status and Prospects—A Review. *Applied Sciences*, 13(8): 4978. https://doi.org/10.3390/app13084978

Alexandrova-Stefanova, N., Nosarzewski, K., Mroczek, Z.K., Audouin, S., Djamen, P., Kolos, N. & Wan, J. 2023. *Harvesting change: Harnessing emerging technologies and innovations for agrifood system transformation*. Rome. https://doi.org/10.4060/cc8498en

Almessabi, H. & Al-kfairy, M. 2024. Unlocking the Future of Farming: A Review of Metaverse Integration in Agriculture. *IEEE Engineering Management Review*: 1–13. https://doi.org/10.1109/EMR.2024.3437655

Arif, I., Batool, M. & Schenk, P.M. 2020. Plant Microbiome Engineering: Expected Benefits for Improved Crop Growth and Resilience. *Trends in Biotechnology*, 38(12): 1385–1396. https://doi.org/10.1016/j.tibtech.2020.04.015

Bandak, S., Movahedi Naeini, S.A.R., Komaki, C.B., Verrelst, J., Kakooei, M. & Mahmoodi, M.A. 2023. Satellite-Based Estimation of Soil Moisture Content in Croplands: A Case Study in Golestan Province, North of Iran. *Remote Sensing*, 15(8): 2155. https://doi.org/10.3390/rs15082155

Barrangou, R. & Doudna, J.A. 2016. Applications of CRISPR technologies in research and beyond. *Nature Biotechnology*, 34(9): 933–941. https://doi.org/10.1038/nbt.3659

Boenink, M. 2013. Anticipating the future of technology and society by way of (plausible) scenarios: fruitful, futile or fraught with danger? *International Journal of Foresight and Innovation Policy*, 9(2/3/4): 148. https://doi.org/10.1504/IJFIP.2013.058608

Bourgeois, R., Karuri-Sebina, G. & Feukeu, K.E. 2022. The future as a public good: decolonising the future through anticipatory participatory action research. *Foresight*, 26(4): 533–549. https://doi.org/10.1108/FS-11-2021-0225

Brownell, L. 2024. Solving Sustainability with Synthetic Biology. In: *Wyss Institute*. [Cited 8 October 2024]. https://wyss.harvard.edu/news/solving-sustainability-with-synthetic-biology/

Burrell, J. 2016. How the machine 'thinks': Understanding opacity in machine learning algorithms. *Big Data & Society*, 3(1): 2053951715622512. https://doi.org/10.1177/2053951715622512

Buterin, V. 2014. A next-generation smart contract and decentralized application platform. *Ethereum white paper*, 3(37), pp.2-1. https://blockchainlab.com/pdf/Ethereum_white_paper-a_next_generation_smart_contract_and_decentralized_application_platform-vitalik-buterin.pdf

Butterworth, S.J., Barton, F. & Lloyd, J.R. 2023. Extremophilic microbial metabolism and radioactive waste disposal. *Extremophiles*, 27(3): 27. https://doi.org/10.1007/s00792-023-01312-4

Carayannis, E.G. & Campbell, D.F.J. 2009. "Mode 3" and "Quadruple Helix": toward a 21st century fractal innovation ecosystem. *International Journal of Technology Management*, 46(3/4): 201. https://doi.org/10.1504/IJTM.2009.023374

Cardoso, A.S., Malta-Pinto, E., Tabik, S., August, T., Roy, H.E., Correia, R., Vicente, J.R. & Vaz, A.S. 2024. Ca citizen science and social media images support the detection of new invasion sites? A deep learning test case with *Cortaderia selloana*. *Ecological Informatics*, 81: 102602. https://doi.org/10.1016/j.ecoinf.2024.102602

Carè, R. 2021. *Developing Social Impact Bonds to Tackle Emerging Social Needs and Promote Social Welfare*. https://doi.org/10.13140/RG.2.2.13319.93601

Castañón, L. 2022. Stanford researchers have designed synthetic genetic circuits that could help plants adapt to pressures from climate change. In *Stanford Report*. [Cited 8 October 2024]. https://news.stanford.edu/stories/2022/08/synthetic-genetic-circuits-help-plants-adapt-climate-change

Cesco, S., Sambo, P., Borin, M., Basso, B., Orzes, G. & Mazzetto, F. 2023. Smart agriculture and digital twins: Applications and challenges in a vision of sustainability. *European Journal of Agronomy*, 146: 126809. https://doi.org/10.1016/j.eja.2023.126809

Chandimali, N., Park, E.H., Bak, S.-G., Won, Y.-S., Lim, H.-J. & Lee, S.-J. 2024. Not seafood but seafood: A review on cell-based cultured seafood in lieu of conventional seafood. *Food Control*, 162: 110472. https://doi.org/10.1016/j.foodcont.2024.110472

Charatsari, C., Lioutas, E.D., De Rosa, M. & Vecchio, Y. 2022. Technological Innovation and Agrifood Systems Resilience: The Potential and Perils of Three Different Strategies. *Frontiers in Sustainable Food Systems*, 6. https://doi.org/10.3389/fsufs.2022.872706

Chaudhary, D., Jeena, A.S., Rohit, null, Gaur, S., Raj, R., Mishra, S., Kajal, null, Gupta, O.P. & Meena, M.R. 2024. Advances in RNA Interference for Plant Functional Genomics: Unveiling Traits, Mechanisms, and Future Directions. *Applied Biochemistry and Biotechnology*. https://doi.org/10.1007/s12010-023-04850-x

Chen, J., Yin, X. & Mei, L. 2018. Holistic Innovation: An Emerging Innovation Paradigm. *International Journal of Innovation Studies*, 2(1): 1–13. https://doi.org/10.1016/j.ijis.2018.02.001

Choi, B.C.K. & Pak, A.W.P. 2006. Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: 1. Definitions, objectives, and evidence of effectiveness. *Clinical and Investigative Medicine. Medecine Clinique Et Experimentale*, 29(6): 351–364.

Christiaens, O., Sweet, J., Dzhambazova, T., Urru, I., Smagghe, G., Kostov, K. & Arpaia, S. 2022. Implementation of RNAi-based arthropod pest control: environmental risks, potential for resistance and regulatory considerations. *Journal of Pest Science*, 95(1): 1–15. https://doi.org/10.1007/s10340-021-01439-3

Christian, M., Cermak, T., Doyle, E.L., Schmidt, C., Zhang, F., Hummel, A., Bogdanove, A.J. & Voytas, D.F. 2010. Targeting DNA double-strand breaks with TAL effector nucleases. *Genetics*, 186(2): 757–761. https://doi.org/10.1534/genetics.110.120717

Clapp, J. & Ruder, S.-L. 2020. Precision Technologies for Agriculture: Digital Farming, Gene-Edited Crops, and the Politics of Sustainability. *Global Environmental Politics*, 20(3): 49–69. https://doi.org/10.1162/glep_a_00566

Dadi, V., Nikhil, S.R., Mor, R.S., Agarwal, T. & Arora, S. 2021. Agri-Food 4.0 and Innovations: Revamping the Supply Chain Operations. *Production Engineering Archives*, 27(2): 75–89. https://doi.org/10.30657/pea.2021.27.10

Djamen, P., Audouin, S., Alexandrova-Stefanova, N., Van Doren, P. & Mroczek, Z.K. 2023. *A Global Foresight Framework for the transformation of national agricultural extension systems: contribution for renewing AKIS*. 26th ESEE conference, Toulouse. https://agritrop.cirad.fr/607363/

Dodón, A., Quintero, V., Chen Austin, M. & Mora, D. 2021. Bio-Inspired Electricity Storage Alternatives to Support Massive Demand-Side Energy Generation: A Review of Applications at Building Scale. *Biomimetics*, 6(3): 51. https://doi.org/10.3390/biomimetics6030051

Dong, H. 2024. Application of genome editing techniques to regulate gene expression in crops. *BMC Plant Biology*, 24(1): 100. https://doi.org/10.1186/s12870-024-04786-2

Donnellon-May, G. 2024. The Impact of Global Food Chokepoint Pressures on Asia's Food Security. In *Asia Society* [Cited 8 October 2024]. https://asiasociety.org/australia/impact-global-food-chokepoint-pressures-asias-food-security

Duckett, T., Pearson, S., Blackmore, S., Grieve, B., Chen, W.-H., Cielniak, G., Cleaversmith, J. *et al.* 2018. *Agricultural Robotics: The Future of Robotic Agriculture*. UK Robotics and Autonomous Systems (RAS) Network. http://arxiv.org/abs/1806.06762

Dung, T.T., Oh, Y., Choi, S.-J., Kim, I.-D., Oh, M.-K. & Kim, M. 2018. Applications and Advances in Bioelectronic Noses for Odour Sensing. *Sensors*, 18(1): 103. https://doi.org/10.3390/s18010103

Dunlap, R.A. 2021. *Energy from Nuclear Fusion*. IOP Publishing. https://iopscience.iop.org/book/mono/978-0-7503-3307-8

Ezziane, Z. 2005. DNA computing: applications and challenges. *Nanotechnology*, 17(2): R27. https://doi.org/10.1088/0957-4484/17/2/R01

FAO. 2017. *The future of food and agriculture – Trends and challenges*. Rome. https://www.fao.org/3/a-i6583e.pdf

FAO. 2018a. *The future of food and agriculture – Alternative pathways to 2050*. Rome. https://www.fao.org/3/I8429EN/i8429en.pdf

FAO. 2018b. Nature-based Solutions. In: *FAO*. [Cited 8 October 2024]. https://www.fao.org/platforms/green-agriculture/areas-of-work/natural-resources-biodiversity-green-production/nature-based-solutions/en

FAO. 2018c. *Catalysing Dialogue and Cooperation to Scale up Agroecology: Outcomes of FAO Regional Seminars on Agroecology*. Rome. https://openknowledge.fao.org/handle/20.500.14283/i8992en

FAO. 2020. *Building sustainable and resilient food systems in Asia and the Pacific*. FAO Regional Conference for Asia and the Pacific, FAO, 1 September 2020. https://openknowledge.fao.org/server/api/core/bitstreams/7de24625-196b-41e8-bc84-4c9d3718cbdc/content

FAO. 2021a. *The State of Food and Agriculture 2021. Making agrifood systems more resilient to shocks and stresses.* Rome. https://www.fao.org/3/cb4476en/cb4476en.pdf

FAO. 2021b. Five ways nuclear technology is improving agriculture and food security. In: *Newsroom*. [Cited 8 October 2024]. https://www.fao.org/newsroom/story/Five-ways-nuclear-technology-is-improving-agriculture-and-food-security/en

FAO. 2022a. *The future of food and agriculture – Drivers and triggers for transformation*. Rome. https://doi.org/10.4060/cc0959en

FAO. 2022b. *FAO Science and Innovation Strategy*. Rome.

FAO. 2022c. Cell-based food and precision fermentation In: *FAO*. [Cited 8 October 2024]. https://www.fao.org/food-safety/scientific-advice/crosscutting-and-emerging-issues/cell-based-food/en/

FAO. 2022d. *Gene editing and agrifood systems*. Rome. https://doi.org/10.4060/cc3579en

Frazier, I. 2017. The Vertical Farm In: *The New Yorker*. [Cited 8 October 2024]. https://www.newyorker.com/magazine/2017/01/09/the-vertical-farm

Frewer, L.J., Scholderer, J. & Bredahl, L. 2003. Communicating about the Risks and Benefits of Genetically Modified Foods: The Mediating Role of Trust. *Risk Analysis*, 23(6): 1117–1133. https://doi.org/10.1111/j.0272-4332.2003.00385.x

Gill, S.E., Handley, J.F., Ennos, A.R. & Pauleit, S. 2007. Adapting Cities for Climate Change: The Role of the Green Infrastructure. *Built Environment*, 33(1): 115–133. https://doi.org/10.2148/benv.33.1.115

Govindan, G., Harini, P., Alphonse, V. & Parani, M. 2024. From swamp to field: how genes from mangroves and its associates can enhance crop salinity tolerance. *Molecular Biology Reports*, 51(1): 598. https://doi.org/10.1007/s11033-024-09539-w

Gudelė, G.M. & Visockienė, J.S. 2024. Remote Sensing Data Application to Monitor Carbon Farming Practices. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-4-W9-2024: 257–265. https://doi.org/10.5194/isprs-archives-XLVIII-4-W9-2024-257-2024

Hauber, G. 2024. The Asia Pacific renewable supply chain opportunity. In: *Institute for Energy Economics and Financial Analysis.* [Cited 8 October 2024]. https://ieefa.org/resources/asia-pacific-renewable-supply-chain-opportunity

Helmy, M., Smith, D. & Selvarajoo, K. 2020. Systems biology approaches integrated with artificial intelligence for optimized metabolic engineering. *Metabolic Engineering Communications*, 11: e00149. https://doi.org/10.1016/j.mec.2020.e00149

Hernandez, T. 2012. Samoan Circle. In: *prezi.com*. [Cited 9 October 2024]. https://prezi.com/0e71sdjhieew/samoan-circle/

HLPE (High-Level Panel of Experts). 2017. *Nutrition and food systems.* A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome. https://www.fao.org/3/a-i7846e.pdf

HLPE. 2019. *Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.* Rome. https://www.fao.org/3/ca5602en/ca5602en.pdf

Holden, N.M., White, E.P., Lange, M.C. & Oldfield, T.L. 2018. Review of the sustainability of food systems and transition using the Internet of Food. *npj Science of Food*, 2(1): 18. https://doi.org/10.1038/s41538-018-0027-3

IMF (International Monetary Fund). 2024. *World Economic Outlook Update: The Global Economy in a Sticky Spot*. https://www.imf.org/en/Publications/WEO/Issues/2024/07/16/world-economic-outlook-update-july-2024

IPCC (Intergovernmental Panel on Climate Change). 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. New York. https://doi.org/10.1017/9781009325844

Iseman, T. and Miralles-Wilhelm, F. 2021. *Nature-based solutions in agriculture – The case and pathway for adoption.* Virginia. FAO and The Nature Conservancy. https://doi.org/10.4060/cb3141en

Islam, M.R., Oliullah, K., Kabir, M.M., Alom, M. & Mridha, M.F. 2023. Machine learning enabled IoT system for soil nutrients monitoring and crop recommendation. *Journal of Agriculture and Food Research*, 14: 100880. https://doi.org/10.1016/j.jafr.2023.100880

ISPA (International Society of Precision Agriculture). 2024. Precision Agriculture Definition. In: I*nternational Society of Precision Agriculture.* [Cited 8 October 2024]. https://www.ispag.org/about/definition

ITU (International Telecommunication Union). 2023. *ITU Focus Group Technical Specification: Definition of metaverse*. Geneva. https://www.itu.int/en/ITU-T/focusgroups/mv/Documents/List%20of%20FG-MV%20deliverables/FGMV-20.pdf

IUCN (International Union for Conservation of Nature). 2016. *Nature-based solutions to address global societal challenges*. Gland. https://iucn.org/resources/publication/nature-based-solutions-address-global-societal-challenges

Jakšić, Z. & Jakšić, O. 2020. Biomimetic Nanomembranes: An Overview. *Biomimetics*, 5(2): 24. https://doi.org/10.3390/biomimetics5020024

Jahel, C., Bourgeois, R., Pesche, D., De Lattre-Gasquet, M. & Delay, E. 2021. *Has the COVID-19 Crisis Changed Our Relationship to the Future? Future & Foresight Science* 3 (2): e75. https://doi.org/10.1002/ffo2.75.

Janga, J.K., Reddy, K.R. & Raviteja, K.V.N.S. 2023. Integrating artificial intelligence, machine learning, and deep learning approaches into remediation of contaminated sites: A review. *Chemosphere*, 345: 140476. https://doi.org/10.1016/j.chemosphere.2023.140476

Javaid, M., Haleem, A., Khan, I.H. & Suman, R. 2023. Understanding the potential applications of Artificial Intelligence in Agriculture Sector. *Advanced Agrochem*, 2(1): 15–30. https://doi.org/10.1016/j.aac.2022.10.001

Javed, M.U., Mukhtar, H., Hayat, M.T., Rashid, U., Mumtaz, M.W. & Ngamcharussrivichai, C. 2022. Sustainable processing of algal biomass for a comprehensive biorefinery. *Journal of Biotechnology*, 352: 47–58. https://doi.org/10.1016/j.jbiotec.2022.05.009

Jhu, M.-Y., Ellison, E.E. & Sinha, N.R. 2023. CRISPR gene editing to improve crop resistance to parasitic plants. *Frontiers in Genome Editing*, 5. https://doi.org/10.3389/fgeed.2023.1289416

Jimenez, J., Gamble-George, J., Danies, G., Hamm, R.L. & Porras, A.M. 2022. Public Engagement with Biotechnology Inside and Outside the Classroom: Community-Focused Approaches. *GEN Biotechnology*, 1(4): 346–354. https://doi.org/10.1089/genbio.2022.0024

Jin, S., Camps, A., Jia, Y., Wang, F., Martin-Neira, M., Huang, F., Yan, Q. *et al.* 2024. Remote sensing and its applications using GNSS reflected signals: advances and prospects. *Satellite Navigation*, 5(1): 19. https://doi.org/10.1186/s43020-024-00139-4

Joga, M.R., Mogilicherla, K., Smagghe, G. & Roy, A. 2021. RNA Interference-Based Forest Protection Products (FPPs) Against Wood-Boring Coleopterans: Hope or Hype? *Frontiers in Plant Science*, 12. https://doi.org/10.3389/fpls.2021.733608

Kabir, M. & Ekici, S. 2024. Energy-agriculture nexus: Exploring the future of artificial intelligence applications. *Energy Nexus*, 13: 100263. https://doi.org/10.1016/j.nexus.2023.100263

Kang, D.-H., Louis, F., Liu, H., Shimoda, H., Nishiyama, Y., Nozawa, H., Kakitani, M. *et al.* 2021. Engineered whole cut meat-like tissue by the assembly of cell fibers using tendon-gel integrated bioprinting. *Nature Communications*, 12(1): 5059. https://doi.org/10.1038/s41467-021-25236-9

Khan, M.A., Khan, R., Praveen, P., Verma, A.R. & Panda, M.K. 2024. *Infrastructure Possibilities and Human-Centered Approaches with Industry 5.0*. IGI Global. https://doi.org/10.4018/979-8-3693-0782-3

Khan, N., Medlock, G., Graves, S., Anwar, S., Khan, N., Medlock, G., Graves, S. & Anwar, S. 2018. *GPS Guided Autonomous Navigation of a Small Agricultural Robot with Automated Fertilizing System*. WCX World Congress Experience, SAE International, 3 April 2018. https://doi.org/10.4271/2018-01-0031

Khan, S., Singh, R., Khan, S. & Ngah, A.H. 2023. Unearthing the barriers of Internet of Things adoption in food supply chain: A developing country perspective. *Green Technologies and Sustainability*, 1(2): 100023. https://doi.org/10.1016/j.grets.2023.100023

Kouzinopoulos, C.S., Pechlivani, E.M., Giakoumoglou, N., Papaioannou, A., Pemas, S., Christakakis, P., Ioannidis, D. & Tzovaras, D. 2024. A Citizen Science Tool Based on an Energy Autonomous Embedded System with Environmental Sensors and Hyperspectral Imaging. *Journal of Low Power Electronics and Applications*, 14(2): 19. https://doi.org/10.3390/jlpea14020019

Kuhn, T.S. 1962/1970. *The Structure of Scientific Revolutions*. 2nd edition, with postscript. Chicago, USA, University of Chicago Press

Kumar, B. & Verma, P. 2021. Biomass-based biorefineries: An important architype towards a circular economy. *Fuel*, 288: 119622. h ttps://doi.org/10.1016/j.fuel.2020.119622

LaFleur, M.W., Nguyen, T.H., Coxe, M.A., Yates, K.B., Trombley, J.D., Weiss, S.A., Brown, F.D. ***et al.*** 2019. A CRISPR-Cas9 delivery system for in vivo screening of genes in the immune system. *Nature Communications*, 10(1): 1668. https://doi.org/10.1038/s41467-019-09656-2

Leakey, R. 2024. *Living With the Trees of Life: A Practical Guide to Rebooting the Planet through Tropical Agriculture and Putting Farmers First, 2nd Edition*. CABI.

Li, G. & Yao, J. 2024. Direct Air Capture (DAC) for Achieving Net-Zero CO2 Emissions: Advances, Applications, and Challenges. *Eng*, 5(3): 1298–1336. https://doi.org/10.3390/eng5030069

Li, Z. & Ning, H. 2023. Autonomous GIS: the next-generation AI-powered GIS. *International Journal of Digital Earth*, 16(2): 4668–4686. https://doi.org/10.1080/17538947.2023.2278895

Liakos, K.G., Busato, P., Moshou, D., Pearson, S. & Bochtis, D. 2018. Machine Learning in Agriculture: A Review. *Sensors*, 18(8): 2674. https://doi.org/10.3390/s18082674

Lin, Z. 2022. Nano-chitin in 3D Printing Technology: Its Structure, Preparation and Application. *Academic Journal of Science and Technology*, 4(1): 63–66. https://doi.org/10.54097/ajst.v4i1.3254

Liu, Z., Xiang, Y., Shi, J., Gao, P., Wang, H., Xiao, X., Wen, B., Li, Q. & Hu, Y.-C. 2022. Make Web3.0 Connected. *IEEE Transactions on Dependable and Secure Computing*, 19(5): 2965–2981. https://doi.org/10.1109/TDSC.2021.3079315

Lu, G., Li, S., Mai, G., Sun, J., Zhu, D., Chai, L., Sun, H. ***et al.*** 2023. AGI for Agriculture. In: *arXiv.org*. [Cited 8 October 2024]. https://arxiv.org/abs/2304.06136v1

Lu, K., Li, L., Jiang, S., Chen, X., Chang, Q., Shi, Y. & Li, Y. 2023. Advanced Bioinspired Organic Sensors for Future-Oriented Intelligent Applications. *Advanced Sensor Research*, 2(7): 2200066. https://doi.org/10.1002/adsr.202200066

Lum, K.K., Kim, J. & Lei, X.G. 2013. Dual potential of microalgae as a sustainable biofuel feedstock and animal feed. *Journal of Animal Science and Biotechnology*, 4(1): 53. https://doi.org/10.1186/2049-1891-4-53

Lv, X., Wu, Y., Gong, M., Deng, J., Gu, Y., Liu, Y., Li, J. ***et al.*** 2021. Synthetic biology for future food: Research progress and future directions. *Future Foods*, 3: 100025. https://doi.org/10.1016/j.fufo.2021.100025

Macnaghten, P., Owen, R., Stilgoe, J., Wynne, B., Azevedo, A., de Campos, A., Chilvers, J. ***et al.*** 2014. Responsible innovation across borders: tensions, paradoxes and possibilities. *Journal of Responsible Innovation*, 1(2): 191–199. https://doi.org/10.1080/23299460.2014.922249

Miller, R. 2019. *Transforming the Future: Anticipation in the 21st Century*. First edition. Routledge. https://www.routledge.com/Transforming-the-Future-Anticipation-in-the-21st-Century/Miller/p/book/9780367855888

Millner, R. & Meyer, M. 2021. Collaborative governance in Social Impact Bonds: aligning interests within divergent accountabilities? *Public Management Review*, 24(5): 729–751. https://doi.org/10.1080/14719037.2021.2000253

Mohamed, A.R., Ochsenkühn, M.A., Kazlak, A.M., Moustafa, A. & Amin, S.A. 2023. The coral microbiome: towards an understanding of the molecular mechanisms of coral–microbiota interactions. *FEMS Microbiology Reviews*, 47(2): fuad005. https://doi.org/10.1093/femsre/fuad005

Mohammad, Z.H. & Ahmad, F. 2024. Nanocoating and its application as antimicrobials in the food industry: A review. *International Journal of Biological Macromolecules*, 254: 127906. https://doi.org/10.1016/j.ijbiomac.2023.127906

Monteiro, J. & Barata, J. 2021. Artificial Intelligence in Extended Agri-Food Supply Chain: A Short Review Based on Bibliometric Analysis. *Procedia Computer Science*, 192: 3020–3029. https://doi.org/10.1016/j.procs.2021.09.074

Mourad, K.A., Hosseini, S.H. & Avery, H. 2020. The Role of Citizen Science in Sustainable Agriculture. *Sustainability*, 12(24): 10375. https://doi.org/10.3390/su122410375

Nijak, M., Skrzypczyński, P., Ćwian, K., Zawada, M., Szymczyk, S. & Wojciechowski, J. 2024. On the Importance of Precise Positioning in Robotised Agriculture. *Remote Sensing*, 16(6): 985. https://doi.org/10.3390/rs16060985

OECD (Organisation for Economic Cooperation and Development). 2017. *Behavioural Insights and Public Policy: Lessons from Around the World*. Paris. https://doi.org/10.1787/9789264270480-en

OECD. 2020. *Nature-based solutions for adapting to water-related climate risks*. Paris. https://doi.org/10.1787/2257873d-en.

Ofori, K.F., Antoniello, S., English, M.M. & Aryee, A.N.A. 2022. Improving nutrition through biofortification–A systematic review. *Frontiers in Nutrition*, 9. https://doi.org/10.3389/fnut.2022.1043655

Olabi, A.G., Onumaegbu, C., Wilberforce, T., Ramadan, M., Abdelkareem, M.A. & Al – Alami, A.H. 2021. Critical review of energy storage systems. *Energy*, 214: 118987. https://doi.org/10.1016/j.energy.2020.118987

Orozco-Meléndez, J.F. & Paneque-Gálvez, J. 2022. A role for grassroots innovation toward agroecological transitions in the Global South? Evidence from Mexico. *Ecological Economics*, 201: 107582. https://doi.org/10.1016/j.ecolecon.2022.107582

Peladarinos, N., Piromalis, D., Cheimaras, V., Tserepas, E., Munteanu, R.A. & Papageorgas, P. 2023. Enhancing Smart Agriculture by Implementing Digital Twins: A Comprehensive Review. *Sensors*, 23(16): 7128. https://doi.org/10.3390/s23167128

Prasad, R., Bhattacharyya, A. & Nguyen, Q.D. 2017. Nanotechnology in Sustainable Agriculture: Recent Developments, Challenges, and Perspectives. *Frontiers in Microbiology*, 8. https://doi.org/10.3389/fmicb.2017.01014

Pylianidis, C., Osinga, S. & Athanasiadis, I.N. 2021. Introducing digital twins to agriculture. *Computers and Electronics in Agriculture*, 184: 105942. https://doi.org/10.1016/j.compag.2020.105942

Rafeeq, H., Afsheen, N., Rafique, S., Arshad, A., Intisar, M., Hussain, A., Bilal, M. & Iqbal, H.M.N. 2023. Genetically engineered microorganisms for environmental remediation. *Chemosphere*, 310: 136751. https://doi.org/10.1016/j.chemosphere.2022.136751

Ranganathan, V., Kumar, P., Kaur, U., Li, S.H.Q., Chakraborty, T. & Chandra, R. 2022. Re-Inventing the Food Supply Chain with IoT: A Data-Driven Solution to Reduce Food Loss. *IEEE Internet of Things Magazine*, 5(1): 41–47. https://doi.org/10.1109/IOTM.003.2200025

Rathore, A., Hasan, W., M, R.N., Pujar, K., Singh, R., Panotra, N. & Satapathy, S.N. 2024. Nanotech for Crop Protection: Utilizing Nanoparticles for Targeted Pesticide Delivery. *UTTAR PRADESH JOURNAL OF ZOOLOGY*, 45(6): 46–71. https://doi.org/10.56557/upjoz/2024/v45i63950

Ravelo, S., Alejandro, A., Rocandio-Rodríguez, M. & Vanoye-Eligio, V. 2016. Bioremediation of wastewater for reutilization in agricultural systems: A review. *Applied Ecology and Environmental Research*, 15: 33–50. https://doi.org/10.15666/aeer/1501_033050

Reynolds, C., Oakden, L., West, S., Pateman, R., Elliott, C., Armstrong, B., Gillespie, R. & Patel, M. 2021. Citizen science for the food system. pp. 55–69

Rob, W. 2016. RoboBees: Autonomous Flying Microrobots. In: *Wyss Institute*. [Cited 8 October 2024]. https://wyss.harvard.edu/technology/robobees-autonomous-flying-microrobots/

Rodrigues, C.I.D., Brito, L.M. & Nunes, L.J.R. 2023. Soil Carbon Sequestration in the Context of Climate Change Mitigation: A Review. *Soil Systems*, 7(3): 64. https://doi.org/10.3390/soilsystems7030064

Rylott, E.L. & Bruce, N.C. 2020. How synthetic biology can help bioremediation. *Current Opinion in Chemical Biology*, 58: 86–95. https://doi.org/10.1016/j.cbpa.2020.07.004

Saito, M., Xu, P., Faure, G., Maguire, S., Kannan, S., Altae-Tran, H., Vo, S. *et al.* 2023. Fanzor is a eukaryotic programmable RNA-guided endonuclease. *Nature*, 620(7974): 660–668. https://doi.org/10.1038/s41586-023-06356-2

Sankhla, M.S., Kumar, R. & Shefali. 2020. New and Advanced Technologies in Aquaculture to Support Environmentally Sustainable Development. In: J. Singh, A. Vyas, S. Wang & R. Prasad, eds. *Microbial Biotechnology: Basic Research and Applications*. pp. 249–263. Singapore, Springer. https://doi.org/10.1007/978-981-15-2817-0_11

Santhakumaran, P., Kookal, S.K. & Ray, J.G. 2018. Biomass yield and biochemical profile of fourteen species of fast-growing green algae from eutrophic bloomed freshwaters of Kerala, South India. *Biomass and Bioenergy*, 119: 155–165. https://doi.org/10.1016/j.biombioe.2018.09.021

Schubert, M.G., Goodman, D.B., Wannier, T.M., Kaur, D., Farzadfard, F., Lu, T.K., Shipman, S.L. & Church, G.M. 2021. High-throughput functional variant screens via in vivo production of single-stranded DNA. *Proceedings of the National Academy of Sciences*, 118(18): e2018181118. https://doi.org/10.1073/pnas.2018181118

Seyfang, G. & Longhurst, N. 2013. Desperately seeking niches: Grassroots innovations and niche development in the community currency field. *Global Environmental Change*, 23(5): 881–891. https://doi.org/10.1016/j.gloenvcha.2013.02.007

Seyfang, G. & Smith, A. 2007. Grassroots innovations for sustainable development: Towards a new research and policy agenda. *Environmental Politics*, 16(4): 584–603. https://doi.org/10.1080/09644010701419121

Soto, M.J., López-Lara, I.M., Geiger, O., Romero-Puertas, M.C. & van Dillewijn, P. 2021. Rhizobial Volatiles: Potential New Players in the Complex Interkingdom Signaling With Legumes. *Frontiers in Plant Science*, 12. https://doi.org/10.3389/fpls.2021.698912

Stamford, C. 2024. Gartner 2024 Hype Cycle for Emerging Technologies Highlights Developer Productivity, Total Experience, AI and Security. In: *Gartner*. [Cited 9 October 2024]. https://www.gartner.com/en/newsroom/press-releases/2024-08-21-gartner-2024-hype-cycle-for-emerging-technologies-highlights-developer-productivity-total-experience-ai-and-security

Stilgoe, J., Owen, R. & Macnaghten, P. 2013. Developing a framework for responsible innovation. *Research Policy*, 42(9): 1568–1580. https://doi.org/10.1016/j.respol.2013.05.008

Sufyan, A., Khan, K.B., Khashan, O.A., Mir, T. & Mir, U. 2023. From 5G to beyond 5G: A Comprehensive Survey of Wireless Network Evolution, Challenges, and Promising Technologies. *Electronics*, 12(10): 2200. https://doi.org/10.3390/electronics12102200

Tanaka, S., Asignacion, A., Nakata, T., Suzuki, S. & Liu, H. 2022. Review of Biomimetic Approaches for Drones. *Drones*, 6(11): 320. https://doi.org/10.3390/drones6110320

TAP (Tropical Agriculture Platform). 2016. Common Framework on Capacity Development for Agricultural Innovation Systems: Conceptual Background. Wallingford, UK. https://www.cabi.org/Uploads/CABI/about-us/4.8.5-other-business-policies-and-strategies/tap-conceptual-background.pdf

TAPipedia. 2017. The 4 + 1 Capacities. In: *TAPipedia*. [Cited 8 October 2024]. https://tapipedia.org/framework/4-1-capacities

Tarhini, M. 2021. Application of asset tokenization, smart contracts and decentralized finance in agriculture. *Journal of Financial Studies*, 10(6): 152–163.

Tchonkouang, R.D., Onyeaka, H. & Nkoutchou, H. 2024. Assessing the vulnerability of food supply chains to climate change-induced disruptions. *Science of The Total Environment*, 920: 171047. https://doi.org/10.1016/j.scitotenv.2024.171047

The World Bank. 2024. Energy Efficiency Drives Greener Economies in Europe and Central Asia. In: *World Bank*. [Cited 8 October 2024]. https://www.worldbank.org/en/news/infographic/2024/06/25/energy-efficiency-drives-greener-economies-in-europe-and-central-asia

Theissinger, K., Fernandes, C., Formenti, G., Bista, I., Berg, P.R., Bleidorn, C., Bombarely, A. *et al.* 2023. How genomics can help biodiversity conservation. *Trends in Genetics*, 39(7): 545–559. https://doi.org/10.1016/j.tig.2023.01.005

Theodore Armand, T.P., Nfor, K.A., Kim, J.-I. & Kim, H.-C. 2024. Applications of Artificial Intelligence, Machine Learning, and Deep Learning in Nutrition: A Systematic Review. *Nutrients*, 16(7): 1073. https://doi.org/10.3390/nu16071073

Toffolini, Q., Hannachi, M., Capitaine, M. & Cerf, M. 2023. Ideal-types of experimentation practices in agricultural Living Labs: Various appropriations of an open innovation model. *Agricultural Systems*, 208: 103661. https://doi.org/10.1016/j.agsy.2023.103661

Torres-Vanegas, J.D., Cruz, J.C. & Reyes, L.H. 2021. Delivery Systems for Nucleic Acids and Proteins: Barriers, Cell Capture Pathways and Nanocarriers. *Pharmaceutics*, 13(3): 428. https://doi.org/10.3390/pharmaceutics13030428

Udeh, C.A., Orieno, O.H., Daraojimba, O.D., Ndubuisi, N.L. & Oriekhoe, O.I. 2024. Big data analytics: a review of its transformative role in modern business intelligence. *Computer Science & IT Research Journal*, 5(1): 219–236. https://doi.org/10.51594/csitrj.v5i1.718

Ukoba, K., Olatunji, K.O., Adeoye, E., Jen, T.-C. & Madyira, D.M. 2024. Optimizing renewable energy systems through artificial intelligence: Review and future prospects. *Energy & Environment*: 0958305X241256293. https://doi.org/10.1177/0958305X241256293

UN Futures Lab. 2023. *UN Strategic Foresight Guide*. https://un-futureslab.org/media/uploads/2024/03/UN-Futures-Lab-2023-UN-Strategic-Foresight-Guide.pdf

UNDESA (United Nations Department of Economic and Social Affairs). 2021. *Circular agriculture for sustainable rural development*. https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/publication/PB_105.pdf

UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific). 2022. Accelerating one health in Asia and the Pacific. https://repository.unescap.org/handle/20.500.12870/4408

United Nations. 2024. *Reinforcing the 2030 Agenda for Sustainable Development and eradicating poverty in times of multiple crises: the effective delivery of sustainable, resilient and innovative solutions: report of the Secretary-General*. New York. http://digitallibrary.un.org/record/4049579

Urnov, F.D., Rebar, E.J., Holmes, M.C., Zhang, H.S. & Gregory, P.D. 2010. Genome editing with engineered zinc finger nucleases. *Nature Reviews Genetics*, 11(9): 636–646. https://doi.org/10.1038/nrg2842

Urueña, S., Rodríguez, H. & Ibarra, A. 2021. Foresight and responsible innovation: Openness and closure in anticipatory heuristics. *Futures*, 134: 102852. https://doi.org/10.1016/j.futures.2021.102852

van de Gevel, J., van Etten, J. & Deterding, S. 2020. Citizen science breathes new life into participatory agricultural research. A review. *Agronomy for Sustainable Development*, 40(5): 35. https://doi.org/10.1007/s13593-020-00636-1

van Hooijdonk, R. 2022. Are floating cities the solution to rising sea levels? In: *Richard van Hooijdonk Blog*. [Cited 8 October 2024]. https://blog.richardvanhooijdonk.com/en/are-floating-cities-the-solution-to-rising-sea-levels/

Vasen, F. 2017. Responsible Innovation in Developing Countries: An Enlarged Agenda. In: *Responsible Innovation 3: A European Agenda?* pp. 93–109. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-319-64834-7_6

Verma, K. & Modgil, M. 2024. RNA interference (RNAi) mediated technique for combating plant diseases: Harnessing nanoparticles for effective delivery and enhanced efficacy. *Plant Cell, Tissue and Organ Culture (PCTOC)*, 157(3): 53. https://doi.org/10.1007/s11240-024-02773-x

WEF (World Economic Forum). 2024. How the top 10 emerging technologies of 2024 will impact the world. In: *World Economic Forum*. [Cited 8 October 2024]. https://www.weforum.org/agenda/2024/06/top-10-emerging-technologies-of-2024-impact-world/

WIPO (World Intellectual Property Organization). 2024a. *World Intellectual Property Report 2024: Making innovation policy worth for development*. Geneva. https://www.wipo.int/web-publications/world-intellectual-property-report-2024/assets/60090/944_WIPR_2024_WEB.pdf

WIPO. 2024b. *Global Innovation Index 2024: Unlocking the Promise of Social Entrepreneurship*. Geneva. https://www.wipo.int/web-publications/global-innovation-index-2024/index.html

Wolfert, S., Ge, L., Verdouw, C. & Bogaardt, M.-J. 2017. Big Data in Smart Farming – A review. *Agricultural Systems*, 153: 69–80. https://doi.org/10.1016/j.agsy.2017.01.023

Yadav, A., Yadav, K. & Abd-Elsalam, K.A. 2023. Nanofertilizers: Types, Delivery and Advantages in Agricultural Sustainability. *Agrochemicals*, 2(2): 296–336. https://doi.org/10.3390/agrochemicals2020019

Yadav, N., Garg, V.K., Chhillar, A.K. & Rana, J.S. 2023. Recent advances in nanotechnology for the improvement of conventional agricultural systems: A review. *Plant Nano Biology*, 4: 100032. https://doi.org/10.1016/j.plana.2023.100032

Yang, Z., Zeng, X., Zhao, Y. & Chen, R. 2023. AlphaFold2 and its applications in the fields of biology and medicine. *Signal Transduction and Targeted Therapy*, 8(1): 1–14. https://doi.org/10.1038/s41392-023-01381-z

Yoo, H. & Park, D. 2021. AI-Based 3D Food Printing Using Standard Composite Materials. In: J. Kim & R. Lee, eds. *Data Science and Digital Transformation in the Fourth Industrial Revolution*. pp. 123–135. Cham, Springer International Publishing. https://doi.org/10.1007/978-3-030-64769-8_10

Yu, I.K.M. & Wong, K.-H. 2023. Food waste-derived 3D printable materials: A carbon neutral solution to global foodloss. *Trends in Food Science & Technology*, 137: 156–166. https://doi.org/10.1016/j.tifs.2023.05.014

Zhang, A., Shan, T., Sun, Y., Chen, Z., Hu, J., Hu, Z., Ming, Z. *et al.* 2023. Directed evolution rice genes with randomly multiplexed sgRNAs assembly of base editors. *Plant Biotechnology Journal*, 21(12): 2597–2610. https://doi.org/10.1111/pbi.14156

Zhang, F., Zhang, Y., Lu, W., Gao, Y., Gong, Y. & Cao, J. 2022. 6G-Enabled Smart Agriculture: A Review and Prospect. *Electronics*, 11(18): 2845. https://doi.org/10.3390/electronics11182845

Zhang, M., Liu, R. & Li, Y. 2022. Diversifying Water Sources with Atmospheric Water Harvesting to Enhance Water Supply Resilience. *Sustainability*, 14(13): 7783. https://doi.org/10.3390/su14137783

CONTACT

Office of Innovation
OIN-Director@fao.org

Food and Agriculture Organization of the United Nations
Rome, Italy

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