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Harvesting change: Harnessing emerging technologies and innovations for agrifood systems transformation

Global foresight synthesis report

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Acknowledgements

The horizon scanning and strategic foresight on emerging technologies and innovations in the agrifood systems was developed to inform strategic long-term planning for a conducive policy environment to ensure that technologies and innovations are effective, inclusive and sustainable, and can address intertwined and complex challenges facing agrifood systems.

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Abbreviations

AFS	agrifood systems
AI	artificial intelligence
AIS	Agricultural innovation systems
AR	Augmented reality
CIRAD	French Agricultural Research Centre for International Development
CSO	Civil society organizations
ETM	Earliest time to mature
FAO	Food and Agriculture Organization of the United Nations
FOFA	Future of Food and Agriculture publication series of FAO
GIS	Geographic information system
IAFN	International Agrifood Network
IO	International organizations
MEL	Monitoring, evaluation and learning
PPP	Public-private partnerships
PS	Private sector
RA	Relative advantage
R&D	Research and development
RNA	Ribonucleic acid
SIF	Science and Innovation Forum
SDGs	Sustainable Development Goals
SOFA	State of Food and Agriculture
STI	Science, technology and innovations
VR	Virtual reality
WIF	World Investment Forum
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.

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.

Agricultural 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".

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.

Pre-emerging technologies: technologies that are under development but not yet in use outside the community of developers.

Emerging technologies: technologies that are developing, have moved away from their source of origin – often, but not always, research stations, laboratories and academic journals – into the real world but not fully and largely adopted.

ETM (Earliest Time to Mature): the minimal amount of time needed for the large application of a solution or reaching full maturity. 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 is 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.

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.

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.

Relative advantage (RA): the degree of improvement that the proposed solutions might bring to the realisation 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 realisation 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.

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 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 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 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

We find ourselves amidst an era marked by an unprecedented polycrisis, where our agrifood systems grapple with intricate challenges that demand immediate attention. In the face of this complexity, technology and innovation emerge as powerful tools, capable of hastening the transformation towards agrifood systems that are not only resilient but also sustainable and inclusive.

A critical aspect of this transformation lies in bridging the gap between the inception of a technology or innovation and its practical application. Success in this endeavor hinges on the creation of an environment conducive to maximizing benefits and minimizing challenges posed by potentially disruptive technologies. This report, employing foresight methodologies such as horizon scanning, scenario building, and strategic foresight, aims to address the knowledge gap surrounding emerging agrifood technologies and innovations across different time horizons—ranging from 2030 to 2050 and beyond.

A clarion call to action, the report urges the improvement and repurposing of research and development programmes, policies, and investments within the realm of agrifood science, technology, and innovation. Beyond the confines of agrifood, the exploration extends to broader technological arenas, encompassing quantum physics, energy, materials, policy, market dynamics, and social innovations.

In chapter 1, we present the rationale, goals and methodology of the foresight on emerging technologies and innovations.

167 emerging agrifood technologies and innovations have been identified so far and a typology has been proposed. Chapter 2 undertakes a comprehensive horizon scan of 32 the most promising ones, categorizing them based on impact, timeline, and place of application. These 32 technologies and innovations, spread across all components of agrifood systems, have been further analysed through collective intelligence for their perceived potential to address multiple and single agrifood challenges and their horizon of emergence. Furthermore, 20 were singled out for special attention by decision-makers and a broader multistakeholder community. One of the salient insights from this section is that the innovations centered around policy, nature-based solutions and data-driven technologies seem to be the most impactful and are expected to be adopted sooner. Regional analyses underscore the imperative of global collaboration to ensure the equitable distribution of benefits across diverse parts of the world.

The foresight on emerging technologies and innovations in agrifood systems is intended to inform long-term policy making and investments in science, technology and innovation (STI) while building multistakeholder consensus with the ultimate goal of accelerating the transformation of agrifood systems towards more sustainable, resilient and inclusive patterns. Delving into strategic foresight in Chapter 3, the report prioritizes the 18 drivers of agrifood systems and dissects internal trends within technology and innovation. It identifies potential low-probability, high-impact events (wildcards) and triggers for change that could influence the emergence of agrifood technologies. Expert consultation and collective intelligence sessions result in the development of five future scenarios, offering nuanced and plausible visions of the future. These scenarios, including struggling between technological illusions and sustainability, mess and muddle in technologies and innovations, sustainable prosperity, artificial intelligence in charge, and technologies as our best-last chance, guide actions toward desirable futures while avoiding non-desirable outcomes.

Executive summary

The lessons drawn from this foresight exercise underscore the pivotal role of governance, partnerships, ethical considerations, and the engagement of stakeholders in shaping a desirable future. Lastly, chapter 4 presents final considerations for strategic planning and recommendations, emphasizing that the solution lies not solely in technology but also in policy, social, and financial innovations that facilitate access to science, technology, and innovation (STI).

The report emphasizes that no singular technology or innovation serves as a "silver bullet." Instead, the emphasis is on having a myriad of options at hand and combining them judiciously, in partnership with diverse stakeholders, to effect transformative change and create impact where it is most needed.

Recognizing that different pathways of change, whether incremental or disruptive, will coexist, the report notes that disruptive technologies necessitate longer emergence times due to changes required in infrastructure, investments, human and social capital, policy environments, and mindsets. The more disruptive the technology, the greater the uncertainty it brings. Hence, in the short term, there is a call to focus on ex-ante risk-benefit assessment frameworks to fully leverage the potential of disruptive technologies.

A systemic, co-creative, and anticipatory approach is advocated to decrease the time lag between research and investment phases, ensuring that technologies remain relevant when applied. The report stresses the need for an inclusive feedback mechanism, enabling technologies and innovations to evolve alongside users' needs and the dynamic context of agrifood systems. Through such holistic and collaborative efforts, the report envisions a future where technology, innovation, and policy seamlessly converge to address the multifaceted challenges of agrifood systems, steering them towards sustainability, resilience, and inclusivity.


CO2
AI

1

Introduction

CALL TO ACTION – TURNING OUR WORLD TOWARDS 2030[1]

We have entered an age of polycrisis that affects the way we produce, distribute and consume food. The UN Sustainable Development Goals Progress report: Special Edition (UN, 2023) informed that just 12 percent of the SDG targets are on track, while we have stalled or gone into reverse on more than 30 percent of the SDGs: for example, hunger is back to 2005 levels. The report calls for renewed commitments and immediate actions from governments and stakeholders to reduce hunger, poverty and inequalities including gender inequality, merge the digital divide and make advances in new business models, regulatory frameworks and capacities to close the gaps in the achievement of SDGs.

But agrifood systems face complex, intertwined and unprecedented challenges that impede the much-needed transformation of agrifood systems.

FAO has formulated 12 challenges faced by agrifood systems in the book Trends and Challenges (FAO, 2017). Taking into account the findings of the FAO flagship publication SOFA (FAO, 2021), we also enriched and consolidated the agrifood challenges to eight, as follows; (i) population and development dynamics, food and nutrition security, sustainable diets; (ii) climate change, disasters, conflicts and protracted crises; (iii) erosion of natural resource base, loss of biodiversity; (iv) food loss and waste; (v) energy demand and use in agrifood systems; (vi) inclusion of the most vulnerable; (vii) transboundary and emerging agrifood systems threats; and (viii) national and international governance Annex 1.

ACCELERATING THE AGRIFOOD SYSTEMS TRANSFORMATION THROUGH EMERGING AGRIFOOD TECHNOLOGIES AND INNOVATIONS

Advancements in technology and innovation have unquestionably shaped the trajectory of agriculture throughout human history. Technologies and innovations are essential for achieving the Sustainable Development Goals and are key triggers for transforming the agrifood systems towards more efficient, resilient, sustainable and inclusive patterns (FOFA. FAO, 2022). The impact of agrifood technologies and innovations is real and immediate.

In the digital innovation domain only, with the introduction of big data analytics, cloud computing, cheap and improved sensors and high-bandwidth mobile communication, a revolution in agriculture has been observed in the past decade, known as Agriculture 4.0. It paved the way for the next (r)evolution, consisting of unmanned operations and autonomous decision systems, and based on quantum computing and artificial intelligence.

1 *UN General Assembly. Political declaration of the high-level political forum on sustainable development convened under the auspices of the General Assembly. Draft resolution. A/HLPF/2023/L.1, also at https://hlpf.un.org/sites/default/files/2023-09*

However, technology and innovation dividends are not automatic, and not everyone can benefit equally. The impact of new disruptive technologies is still unknown. Furthermore, conceiving a technology or innovation from its ideation phase – through experimenting in the lab and later on the field when the technology or innovation emerges to its full maturity when it is in use and impacts for change – is often a lengthy process that may involve high investment cost. Despite those investments in time, effort and capital, and the pressing need to address agrifood challenges, many technologies and innovations show a very low adoption rate (for example 9 percent for farm automation and robotics in China and India among row- and specialty-crop farmers, Fiocco D. *et al.* 2023).

To maximize the benefits and minimize challenges associated with emerging technologies and innovations for the agrifood systems transformation, we need to reduce the time lag between technology generation and its use for impact, and accelerate its upscaling in other locations and contexts, while using the technology safely and responsibly in a sustainable manner, looking at environmental and socio-economic impacts.

WHY FORESIGHT?

To help navigate the uncertainty of challenges and trends in a science-based manner, the foresight practice is being increasingly used to connect the dots, with the help of collective intelligence, when evidence is not yet available. This concerns some innovation domains, due to their novelty and complexity.

Strategic foresight is increasingly applied in long-term public planning and shaping policy processes. Horizon scanning foresight could be very instrumental for envisaging potentially vital technological developments and anticipating their impact, threats and opportunities, especially in innovation areas, where knowledge-intensity, uncertainties, wide consensus-building needs and therefore policy stakes are greater. Foresight capacity is therefore recognized by the UN 2.0[2] as a core innovative skillset of change.

Building on previous FAO work on foresight of the agrifood systems (FOFA. FAO, 2022), FAO embarked on horizon scanning and strategic foresight on emerging technologies and innovations in agrifood systems to assist governments, practitioners, as well as other agricultural innovation system (AIS) actors and stakeholders to navigate complex challenges and trends, to establish the long-term vision and a large consensus and to efficiently plan resources for technologies and innovations in a more risk-averse agrifood sector.

Although the foresight instrument is powerful in long-term planning and consensus building, it is not absolute: it is just one of the many tools that policy and decision-makers can use. Foresight is not a forecast or a simple extrapolation of trends and indicators with an extended timeline. It is therefore not a prediction; it is meant to inform on contrasting but plausible future scenarios to provoke evidence-based and collectively informed actions today to avoid an undesirable future or achieve a desired goal tomorrow.

2 *UN 2.0 Quintet of Change. Available at https://www.un.org/sites/un2.un.org/files/2021/09/un_2.0_-_quintet_of_change.pdf*

GOALS

This foresight intends to:

- identify the technologies and innovations emerging in 2030, 2040, 2050 and beyond, and create a database and typology of them;
- survey and analyse the most impactful agrifood technologies and innovations as perceived by the expert- and broader stakeholder community for their potential to respond to single and multiple agrifood challenges, and timeline of emergence, including the timeline of the main breakthroughs expected per area of application;
- develop contrasting and plausible scenarios reflecting the conditions of emergence of technologies and innovations;
- provide insights on strategic planning of investments, incentives, research and innovation programmes and development initiatives as well as future policies and regulatory frameworks in the innovation domains

This report represents a synthesis of the horizon scanning and strategic foresight analysis that brings about insights for strategic planning on incentives, investments, research programmes and development initiatives. The forthcoming full report will analyse in depth the interface between drivers, trends and triggers, and further elaborate on regional aspects, transformative options and the way forward.

METHODS

To deliver on this ambitious goal, FAO has collaborated with CIRAD and other partners from research and education organizations, extension and advisory services, IAFN and other private business organizations and enterprises, policy makers and public institutions.

The findings were generated from July to October 2023 and are based on previous FAO work on foresight, a literature review of publications from the United Nations, other intergovernmental organizations, and non-governmental organizations, and also academic literature, a consensus-building Real-time Delphi[3] survey with the participation of expert- and multistakeholder communities, expert and multistakeholder consultations, interviews and high-level panel discussions with various stakeholders during the 8th session of the World Investment Forum, Abu Dhabi, United Arab Emirates on 17 October 2023 and FAO Science and Innovation Forum, Rome Italy on 19 October 2023. Over 250 experts and stakeholders took part in the foresight process.

The Real-time Delphi survey covered more emerging agrifood technologies and innovations that were pre-selected by the FAO team, stemming from a detailed expert interview process. While this list was comprehensive, it was not exhaustive. Participants were thus encouraged to suggest additional emerging agrifood technologies and innovations for potential analysis in subsequent FAO studies. Beyond just emerging agrifood technologies and innovations, participants had been tasked with

3 *A Real-Time Delphi (RTD) study is a variation of the traditional Delphi method. The Delphi method is a structured communication technique that relies on a panel of experts to achieve consensus on a particular subject. The process involves multiple rounds of questioning, and after each round, the results are aggregated and shared with the panel. Experts then have the opportunity to revise their answers based on feedback from the group. This iterative process continues until a consensus is reached or diminishing returns are observed. RTD is, conversely, a round-less process, in which experts receive immediate feedback on their input and the input of others. They can then adjust their answers in real time, without waiting for subsequent rounds.*

evaluating regional advantages and disadvantages concerning the adoption of these emerging technologies and innovations. They were also guided to pinpoint crucial agrifood systems drivers, change triggers, and the overarching trends propelling the evolution and adoption of the emerging technologies and innovations. Furthermore, they had been queried about the potential for significant breakthroughs in specific application domains. For every inquiry, detailed parameters for assessments and corresponding scales were provided. The participants weren't obliged to give feedback on topics they weren't well-versed in, especially those concerning regional specificities. A good coverage of regional expertise has been ensured, also during the expert and stakeholder consultations.

The following chart illustrates the methodology in brief Figure. 1 .

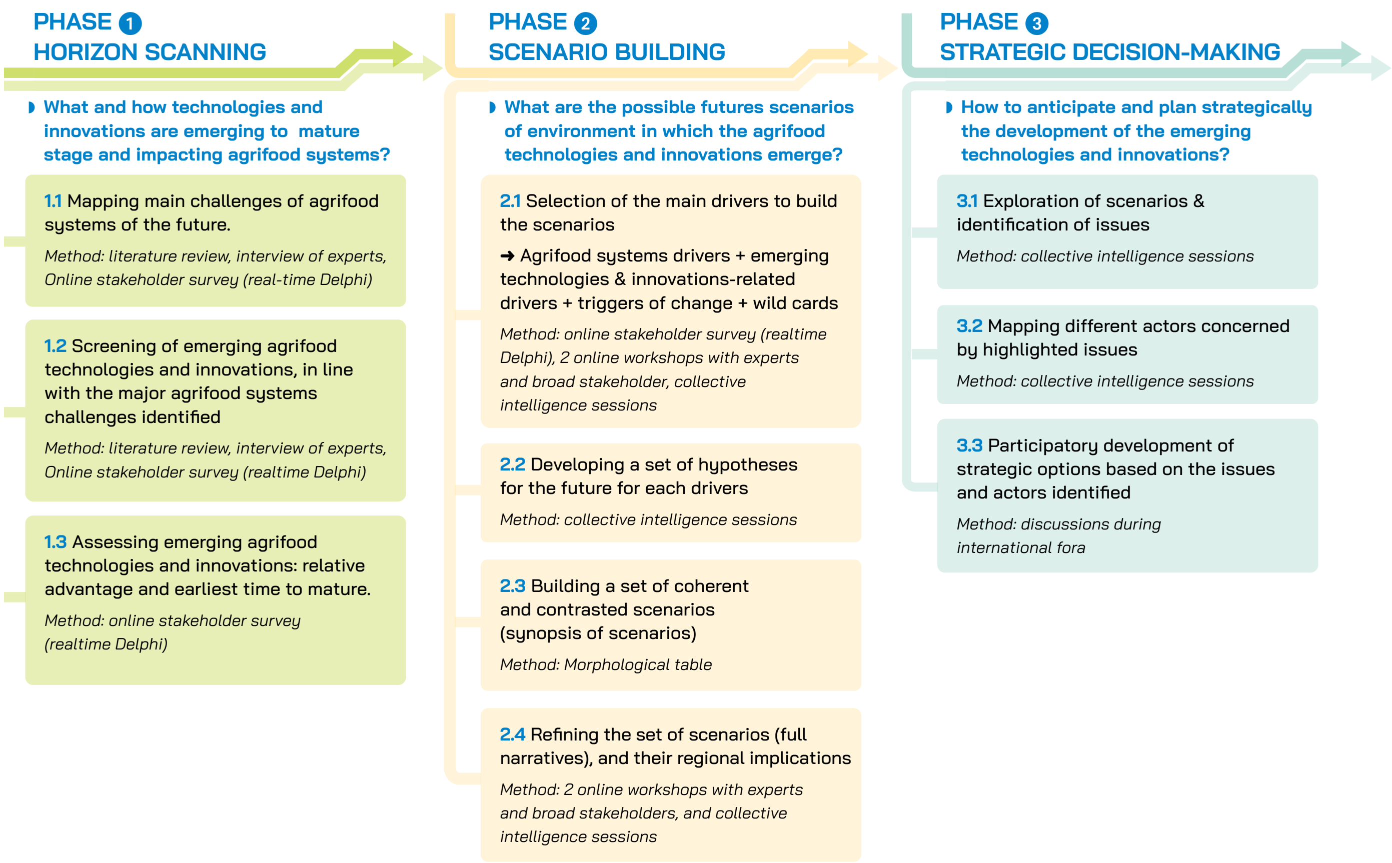

Figure 1: The three sequential phases of the foresight process on emerging agricultural technologies and innovations for agrifood systems of the future.

Despite being able to produce strategic recommendations, the more detailed decision-making results will be presented in the full report (forthcoming).

2

Horizon scanning of emerging agrifood technologies and innovations

SELECTED EMERGING AGRIFOOD TECHNOLOGIES AND INNOVATIONS: TYPOLOGY AND OVERVIEW

In the Horizon scanning process we identified more than 200 individual potential emerging agrifood technologies and innovations. This list has been subsequently revised to 167, reducing overlap and letting go of less innovative items. Subsequently, we identified 32 of the most promising ones and grouped them into eight clusters:

Figure 2: Emerging technologies and innovations clusters

Next, taking into account that some of the identified emerging agrifood technologies and innovations could potentially be of paramount importance in addressing some (or all) of the challenges Annex 1 facing global and regional agrifood systems, while others, although original, innovative and stimulating may have a lesser impact, we pre-selected those which had above-average positive scores in these terms.

The results of the Delphi final assessment of the selected emerging agrifood technologies and innovations are summarized and visualized below.

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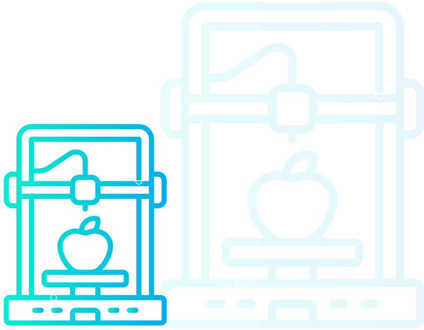


1 3D printing of food and liquids

Description
It is the process of utilizing 3D printing technology to create edible and liquid-based products. This innovative approach involves depositing and layering edible materials or liquids to produce a wide range of food items, beverages, and culinary creations. It offers the potential for customization, precise portion control, and the ability to design intricate structures, making it a promising tool in the food industry for creating unique and personalized culinary experiences.

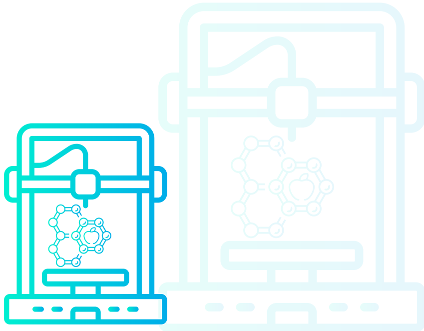
Allocation to clusters Food manufacturing technologies and nutrition

Relative advantage
3.3

Earliest time to mature
2052

Delphi Participants' Comments
3D food printing has the potential to alleviate pressures on natural resources and tackle issues related to healthy diets and transboundary diseases. However, its effectiveness hinges on its implementation and ensuring universal access. While this technology presents opportunities, it may adversely affect traditional diets and regional value chains. Notably, restaurants using 3D food printing have already emerged.

Additional consideration of sustainability trade-offs
Mature the 3D printing of food and liquids may raise significant food safety concerns due to the complexity of printing edible materials, and could also face challenges in terms of affordability, potentially limiting access for certain populations, especially those that are economically vulnerable. Despite the technology already exists and is in use in a few places, the Delphi participants perceived its large adoption with an extended timeline.



2 4D nanoscale printing

Description
An advanced manufacturing technique that involves the precise and controlled assembly of nanoscale materials and structures in a dynamic, time-dependent manner. This technology extends beyond traditional 3D printing by incorporating an additional dimension of time, allowing the printed objects to change their shape, properties or functionality in response to external stimuli or predefined triggers. It leverages the manipulation of materials at the nanoscale to create dynamic, self-transforming structures.

Allocation to clusters
Food manufacturing technologies and nutrition

Relative advantage
3.54

Earliest time to mature
2053

Delphi Participants' Comments
(there were no comments from the delphi experts on this technology)

Additional consideration of sustainability trade-offs
The adoption of 4D nanoscale printing in agrifood systems brings forth environmental and health concerns, particularly regarding the safety and potential adverse effects of nanomaterials used in the printing process. This concern may however prove unfounded, if 4D printing is performed on nuclear rather than molecular level.

3 6G-10G connectivity in agrifood systems

Description
The implementation and deployment of advanced communication technologies, operating within the electromagnetic spectrum from sixth to tenth generation, with the primary objective of enhancing and revolutionizing various aspects of agricultural practices. It enables seamless and real-time data exchange, analysis, and decision-making, including in agrifood systems.

Allocation to clusters
Advanced digital technologies

Relative advantage
6.17

Earliest time to mature
2043

Delphi Participants' Comments
6G-10G holds transformative potential across all agrifood sectors, but there's a need to ensure equitable access across urban and rural areas, demographic groups and countries. Its impact on agrifood systems might not be majorly distinct from current connectivity standards like 5G, but reliable internet and mobile coverage remains key for sustainable agrifood systems practices. However, beyond technological strides, political and regulatory barriers could hinder its global adoption. There are also concerns about furthering the digital divide among vulnerable populations without access or affordability.

Additional consideration of sustainability trade-offs
While 6G-10G connectivity can enhance data transfer and communication in agriculture (weather and price information, advisory services etc.), it also introduces accessibility issues, as not all regions may have equal access to these advanced network capabilities, and it raises concerns about cybersecurity threats that could disrupt critical agrifood systems operations, such as related to e- government in agriculture. As it will operate with a massive amount of data, it could potentially involve increased vulnerability of privacy of users and data. Also, the required infrastructure overhaul of terrestrial ICT infrastructure will entail a significant ecological cost due to extraction, processing, transportation, deployment and servicing of the telecommunications modules. To cope with these challenges, 6G networks will need to implement robust and adaptive security and privacy mechanisms, such as encryption, authentication, blockchain, and advanced machine learning, as well as data sovereignty standards.

4 Aerial robotics and drones

Description

The utilization of robotic systems and unmanned aerial vehicles which find extensive application in diverse tasks, encompassing data collection, monitoring, analysis and physical interventions. It plays a crucial role, particularly in areas like crop fields and orchards. By integrating advanced robotics, sensor technologies, artificial intelligence and communication systems, they achieve autonomous navigation and task execution, substantially enhancing the efficiency, safety and precision of traditionally challenging agricultural operations.

Allocation to clusters

Advanced digital technologies

Relative advantage

5.89

Earliest time to mature

2040

Delphi Participants' Comments Aerial robotics hold immense value in agrifood systems, not only for commercial applications but also in managing biodiversity and food security. However, their impact is determined by their specific application and use. There are concerns about the risks associated with cyber security, the technology's association with chemical-based agriculture and its potential to sideline smaller farmers in favour of larger companies. Accessibility, scalability and affordability will be decisive factors in their broader adoption.

Additional consideration of sustainability trade-offs

The use of aerial robotics and drones for agricultural purposes, while promising for improving efficiency, brings privacy and safety concerns related to the collection of data and airspace management, as well as ecological concerns related to the material life cycle of robots and drones.

5 Agricultural innovation policy labs

Description

An innovative evidence-based, participatory and behaviourally informed co-creative approach in policy making. It aims to bring together all the stakeholders and place them in the driver's seat of policy making by freely voicing their demands and concerns and enriching the process with their knowledge and diverse perspectives. The policy co-creation cuts through all phases of the policy process: data analysis, formulation, implementation and monitoring, evaluation and learning (MEL). It combines various innovative tools such as foresight and behavioural insights. Instead of having a policy made by one or a few experts, it consists in bringing diverse actors from the agrifood systems in a multistakeholder setting to jointly discuss and elaborate inclusive, participatory, evidence-based and impactful policies.

Allocation to clusters

Policy innovation

Relative advantage

6.48

Earliest time to mature

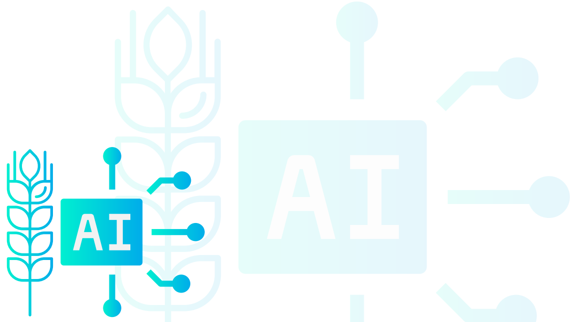
2035

Delphi Participants' Comments

These labs play a pivotal role in closing the spatial gap between policy formulation and implementation, in particular for removing policy barriers in innovation domains, characterized with novelty, complexity and uncertainty in a responsive and responsible manner. Cross-functional and stakeholder-inclusive policy development is hailed as best practice, but there's a call for greater distinction between technological and social innovations. Efficient policy co-creation between formulators and implementers can accelerate transformative changes. However, a dramatic shift from conservative policies is deemed essential and it will take time to mature and become the new normal, unless proper incentives are not put in place in a timely manner.

Additional consideration of sustainability trade-offs

The large-scale deployment of agricultural innovation policy labs with limited oversight and expert coverage can potentially lead to policies that do not effectively align with sustainable agrifood goals, especially if these labs are influenced by conflicting interests or lack transparency in their decision-making processes. They therefore do not constitute a stand-alone mechanism but should feed national or regional policy processes.



6 Artificial general intelligence in agriculture

Description

Artificial general intelligence (AGI) is a hypothetical type of intelligent agent or an autonomous system that surpasses human capabilities in the majority of valuable tasks. If realized, an AGI could learn to accomplish any intellectual task that human beings or animals can perform. By leveraging the power of AGI, these emerging technologies such as agriculture image processing, natural language processing and knowledge graphs can provide farmers with actionable insights, allowing for optimized decision-making and increased productivity.

Allocation to clusters

Advanced digital technologies

Relative advantage

6.54

Earliest time to mature

2035

Delphi Participants' Comments

While AGI holds potential, there are concerns about it overshadowing human decision-making, leading to governance challenges. For AGI to revolutionize agrifood, it must be more reliable and inclusive, and its implications thoroughly studied. There's an emphasis on safeguarding data sovereignty amidst its rise. At the present state of AGI science, although AGI overcomes the human brain speed it is far behind in its efficiency: while AI systems require massive amounts of computational power and energy to function, the human brain operates on a mere 20 watts of power, equivalent to a dim light bulb. Massive use of AGI would therefore only be possible with sufficient energy and invokes a trade-off with the environmental concerns.

Additional consideration of sustainability trade-offs

There are no robust ethical guidelines for AGI development and the social as well as psychological impact of this technology on populations remains an enigma.

7 Artificial neurons

Description
This technology consists of computational units designed to emulate the behaviour of biological neurons, which are used within the context of agricultural systems and practices.

These artificial neurons are integrated into computational models or systems that analyse various data inputs related to agricultural processes such as soil conditions, weather patterns, crop growth stages and pest presence.

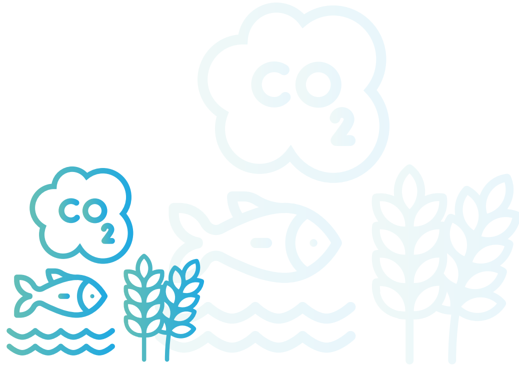
Allocation to clusters
Advanced biotechnologies

Relative advantage
5.19

Earliest time to mature
2051

Delphi Participants' Comments
Concern was raised by one participant about the possibility to apply the potential of artificial neurons in agriculture.

Additional consideration of sustainability trade-offs
The use of artificial neuron networks presents cybersecurity risks as well as a potential for catastrophic optimization mistakes being replicated at scale in real time.



8 Carbon credits in agriculture and aquaculture

Description
Carbon credits are a bulk of financial innovations representing a tradable unit that represents a reduction or removal of one metric ton of carbon dioxide (CO2) or its equivalent in greenhouse gas emissions. It is a financial incentive aimed at mitigating climate change by encouraging individuals, companies or countries to invest in activities that reduce their carbon footprint. By quantifying and valuing carbon reduction efforts, carbon credits create a market mechanism to reward sustainable practices and promote emission reductions.

Allocation to clusters
Financial and social innovations

Relative advantage
5.56

Earliest time to mature
2034

Delphi Participants' Comments
Carbon credits in agriculture and aquaculture serve as an essential tool to incentivize farmers to adopt best management practices (BMPs). However, the approach of granting credits to smallholders and vulnerable farmers, potentially reducing their productivity to offset emissions from major polluters, raises significant ethical concerns.

Additional consideration of sustainability trade-offs
The application of carbon credits in agriculture and aquaculture can face challenges related to the potential exploitation and inequitable distribution of credits, which may not effectively incentivize sustainable practices among all stakeholders, as well as an inadequate estimation of the ecosystemic and climatic value of a unit of carbon emissions.

9 Digital twins

Description

This technology refers to a digital replica of physical assets that update and change as its physical counterpart changes. It provides previously unheard levels of control over physical entities and helps to manage complex systems by integrating an array of technologies. It integrates artificial intelligence, machine learning and software analytics. In agriculture, digital twins are created to model various aspects such as farmland, crops, livestock and farm operations, but it is now facing a challenge in capturing the interactions between living systems and their environment.

Allocation to clusters

Advanced digital technologies

Relative advantage

5.92

Earliest time to mature

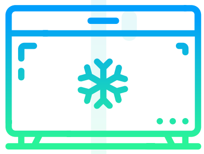
2045

Delphi Participants' Comments

Digital twins have the potential to revolutionize sectors like crop breeding where they can save two decades worth of research, land, energy and human resources. However, there are concerns about the rush to model processes without a solid grasp of the underlying basics, suggesting a need for a return to foundational understanding before these models can be truly beneficial.

Additional consideration of sustainability trade-offs

While digital twins offer benefits in resource management, concerns over privacy and data ownership may arise, especially if sensitive agricultural data is not adequately protected or controlled. This technology is also just an accessory for further optimization and experimentation, contingent on the availability of engineers, experts and perhaps AI that can analyse them and make sound recommendations. Despite the trend of reducing the cost of the technology over time, the cost of deployment and operation of digital twins may be prohibitive to a majority of agricultural actors worldwide, further deepening inequalities in production levels, productivity and profitability.



10 Energy storage technologies

Description

Energy storage technologies are a set of technologies that have the potential to substitute for or complement almost every aspect of a power system, including generation, transmission and demand flexibility. Energy storage benefits agrifood systems, allowing for better energy efficiency, uninterrupted supply and full use of renewable energy potential.

Allocation to clusters

New energy & transportation

Relative advantage

6.46

Earliest time to mature

2038

Delphi Participants' Comments

Energy storage, often referred to as batteries, may imply a need for a more globalized system or increased storage capacity.

Additional consideration of sustainability trade-offs

The adoption of energy storage technologies in agrifood systems can raise environmental concerns due to the extraction and life-cycle management of the materials used in energy storage.

11 Access to science-based information on sustainability matters

Description

This constitutes a set of innovations that refer to the establishment and maintenance of a system that provides readily available, standardized and verifiable data related to sustainability practices in various industries. This system should include science-based standards and associated measures, as well as comprehensive, traceable, trackable and easily accessible product-level data. The goal is to create a transparent and accountable environment where individual companies and entire industries can demonstrate their compliance with sustainability standards, allowing government regulators and consumer groups to independently verify this compliance without relying on costly third-party certification processes.

Allocation to clusters

Policy innovation

Relative advantage

5.99

Earliest time to mature

2040

Delphi Participants' Comments

Unified scientific standards for sustainability measures are essential for governments, consumers and third-party certifiers. Additionally, the innovation plays a significant role in the rise of responsive and responsible technologies and innovations, but it is crucial for surveys to distinguish between various innovations, such as technological and institutional or social ones, as they have different implications and statuses in the innovation process.

Additional consideration of sustainability trade-offs

The challenge in ensuring access to science-based sustainability information lies in the reliability and transparency of information sources, as lack of proper knowledge management, feeding obsolete information, intentional misinformation or biases can hinder informed decision-making in agrifood systems.

12 Environmental biotechnologies

Description

This is a set of biotechnologies, from low tech to high tech, applied to address environmental challenges and problems. These approaches leverage living organisms, biological processes, gene editing and genetic engineering to develop solutions for issues such as pollution remediation, waste management, sustainable agriculture, renewable energy production, and conservation of natural resources.

Allocation to clusters

Advanced biotechnologies

Relative advantage

6.11

Earliest time to mature

2043

Delphi Participants' Comments

These technologies can significantly enhance weather forecasts and high-level scenario building. However, public perceptions and mistrust could be barriers. Also, cost constraints and the broadness of this category might affect its mature adoption.

Additional consideration of sustainability trade-offs

The use of some environmental biotechnologies for pollution mitigation and soil enrichment may carry hazards of unintended ecological consequences, highlighting the importance of thorough monitoring and risk assessment as per the existing international treaties. Policy and standards discrepancies between different geographies may exacerbate inequalities and affect competitiveness.

13 Frugal innovation

Description

This is the practice of simplifying and creatively redesigning products, services or processes to provide high-quality and affordable solutions under limited resource conditions. This creates pressure on companies to look at how they can do more – and better – with less, to come up with affordable, sustainable products that address the needs of this more value- and values-conscious consumer.
In the context of agriculture, frugal innovation involves developing solutions for agricultural challenges and needs using economical, efficient and innovative approaches, emerging to drive sustainable agricultural development and progress within rural communities.

Allocation to clusters

Policy and social innovations

Relative advantage

5.95

Earliest time to mature

2034

Delphi Participants' Comments

Although the concept of frugal innovation is already in use in rural development and it holds grand promises, it will take time until its full potential is reached to play a transformative role, such as in circular economy.

Additional consideration of sustainability trade-offs

There is low risk in using frugal innovations in agrifood systems, but a possibility of suboptimal choices favouring low-investment, low-yield solutions remains a possible issue.

14 Global logistics network

Description

This is a comprehensive and interconnected system of transportation, distribution and supply chain components that operates across international borders. It is based on a combination of technologies, such as blockchains, artificial intelligence, quantum computing and others.

Allocation to clusters

New energy and transportation

Relative advantage

5.82

Earliest time to mature

2042

Delphi Participants' Comments

Its potential is magnified if linked directly with producers and consumers, facilitated by automated transportation and affordable energy sources.

Additional consideration of sustainability trade-offs

The establishment of a global logistics network may contribute to carbon emissions through increased transportation, but more importantly it also raises concerns regarding equitable access to the network's benefits and potential disruptions of access through conflict, corruption and unbalanced trade policies.

15 Internet of Food

Description

This comprises the interconnected network of smart devices, sensors and data-driven technologies used in the food industry to enhance food production, distribution and consumption processes.

This concept involves the integration of technologies, which can record meta data (temperature, supply chain routes and durations) on foods, into various aspects of the food supply chain, from farming and food processing to transportation, storage and consumer engagement, to optimize efficiency, quality and sustainability in the food ecosystem. It is based on a combination of technologies, such as smart sensors, geospacial technologies, blockchains, artificial intelligence, quantum computing and others.

Allocation to clusters

Advanced digital technologies

Relative advantage

5.97

Earliest time to mature

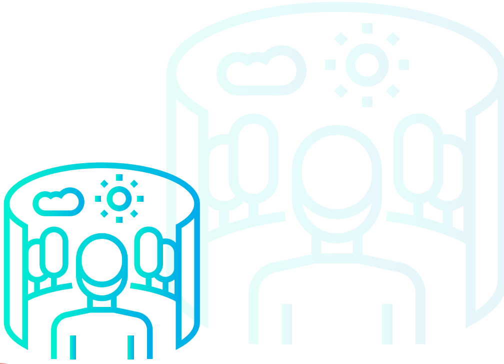
2042

Delphi Participants' Comments

IoF promises enhanced supply chain efficiency and transparency. However, its true potential lies in its globalized application, ensuring fairness in labour and income conditions, and including traditional farming insights.

Additional consideration of sustainability trade-offs

While the internet of food offers traceability and information sharing benefits, food being a fast-moving commodity in great volumes would require a high supply of electricity and infrastructure to support this. It also brings cybersecurity and data privacy concerns regarding the protection of sensitive food-related data.



16 Metaverse, virtual reality and augmented reality

Description

This concerns the interactive platforms for farmers to visualize and manipulate farm data, simulate growing conditions, test innovative farming techniques and gain insights into crop health and management. It can help the growth of crops and the raising of livestock and poultry in the field of agricultural production, provide a three-dimensional and visual virtual leisure agricultural experience, as well as offers immersive environment and learning.

Allocation to clusters

Advanced digital technologies

Relative advantage

4.90

Earliest time to mature

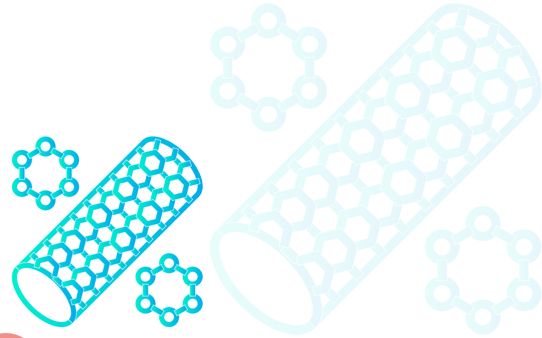
2046

Delphi Participants' Comments

These technologies have more potential in high-level planning, agrifood services and training. However, accessibility constraints in certain countries might hinder their impact on small producers.

Additional consideration of sustainability trade-offs

The adoption of metaverse, VR and AR technologies in agriculture may lead to concerns about technology dependency and alienation through technology, and also exacerbate access disparities if not made widely accessible and affordable to all stakeholders.



17 Nanomaterials for food packaging

Description
It aims to improve the principal features of traditional packaging systems i.e., containment (ease of transportation and handling), convenience (being consumer friendly), protection and preservation (avoids leakage or break-up and protects against microbial contaminants, offering longer shelf life), marketing and communication (real-time information about the quality of enclosed food stuffs.

Allocation to clusters
Micro-, nanotechnologies and nanobiotech

Relative advantage
4.76

Earliest time to mature
2041

Delphi Participants' Comments
While promising, their adoption strategy must ensure access for the vulnerable to make them mature.

Additional consideration of sustainability trade-offs
The use of nanomaterials in food packaging risks being hazardous for food safety and the environmental, necessitating safety assessments and regulations over significant periods of time, thus postponing the mass roll-out.

18 Nanomaterials for water technologies

Description
The utilization of nanoscale materials with distinctive properties and surface characteristics to enhance various aspects of water-related applications. Some nanomaterials offer unique properties and surface characteristics that make them highly effective in improving water quality, enhancing water resource sustainability and enabling advanced water treatment processes. For example, carbon nanotubes can be used for water purification, management and irrigation and desalination.

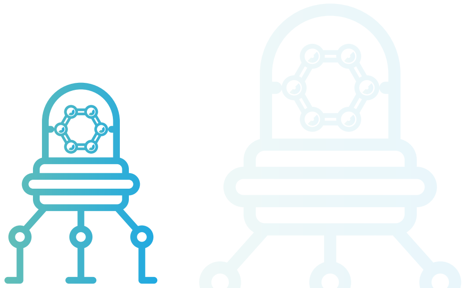
Allocation to clusters
Micro-, nanotechnologies and nanobiotech

Relative advantage
5.41

Earliest time to mature
2042

Delphi Participants' Comments
While promising, their adoption strategy must ensure access for the vulnerable to make them mature.

Additional consideration of sustainability trade-offs
The incorporation of nanomaterials in water technologies raises concerns about safety assessments and potential risks associated with their use in water purification processes, but also could affect trust in water management systems based on misinformation as well as legitimate concern for the long-term effects.



19 Nanorobotics

Description

This is the field of miniaturized robotics and technology focused on designing, fabricating, controlling and applying robots or machines at the nanoscale. These nanorobots, often just nanometers in size, excel at precise tasks like storing, protecting, delivering and releasing payloads. In agriculture, nanorobotics can optimize processes by effectively managing and manipulating payloads. One key advantage is their ability to enhance payload stability against environmental degradation, leading to increased efficiency and reduced material usage. Nanorobotics can also incorporate advanced features, such as sensors for pathogen, microorganism, allergen, chemical and contaminant detection in food, in addition to providing nutritional information. This technology holds great promise for improving agriculture and food safety.

Allocation to clusters

Micro-, nanotechnologies and nanobiotech

Relative advantage

4.72

Earliest time to mature

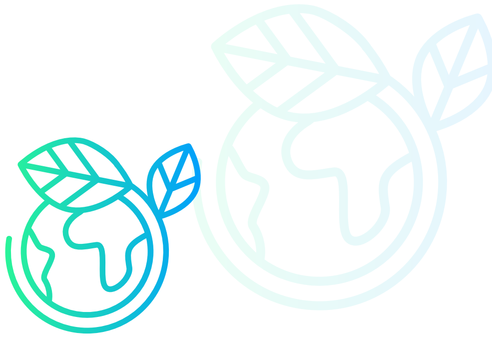
2047

Delphi Participants' Comments

Nanorobotics holds significant potential, but to become mature it requires either a pressing disruptive challenge or political pressure to embrace related concepts like personalized nutrition or the decline of natural pollinators. Ethical considerations and regulations are essential for its adoption and development.

Additional consideration of sustainability trade-offs

The application of nanorobotics in agrifood systems, while managing precise operations, requires robust ethical oversight and environmental as well as sanitary screening over a longer period of technology adoption.



20 Nature-based and ecosystem innovations

Description

It is a set of diverse innovations that promote an effective, long-term, cost-efficient approach to tackling sustainable land and water resources management and climate change. These innovations can help improve water availability and quality as well as to restore ecosystems and soils worldwide, while offering substantial health co-benefits and achieving global food security.

Allocation to clusters

Policy innovation

Relative advantage

6.76

Earliest time to mature

2036

Delphi Participants' Comments

They hold promise when threats are known, the approach is science-based and there's no added strain on natural resources.

Additional consideration of sustainability trade-offs

Balancing ecosystem preservation with agriculture often requires intensive work and substantial time investment, as well as secure land tenure.

21 New methods for controlling gene expression

Description
This is a set of innovative recombinant DNA/RNA techniques that have been developed to manipulate the level of activity or expression of specific genes within cells with increased precision, as well as influencing multiple genes and quantitative traits. Gene editing, despite not being an emerging technology, is an emerging innovation in many parts of the world and is part of this technological group.

Allocation to clusters
Advanced biotechnologies

Relative advantage
5.87

Earliest time to mature
2046

Delphi Participants' Comments
These methods have great potential due to its precision but require further risk assessment, ethics and improved science communication.

Additional consideration of sustainability trade-offs
These methods have great potential) due to its precision but require further risk assessment, ethics and improved science communication.

22 Novel biomass energy

Description
This is a set of innovative methods for utilizing renewable organic materials, such as algae and microorganisms, to generate energy. Biomass can be transformed into usable energy through both direct and indirect means. It can be burned to produce heat directly, converted into electricity directly or processed into biofuel indirectly. These methods often entail novel approaches to biomass energy conversion, production or utilization, with the primary goal of enhancing energy production efficiency, sustainability and environmental friendliness.

Allocation to clusters
New energy and transportation

Relative advantage
5.40

Earliest time to mature
2035

Delphi Participants' Comments
An emphasis on waste-derived biomass energy is needed, balancing its adoption to avoid competition with food production and the over-exploitation of natural resources.

Additional consideration of sustainability trade-offs
The adoption of novel biomass energy sources may require careful consideration of sustainable sourcing and land use.

23 Novel pesticides, fertilizers, antibiotics incl. nanotechnology substances

Description

This is a set of technologies that refer to innovative forms of pesticides, fertilizers and antibiotics that incorporate nanotechnology-based substances. These substances are designed to enhance their effectiveness and control through the integration of nanomaterials, allowing for controlled release and gradual diffusion into the targeted environment, which can include soil or other agricultural settings. This approach leverages nanotechnology to optimize the delivery and performance of these agricultural inputs, potentially leading to improved efficiency and reduced environmental impact in crop protection, nutrient management and disease control.

Allocation to clusters

Micro-, nanotechnologies and nanobiotech

Relative advantage

4.82

Earliest time to mature

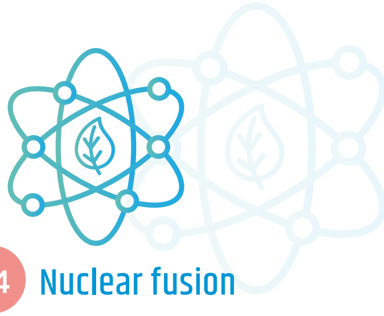
2042

Delphi Participants' Comments

Experts emphasize the need for a chronological vision of changes in agrifood systems, noting that some innovations can be transitional or complement others in a transformative path. These innovations, in synergy with others, could play a part in broader strategies like personalized nutrition or One Health. Additionally, they could incentivize farmers to adopt carbon sequestration and beneficial land management practices.

Additional consideration of sustainability trade-offs

The use of novel substances in agrifood systems necessitates safety and environmental assessments to prevent harm to the environment and human health. It may also divert attention from agricultural practices independent of the intensive use of these substances.



24 Nuclear fusion

Description

It is a set of technologies on the utilization of nuclear energy which involves the use of isotopes, radiation and nuclear fusion techniques in agriculture. This application aims to combat pests and diseases, enhance crop production, safeguard land and water resources, ensure food safety and authenticity and boost livestock production.

Allocation to clusters

New energy and transportation

Relative advantage

4.49

Earliest time to mature

2052

Delphi Participants' Comments

The potential of nuclear fusion is recognized as a possible game-changer for the agrifood systems. However, safety remains of paramount concern.

Additional consideration of sustainability trade-offs

While nuclear fusion is a clean energy source, the handling and disposal of radioactive waste and concerns about proliferation are perceived as potential hazards.

25 Personalized nutrition

Description

AI-driven personalized nutrition solutions use a combination of machine learning algorithms and data from dietary intake surveys, medical records, health questionnaires and other sources to create individualized nutrition plans. These plans take into account an individual's lifestyle, health history and dietary preferences to create a tailored nutrition programme that meets their specific needs.

Allocation to clusters

Food manufacturing technologies and nutrition
Advanced digital technologies

Relative advantage

4.42

Earliest time to mature

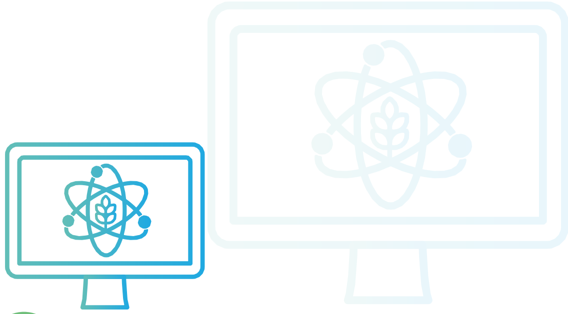
2047

Delphi Participants' Comments

While personalized nutrition holds transformative potential, especially with advancements in metabolomics, there are concerns about data misuse. The significant social dimension is highlighted, and equitable access to technology is essential for scaling its benefits.

Additional consideration of sustainability trade-offs

Concerns about data privacy and affordability may limit access to and trust in personalized nutrition solutions, potentially hindering their widespread adoption. Despite the technology exists in a few places, the Delphi participants have perceived a more extended timeline until it reaches full maturity. It also allows for a fast propagation of misguided nutritional advice.



26 Quantum internet and computing applied to agrifood systems

Description

Quantum computing could revolutionize the agrifood systems by allowing for more accurate and efficient data analysis that could lead to more precise decision-making. Quantum computing has the potential to provide agrifood systems with real-time data analysis that can help optimize land usage and identify and track crop conditions in a much more effective way. As the industry seeks to improve efficiency and reduce costs, the potential of quantum computing in precision agriculture is becoming increasingly clear.

Allocation to clusters

Quantum internet and computing applied to agrifood systems

Relative advantage

5.91

Earliest time to mature

2047

Delphi Participants' Comments

While quantum computing's superior processing power can underpin various advanced applications, including precision agriculture and breakthroughs in crop and animal science, experts warn against over-reliance on such technologies, especially in contexts where small-scale farmers might not have the resources to adopt them. Issues surrounding data access and governance are also highlighted.

Additional consideration of sustainability trade-offs

The integration of quantum technologies may raise cyber security concerns, as well as the need for robust encryption and data protection mechanisms. Access will also likely be very limited due to prohibitive costs and required human capital.

27 Realtime satellite imagery, positioning systems and autonomous GIS

Description

This refers to an integrated system that is designed to support a wide range of functions within agrifood systems by combining the power of up-to-the-minute satellite imagery with autonomous geographic information capabilities. It facilitates both human and automated decision-making processes in agriculture and food-related operations.

Allocation to clusters

Advanced geospatial technologies

Relative advantage

6.20

Earliest time to mature

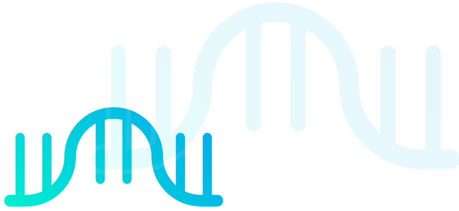
2036

Delphi Participants' Comments

These technologies, while mature, still offer growth potential. Emphasis should be on participatory approaches, citizen science and interoperability. However, experts also flag concerns regarding cybersecurity and ethical issues linked to AI.

Additional consideration of sustainability trade-offs

While beneficial for precision agriculture, real-time satellite imagery and positioning systems require significant infrastructure investment and data privacy safeguards to prevent misuse. There is also a risk of creating vendor dependency and suboptimal pricing.



28 RNA interference

Description

This technology refers to a biological process that uses small RNAs to regulate gene expression. Possible beneficial applications in the agricultural domain can include the development of plants with changed intrinsic properties or an altered interaction with their environment.

Allocation to clusters

Advanced biotechnologies

Relative advantage

5.24

Earliest time to mature

2045

Delphi Participants' Comments

While RNA has the potential of creating climate-resilient crops, biofuels and animal vaccines, biosafety and bioethics considerations are deemed applicable.

Additional consideration of sustainability trade-offs

Managing unintended ecological consequences is critical when implementing RNA interference technologies in agriculture to avoid potential harm to non-target species and ecosystems.

29 Social impact bonds

Description

This is a financial instrument that blends private investment with public funding to support initiatives aimed at addressing agricultural issues. The repayment of these bonds is contingent on the achievement of specific, detailed targets within a given project. It also aims to create broader societal impact by influencing systemic changes in the delivery of social services.

Allocation to clusters

Financial and social innovations

Relative advantage

6.26

Earliest time to mature

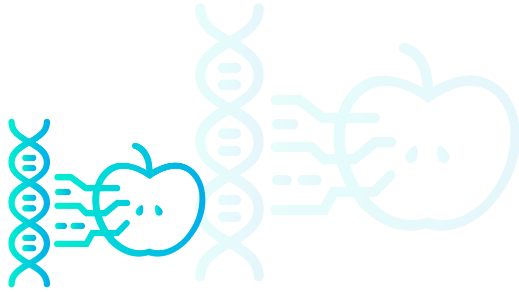
2036

Delphi Participants' Comments

These bonds are considered pivotal in driving responsible and responsive emerging technologies and innovations. Experts suggest that the survey should distinguish between different innovation types. The government's role should be to encourage private sector engagement and ensure unbiased, inclusive outcomes.

Additional consideration of sustainability trade-offs

The effectiveness of social impact bonds in funding sustainable agriculture initiatives may be limited if there is insufficient accountability and impact measurement or outright misuse, potentially leading to inadequate support for critical projects.



30 Synthetic biology

Description

This is a field of science that involves using molecular biology techniques to redesign organisms for useful purposes, engineering them to have new abilities. The engineering of new organisms through synthetic biology research can be applied not only to developing new crops and varieties, but also to some biological aspects and factors in agrifood systems, including soil, waste, energy, preservation and many others. For example, synthetic biology is used as one of the components of cellular agriculture to produce animal products from cell culture.

Allocation to clusters

Cutting-edge (emerging) biotechnologies

Relative advantage

6.09

Earliest time to mature

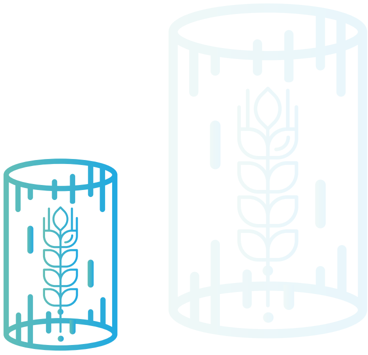
2046

Delphi Participants' Comments

While there's acknowledgment of synthetic biology's potential in addressing climate change challenges and supporting precision farming, there are also concerns about some potential environmental and human health hazards. It is believed that before any release, risks should be assessed in line with international agreements like the Cartagena Protocol on Biosafety. There's also a call to respect traditional knowledge and natural processes.

Additional consideration of sustainability trade-offs

Ethical oversight and safety protocols are used when applying synthetic biology in agrifood systems to ensure responsible use and avoid potential unintended consequences.



31 Teleportation of complex molecules

Description

This is the theoretical concept of instantaneously transmitting intricate molecular components from one location to another within the agrifood systems without the need for traditional physical transportation methods. It envisions the ability to deliver specific molecules directly to plants or soil in a precise and targeted manner, potentially enhancing agricultural processes, crop health and overall agricultural productivity. The practical realization of complex molecule teleportation in agriculture remains a subject of scientific exploration and theoretical speculation due to significant technical and scientific challenges.

Allocation to clusters

New energy and transportation

Relative advantage

4.17

Earliest time to mature

2063

Delphi Participants' Comments

While some experts view this as a far-fetched concept, others see its revolutionary potential, especially in directly addressing plant, animal and human health needs. If technologically possible, the ethics and safety of teleportation would be of paramount concerns.

Additional consideration of sustainability trade-offs

The adoption of teleportation technologies for molecules in food preservation requires rigorous safety assessments to prevent potential risks to human health and the environment, with the technological basis of this technology sitting well beyond the present understanding of physics and life sciences.

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

Description

Territorial or landscape value-chain denote an integrated approach that encompasses the entire sequence of activities involved in producing, processing and marketing specific products within a defined geographical area or landscape. Food-to-consumer economy policy means that food producers sell their products directly to end consumers. This emphasizes leveraging local resources and production potential to support sustainability and enhance the regional economy.

Allocation to clusters

Policy innovation

Relative advantage

5.66

Earliest time to mature

2034

Delphi Participants' Comments

There are ongoing initiatives in this domain, but they lack comprehensive documentation and institutionalization at policy level, which moves the target forward in time of achieving full maturity at global level. Such policies could significantly impact local and regional governance, underscoring their importance in the agrifood systems landscape.

Additional consideration of sustainability trade-offs

Balancing local sustainability with global trade dynamics can be challenging when implementing these policies, potentially impacting global food supply chains and economic stability, especially in the initial phases of deployment of these interventions.

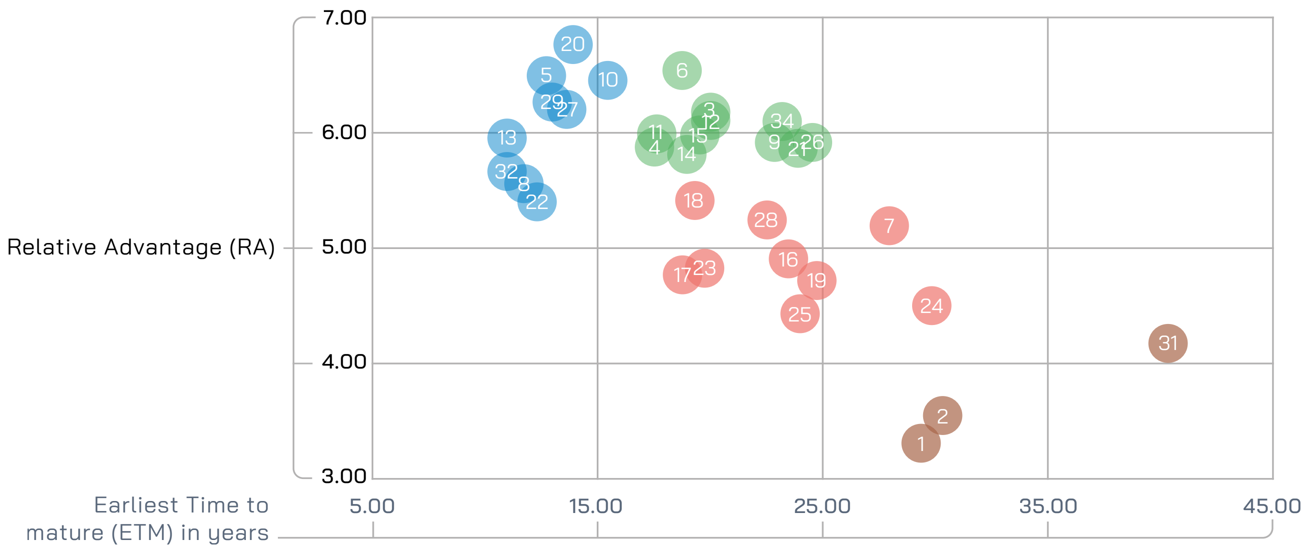
IMPACT

Response of emerging technologies and innovations to multiple challenges

The results are visualized below, using a technique called 4CF Matrix. 4CF Matrix is a simple tool developed for the purpose of identification, verification and systematisation of potential solutions developed in the process of strategic planning and strategic analyses. Each technology solution is evaluated according to two criteria:

- Relative advantage (RA): see the Glossary.
- ETM (Earliest Time to Mature): see the Glossary.

A matrix structured with regard to the above criteria shows areas of importance for strategic planning: from an area of solutions which show little promise with regard to relative advantage but which could be implemented quickly, to very distant fields which contain groundbreaking solutions. Ignoring solutions that have been evaluated as highly advantageous and which are "just around the corner" can potentially be dangerous, as can investing in low-benefit emerging technologies and innovations.



1. 3D printing of food and liquids
2. 4D nanoscale printing
3. 6G-10G connectivity in agrifood systems
4. Aerial robotics and drones
5. Agricultural innovation policy labs
6. Artificial general intelligence in agriculture
7. Artificial neurons
8. Carbon credits in agriculture and aquaculture
9. Digital twins
10. Energy storage technologies
11. Access to science-based sustainability information
12. Environmental Biotechnologies
13. Frugal innovation
14. Global logistics network
15. Internet of food
16. Metaverse, VR and AR
17. Nanomaterials for food packaging
18. Nanomaterials for water technologies
19. Nanorobotics
20. Nature-based and ecosystem innovations
21. New methods for controlling gene expression
22. Novel biomass energy
23. Novel pesticides, fertilizers, antibiotics incl. nanotechnology substances
24. Nuclear fusion
25. Personalized nutrition
26. Quantum internet and computing applied to agrifood systems
27. Realtime satellite imagery, positioning systems and autonomous GIS
28. RNA interference
29. Social impact bonds
30. Synthetic biology
31. Teleportation of complex molecules
32. Territorial or landscape value-chain and food-to-consumer economy policies

Figure 3: 4CF Matrix – Distribution of different emerging technologies and innovations according to their earliest time to mature and their relative advantage. The numbers and their order represent the 32 technologies and innovations on pages 9-25. Blue: high perceived impact with earliest time to mature. Green: high perceived impact, longer time to mature. Red: medium impact, longer time to mature. Brown: lower impact, longest time to mature.

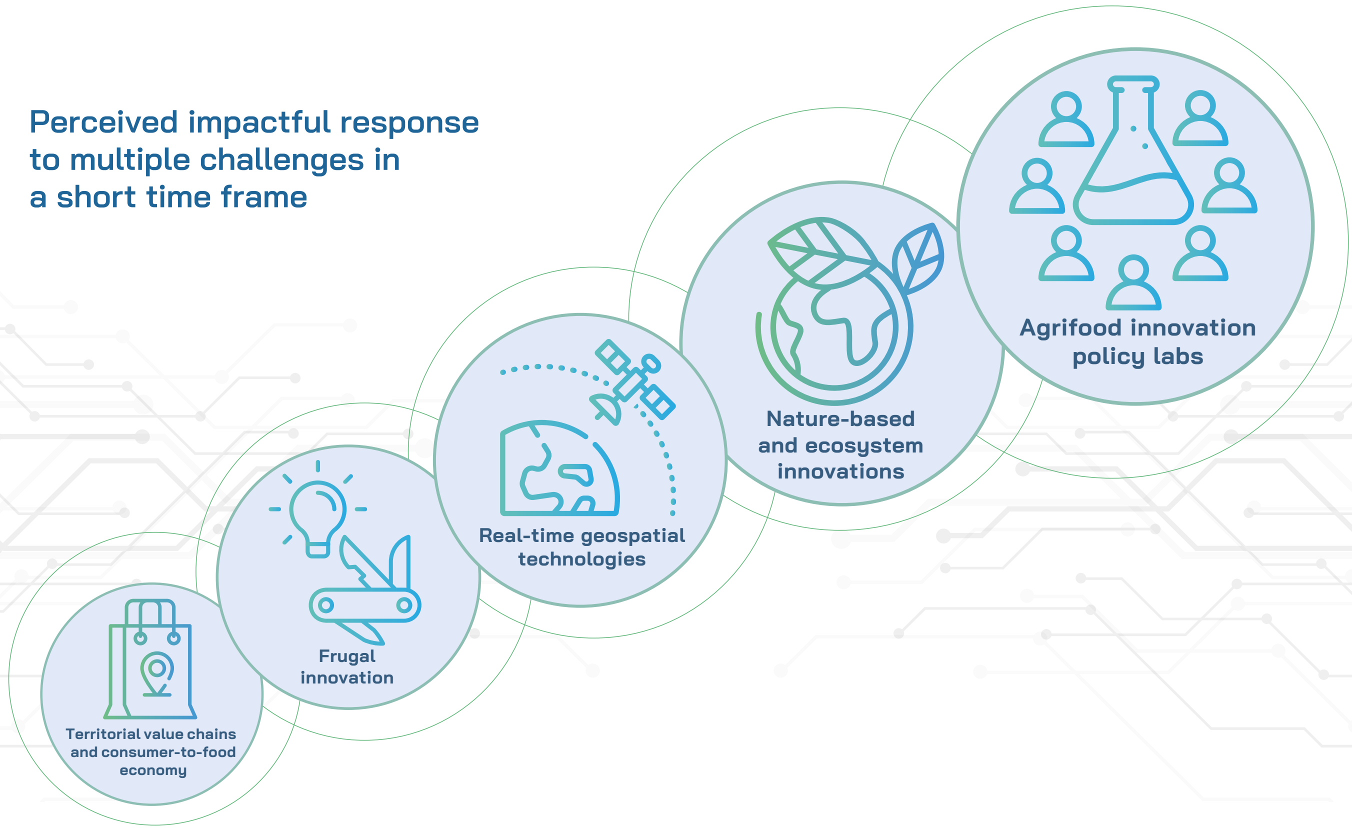


Figure 4: Top 5 technologies and innovations perceived to have the highest impact on multiple challenges

With the provided data on relative advantage (RA) and earliest time to mature (ETM) for various emerging technologies and innovations in agrifood systems, we can derive some insights.

High impact, short time to mature: these are technologies that have a high relative advantage and will be available in a short time frame. Agricultural innovation policy labs have an RA of 6.48 and ETM of 12.75 years. This suggests that creating environments to foster agricultural innovation is seen as a game-changer and will become mature relatively soon. Nature-based and ecosystem innovations have an RA of 6.76 and an ETM of 13.95 years, indicating strong potential for solutions rooted in nature and biodiversity. Real-time satellite imagery, positioning systems, and autonomous GIS, with an RA of 6.20 and ETM of 13.64 years, highlights the importance of real-time data and automation in agriculture. Social impact bonds have an RA of 6.26 and an ETM of 13.00 years, suggesting that financing mechanisms focusing on societal benefits will become crucial in the agrifood domain. Frugal innovation and territorial or landscape value-chain and food-to consumer economy policies both have an RA of around 5.9+ and ETM of 11.00 years. This shows the importance of cost-effective solutions and localized policies in the agrifood system.

High impact, longer time to mature: these are technologies with high potential impact but that might take a longer time to become widely available. Artificial general intelligence in agriculture scores high in RA at 6.54 but will take around 18.78 years to become mature. Synthetic biology with an RA of 6.09 has an ETM of 23.24 years. While it holds promise, the technology will take some time to be widely adopted.

Lower impact, distant future: technologies in this category may not be immediate game-changers and are predicted to take a considerable time to mature. The teleportation of complex molecules has the longest ETM of 40.40 years, with an RA of 4.17, suggesting that, while it is a captivating idea, it is far from realization. Nuclear fusion in agrifood, with an RA of 4.49, is expected to take almost 30 years (ETM of 29.90) to become mature.

Top 20 most promising agrifood emerging technologies and innovations

The list below includes the top 20 most promising agrifood 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.

Technologies that are resource-intensive, especially that require increased extraction of mineral or other resources globally, were rated higher.

Relative advantage, as has already been mentioned, is the degree of improvement that the proposed solutions might bring to the realization of a particular need. The relative advantage of each of the emerging technologies and innovations was evaluated on a scale of 0–10, where 0 denotes a lack of improvement in the realization of a need, and 10 signifies major improvement – a "gamechanger".

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

Table 1: Global relative advantage score of emerging technologies and innovations

The perceived most impactful technologies per challenge

In addition to other ways of exploring the priority of emerging technologies and innovations as well as their clusters, we asked the Delphi survey participants to indicate which areas have the biggest potential to yield break-through advances in terms of meeting the challenges. Items that received an above-average number of indications are listed below. It is worth noting that there is no one technology that acts as a silver bullet. Rather, they can contribute to addressing specific global agrifood challenges in combination with other technologies and innovations. Below is a summary of the top five emerging technologies and innovations corresponding to each of the challenges.

Population and development dynamics, food and nutrition security, sustainable diets

A range of technology clusters appear to influence this domain. Advanced biotechnologies, such as synthetic biology and new methods for controlling gene expression, offer potential avenues for sustainable food solutions. Nature-based and ecosystem innovations highlight methods that could align with sustainable community growth. The global logistics network, from the domain of new energy and transportation, could enhance the food supply chain. Quantum computing holds a potential to boost advancements in personalized nutrition and various analyses of datasets.

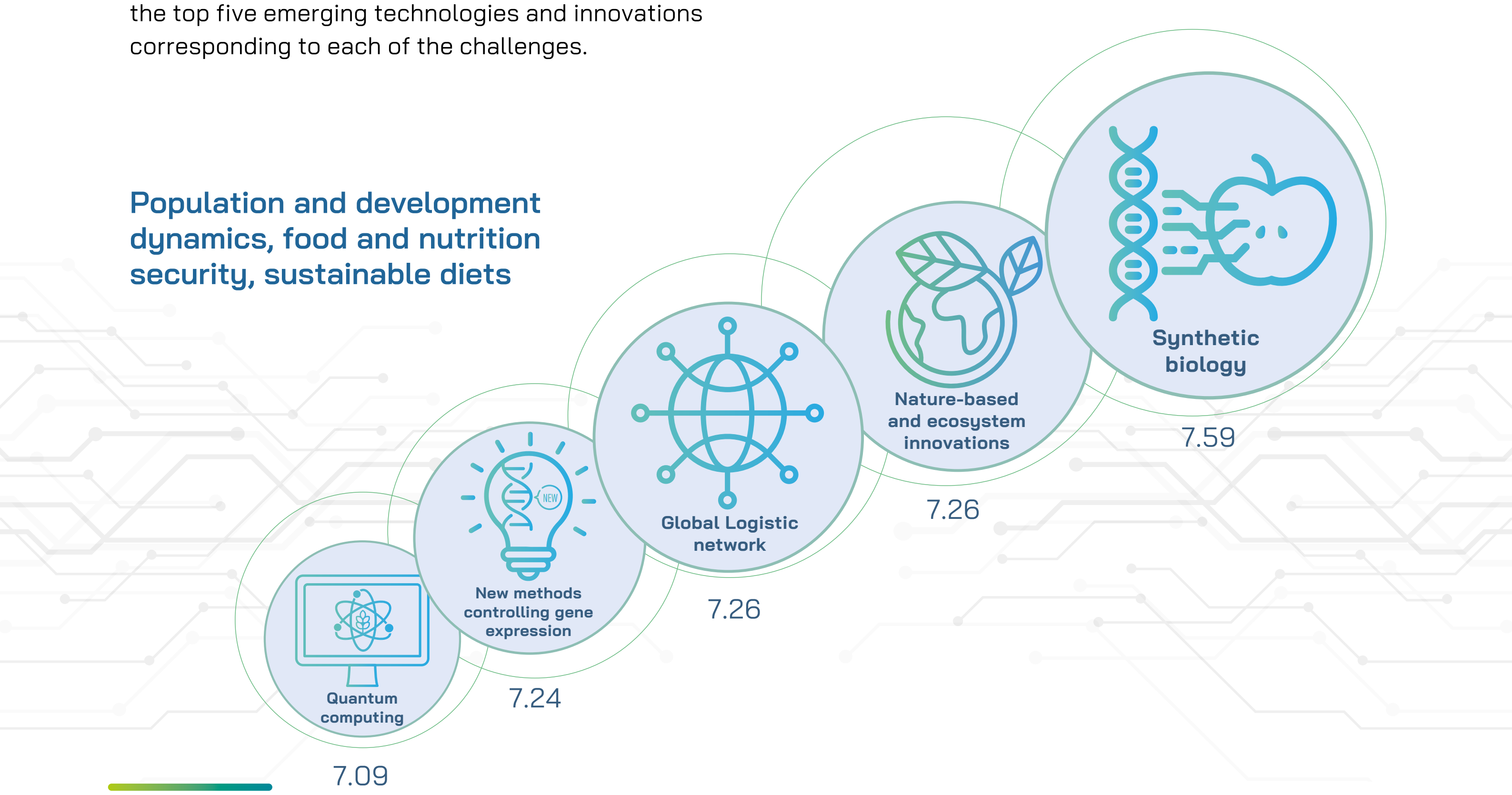


Figure 5: Top five technologies and innovations perceived to have the highest impact on population and development dynamics, food and nutrition security, sustainable diets.

Climate change, disasters, conflicts and protracted crises

In addressing climate-related challenges, several technologies are emerging as potential contributors. Nature-based and ecosystem innovations emphasize approaches in harmony with natural systems. Real-time data from advanced geospatial technologies might aid in disaster response. Energy storage technologies also show promise in this context. In the digital realm, artificial general intelligence in agriculture and quantum internet have been noted for their potential applications in agrifood systems.

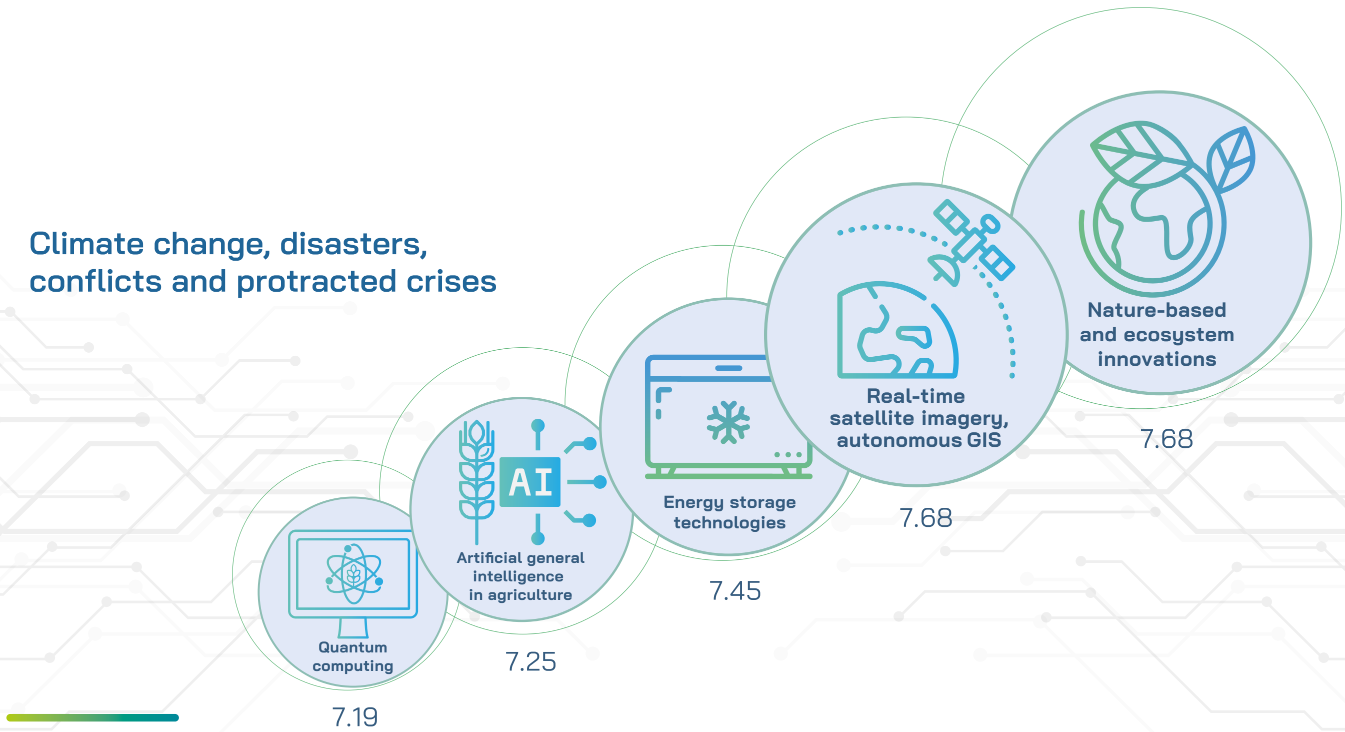


Figure 6: Top five technologies and innovations perceived to have the highest impact on climate change, disasters, conflicts and protracted crises

Erosion of natural resource base, loss of biodiversity

Efforts to counteract resource erosion and biodiversity loss highlight a mix of technologies. Nature-based and ecosystem innovations have been proposed as potential solutions. Real-time satellite imagery and artificial general intelligence in agriculture could offer tools for monitoring and intervention.
Carbon credits in agriculture and aquaculture, a financial innovation, might incentivize sustainable practices, while environmental biotechnologies are also being explored for their potential benefits.

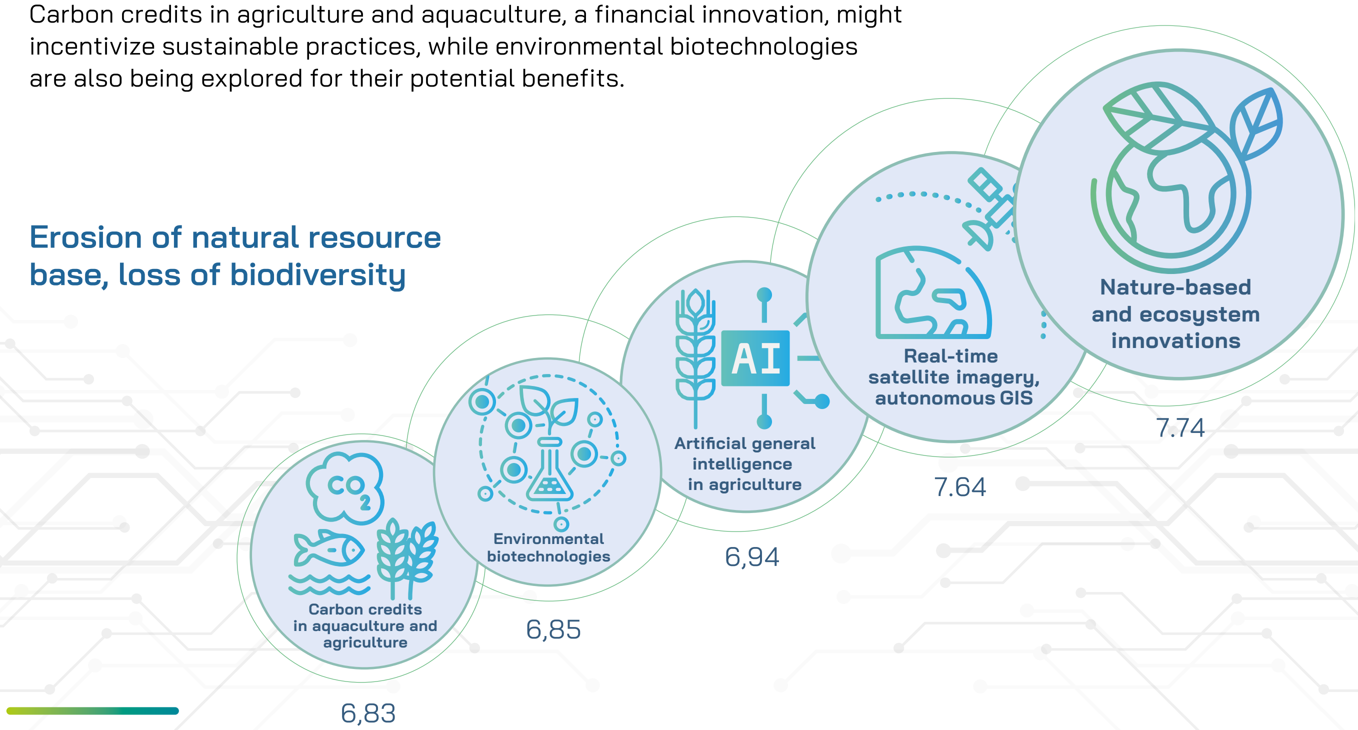


Figure 7: Top five technologies and innovations perceived to have the highest impact on erosion of natural resource base, loss of biodiversity

Food loss and waste

To address food wastage, various technologies are being considered. Artificial general intelligence in agriculture and the internet of food and access to information on sustainability matters could offer data-driven insights. Nanomaterials for food packaging, a product of micro- and nanotechnologies, might extend food shelf life. Nature-based innovation can help recycling and improve circularity.

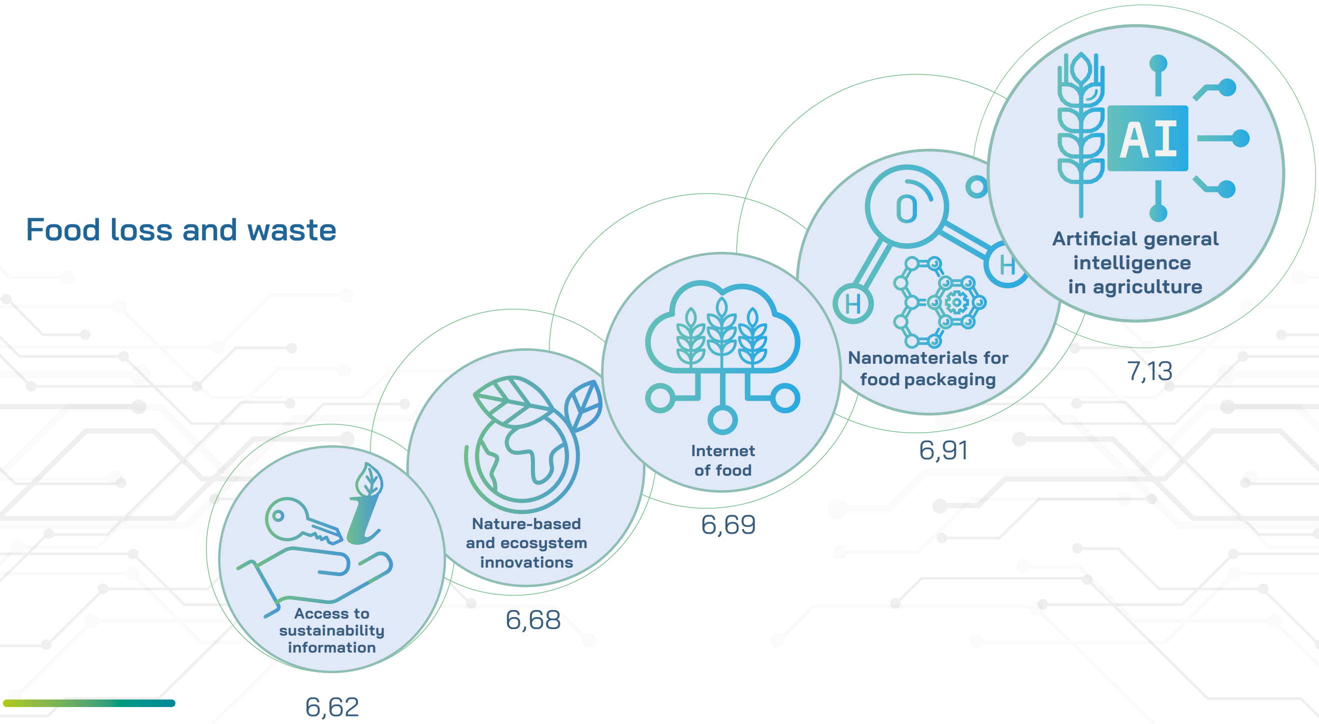


Figure 8: Top 5 technologies and innovations perceived to have the highest impact on food loss and waste

Energy demand and use in agrifood systems

Meeting energy demands in agrifood systems brings forth several potential technological solutions. Energy storage technologies and novel biomass energy are being explored for their energy provision capabilities. Environmental biotechnologies might offer sustainable energy avenues, while Artificial general intelligence in agriculture and nuclear fusion could provide tools for energy optimization
or exacerbate the optimization of agrifood systems.

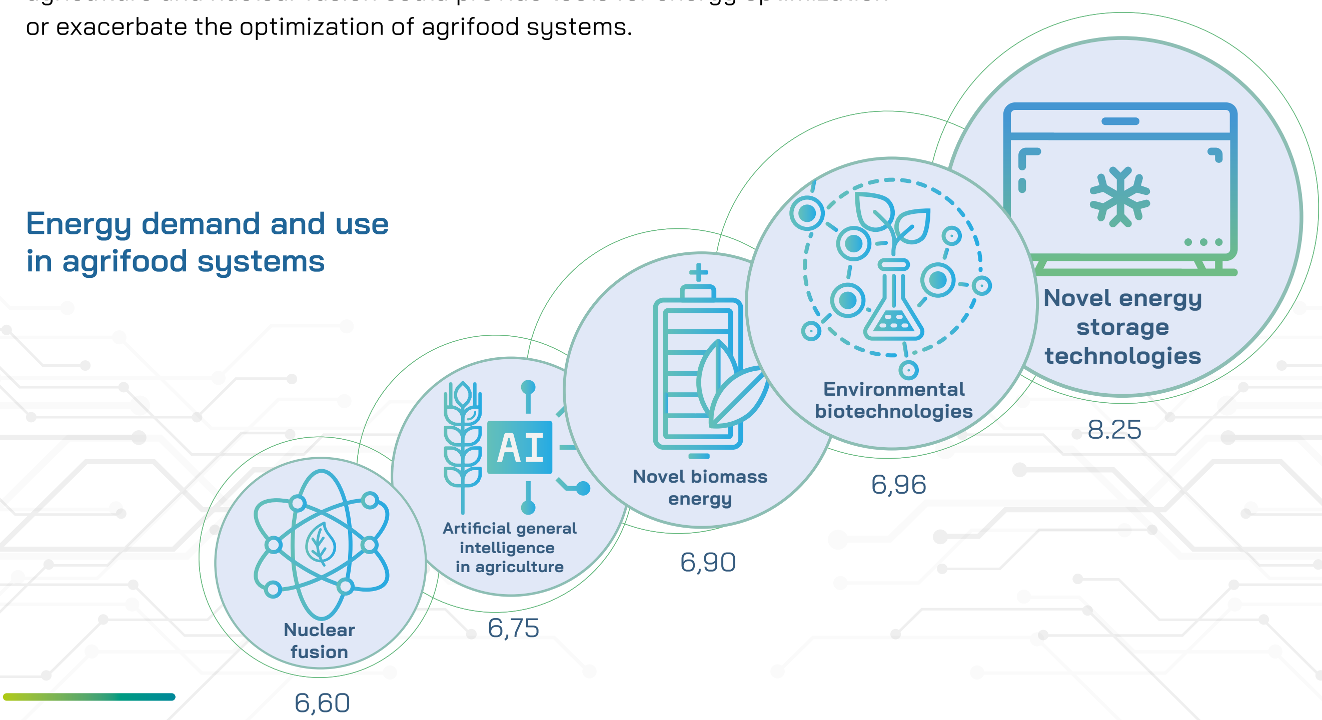


Figure 9: Top five technologies and innovations perceived to have the highest impact on energy demand and use in agrifood systems

Inclusion of the most vulnerable

The aim of including vulnerable populations highlights various technologies and policies. Nature-based and ecosystem innovations, innovation policy labs, frugal innovation and territorial policies have been discussed for their potential alignment with inclusive strategies. Social impact bonds might offer incentives for inclusive practices.

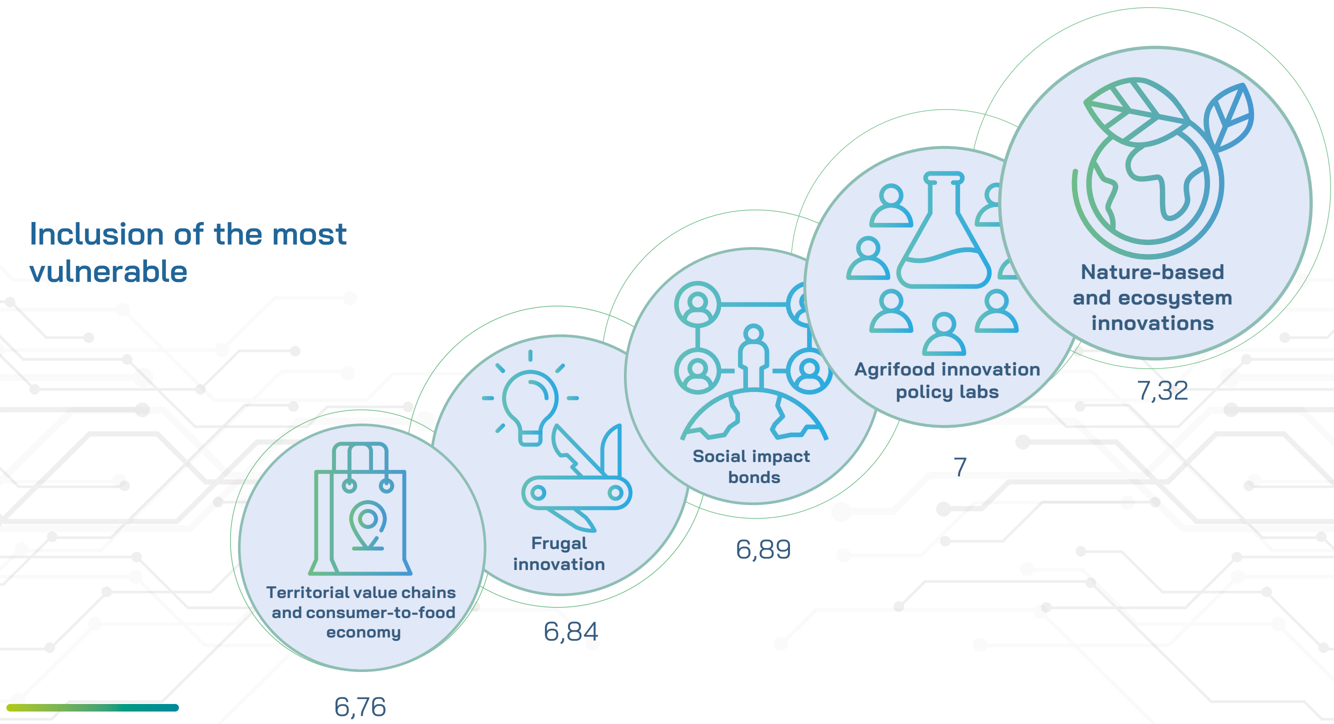


Figure 10: Top five technologies and innovations perceived to have the highest impact on inclusion of the most vulnerable

Transboundary and emerging agrifood systems threats

Addressing global threats to the agrifood systems, technologies such as artificial general intelligence, 6G-10G connectivity and real-time geospatial technologies are being assessed for their potential benefits. Agricultural innovation policy labs and synthetic biology also hold promise in addressing these challenges.

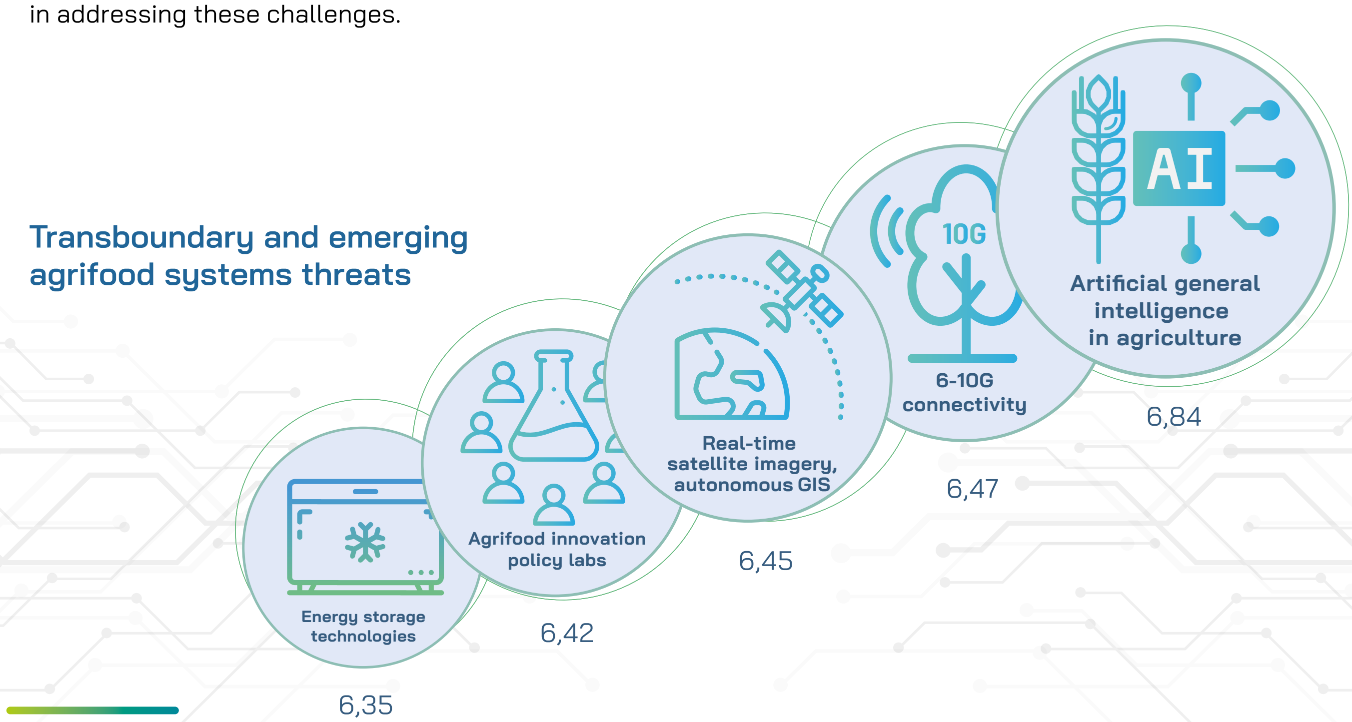


Figure 11: Top five technologies and innovations perceived to have the highest impact on transboundary and emerging agrifood systems threats

National and international governance

In governance, agricultural innovation policy labs have been noted for their potential in fostering collaboration. 6G–10G connectivity might streamline international communication and the global logistics network could facilitate trade. Social impact bonds and carbon credits might encourage sustainable practices, and there are ongoing efforts to ensure that information on sustainability matters remains accessible and based on science.

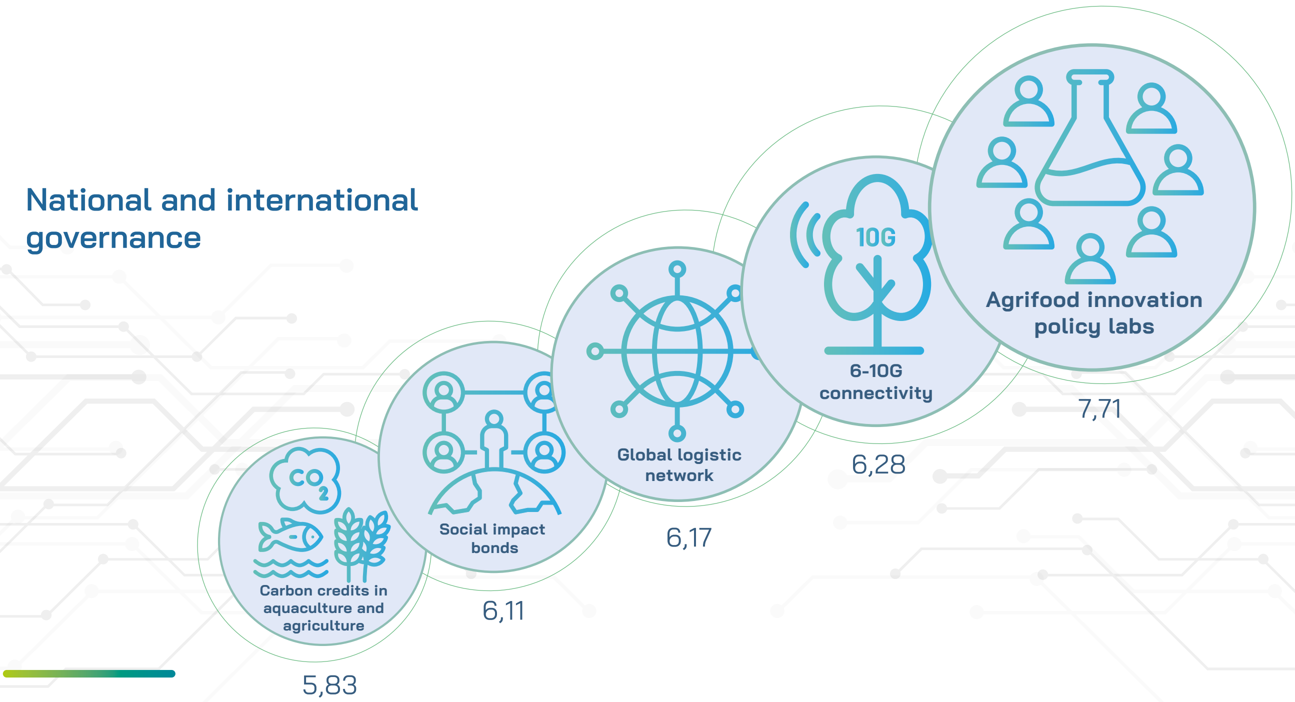


Figure 12: Top five technologies and innovations perceived to have the highest impact on national and international governance

TIMELINE

Addressing agrifood systems challenges in a timely way

When we plotted these observations against the data on maturity of respective technologies and innovations, additional observations were made. Challenges related to population and development dynamics, erosion of natural resource base, loss of biodiversity and energy demand and use in agrifood systems appear to be better covered in the short run (by the early to mid-2030s) given the technologies that are emerging sooner. Technologies like real-time satellite imagery, nature-based innovations and novel biomass energy, which will reach full potential by the late 2030s, can have a transformative impact on these challenges.

Challenges such as climate change, disasters, conflicts and crises might require a longer horizon, with technologies like artificial general intelligence in agriculture emerging around the early 2040s to offer comprehensive solutions.

In the shorter term, the following emerging technologies and innovations can be applied to address the challenges on a global scale:

Population and development dynamics, food and nutrition security, sustainable diets:

1. Real-time satellite imagery, positioning systems and autonomous GIS will reach full potential by 2037, which could provide crucial data for better agricultural decision-making.
2. The global logistics network is expected to emerge by 2042 and could enhance the food supply chain.
3. Nature-based and ecosystem innovations are anticipated for 2037, emphasizing sustainable community growth.
4. Frugal innovation will reach full potential as early as 2034, potentially offering cost-effective solutions.

Climate change, disasters, conflicts and protracted crises:

1. Nature-based and ecosystem innovations reaching maturity by 2037 can offer harmony with natural systems.
2. Energy storage technologies anticipated by 2038 could be significant for alternative energy sources.
3. Artificial general intelligence in agriculture is expected to reach full potential around 2042, potentially aiding in decision-making and modelling climate-related interventions.

Erosion of natural resource base, loss of biodiversity:

1. Real-time satellite imagery and positioning systems are soon to reach full potential in 2037 for monitoring.
2. Carbon credits in agriculture and aquaculture expected by 2035 could incentivize sustainable practices.

Food loss and waste:

1. Nanomaterials for food packaging reach full potential by 2042, can extend the shelf life of food products.
2. A global logistics network, emerging around 2042, could help optimize transportation and reduce waste thus helping advance in achieving circular economy.

Energy demand and use in agrifood systems:

1. Novel biomass energy, reaching full potential by 2035, and energy storage technologies by 2038 will play a pivotal role.
2. Artificial general intelligence in agriculture will reach full potential by 2042 for optimizing energy use.

Inclusion of the most vulnerable:

1. Frugal innovation and territorial policies, both expected around the mid-2030s, could promote inclusive strategies.
2. Social impact bonds, expected by 2036, could offer financial solutions to support vulnerable populations.

For transboundary and emerging agrifood systems threats, only the real-time geospatial technologies reaching full potential by 2037 will become available in the short run.

National and international governance, agrifood innovation policy labs and carbon credits could become mature by the mid-2030s, potentially fostering collaboration and sustainable practices.

Time horizon of clusters' emergence of agrifood technologies and innovations

During the Delphi survey, participants were invited to estimate the time of emergence of each of the 32 technologies and innovations. The results were then grouped by clusters and provided insights with respect to strategic planning and preparedness for the uptake of those technologies and innovations.

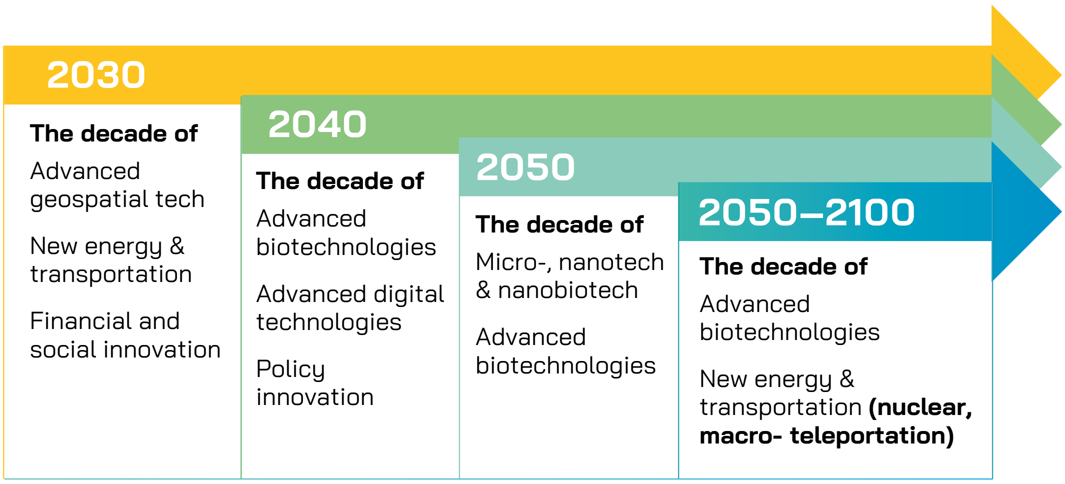


Figure 13: Horizon of emergence of clusters of technologies and innovations

Application areas with the biggest breakthroughs projected until 2050

In parallel to the assessment of emerging technologies and innovations as such, the Delphi respondents were invited to elaborate on which areas of application will be most affected by the gradual deployment of the technology novelties and innovation, in which areas we can expect major breakthroughs and in which timeline. The results, summarized below, reinforce the other assessments made in the study concerning the anticipated pathways of agrifood technology development and the diffusion of innovations globally.

Top application areas by 2030:

1. **Production systems:** Advances in precision agriculture, innovations in farm and land management, expansion of vertical farming in urban areas, enhancements in irrigation and strides in regenerative agriculture and forestry.
2. **Energy and transportation:** Expecting significant shifts and innovations.
3. **Value chains and services:** Anticipating transformative changes and novel approaches.

Top application areas by 2040:

1. **One health and nutrition:** Major innovations leading to improved health outcomes and dietary changes.
2. **Production systems:** Continued progression in precision farming, urban agricultural practices and regenerative techniques in both agriculture and forestry.
3. **Energy and transportation:** Continued evolution with more sustainable and efficient solutions.
4. **Governance and trade:** Expecting reforms and groundbreaking changes in how trade and governance are conducted.
5. **New materials, proteins and circular economy:** Introduction of novel materials, alternative protein sources and comprehensive approaches to a circular economy.

Top application areas by 2050:

1. **New materials, proteins and circular economy:** Deeper advancements in material science, sustainable protein alternatives and perfected circular economic models.
2. **Inclusion:** Greater emphasis on the integration and empowerment of vulnerable groups, including the impoverished, youth, elderly and indigenous communities.
3. **Energy and transportation:** Anticipating groundbreaking developments revolutionizing how energy is harnessed and transportation is conducted.
4. **Production systems:** Sustained innovation in urban agriculture, precision techniques and eco-friendly farming practices.

PLACE: REGIONAL ASPECTS OF THE AGRIFOOD TECHNOLOGY AND INNOVATION EMERGENCE

Asia and Pacific

The main drivers for Asia and Pacific were:

- **Climate change**
- **Population dynamics and urbanization**
- **Economic growth, structural transformation and the macroeconomic outlook**
- **Innovation and science**
- **Big data generation, control, use and ownership**

Given the drivers in this region, technologies like real-time satellite imagery, positioning systems and autonomous GIS (anticipated to be mature by 2037) would address climate change and population dynamics by enhancing resource allocation and monitoring urban growth. For economic growth and innovation, the focus could be on the global logistics network (mature by 2042) and artificial general intelligence in agriculture (mature by 2042). Addressing the big data challenge would involve investing in 6G-10G connectivity for agriculture (mature by 2043).

Europe and Central Asia

The main drivers in Europe and Central asia were:

- **Climate change**
- **Public investment in agrifood systems**
- **Economic growth, structural transformation and the macroeconomic outlook**
- **Innovation and science**
- **Consumption and nutrition patterns**

Considering the regional emphasis on public investment and climate change, nature-based and ecosystem innovations (anticipated to be mature by 2037) and environmental biotechnologies (mature by 2043) would be applicable. For the region's consumption and nutrition patterns, personalized nutrition technologies (mature by 2047) would be relevant.

Latin America

The main drivers in Latin America were:

- **Population dynamics and urbanization**
- **Climate change**
- **Scarcity and degradation of natural resources**
- **Economic growth, structural transformation and the macroeconomic outlook**
- **Innovation and science**

To tackle population dynamics and climate change, technologies such as real-time satellite imagery and autonomous GIS (mature by 2037) and novel biomass energy (mature by 2035) would be beneficial. Addressing the scarcity and degradation of natural resources would necessitate environmental biotechnologies (mature by 2043).

Northern Africa and Near East

The main drivers in Northern Africa and Near East were:

- **Climate change**
- **Public investment in agrifood systems**
- **Population dynamics and urbanization**
- **Geopolitical instability and increasing conflicts**
- **Scarcity and degradation of natural resources**

Considering the challenges of geopolitical instability and resource scarcity, technologies such as aerial robotics and drones (anticipated to be mature by 2041) and nature-based and ecosystem innovations (mature by 2037) would be fitting. To address public investments and population dynamics, agrifood innovation policy labs (mature by 2036) would be appropriate.

Sub-Saharan Africa

The main driver in sub-Saharan Africa were:

- **Climate change**
- **Population dynamics and urbanization**
- **Public investment in agrifood systems**
- **Economic growth, structural transformation and the macroeconomic outlook**
- **Inequalities that are widespread and deep-rooted**

Inequalities and climate change could benefit immensely from nature-based and ecosystem innovations, including environmental biotechnologies, (mature by 2037) and frugal innovation (mature by 2034). Addressing population dynamics might necessitate global logistics network technologies (mature by 2042).

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 around the globe**
- **Concerns that global inequalities that are widespread and increasing**

Given North America's emphasis on public investment, climate change and global inequalities, technologies such as nature-based and ecosystem innovations (mature by 2037), environmental biotechnologies (mature by 2043) and social impact bonds (mature by 2036) would be key.

A noteworthy observation is perhaps that while certain technologies align well with the immediate needs of developed regions, the challenges of lesser-developed regions are at times matched with technologies predicted to become mature much further in the future. This temporal mismatch can perpetuate existing inequalities, emphasizing the need for timely technological adoption and global collaboration to ensure all regions benefit equitably from emerging innovations.

INSIGHTS FROM THE HORIZON SCANNING OF EMERGENT AGRIFOOD TECHNOLOGIES AND INNOVATIONS

Innovations centred around policy, nature-based solutions and data-driven technologies are perceived as the most impactful and are expected to be adopted sooner.

More futuristic concepts like teleportation and nuclear fusion in the agrifood systems are perceived as having a longer horizon before they become mature.

While artificial intelligence and synthetic biology hold great potential in revolutionizing the agrifood systems, their full-fledged adoption is still some years away.

Observing the dataset and keeping in mind the assumption of radical groundbreaking innovations emerging in the long term, we can make the following observations:

- Incremental over disruptive and revolutionary: The data indicates a preference trend towards innovations that seem to be more incremental and evolutionary rather than revolutionary. This could imply that the majority of expected advancements in agrifood systems for the next several decades would be based on refining and enhancing existing technologies rather than introducing entirely new paradigms that may require coordinated, transformative changes into other parts or components of the agrifood systems.
- Risk aversion: A focus on more immediate, incremental innovations could be a sign of a risk-averse approach in the agrifood sector. Stakeholders might prioritize solutions that have a clearer path to realization and implementation, or ones that are close to their usual institutional or practical routines. This implies a need to enhance the focus on managing and mitigating risks to accelerate the pace of innovation.
- Groundwork for the future: Even though many of the technologies listed have shorter ETM values, they might be laying the groundwork for more transformative changes in the future. For instance, once real-time satellite imagery or artificial intelligence becomes mature in agrifood systems, they might pave the way for more radical innovations that we can't currently foresee.
- External limiting factors: The adoption of distant groundbreaking innovations might also be influenced by external factors such as regulatory barriers, ethical concerns or societal acceptance. For instance, technologies like synthetic biology or teleportation of complex molecules might face significant scrutiny and regulation, slowing their path to mature adoption.
- Interdisciplinary innovations: Future groundbreaking innovations in agrifood systems might emerge from the convergence of technologies from different sectors. For instance, advances in quantum computing or energy storage from other sectors might lead to unforeseen breakthroughs in agrifood.
- Underestimation of potential: There's also a possibility that the perceived impact and timelines for some of these technologies might be underestimated. Historically, the adoption curve of certain technologies has proven experts wrong, with innovations becoming mature much faster than anticipated.
- Need for visionary thinking: The data might be signalling a need for more visionary thinking or "blue-sky" research in the agrifood systems. While addressing immediate challenges is crucial, there should also be investment in exploring radical ideas that could transform the agrifood systems in the distant future.

In conclusion, while the dataset suggests a near-term, evolutionary trajectory for innovations in the agrifood systems, it's essential to strike a balance. Immediate challenges require quick solutions, but the sector should also foster an enabling environment where visionary and disruptive ideas can be nurtured and supported for long-term transformative impact.

A century of agrifood innovations

The Delphi data offers a comprehensive glimpse into the expected timeline for various emerging agrifood technologies and innovations to enter mature use. Analyzing the data, there's a clear distinction in the estimated time of adoption between categories and their respective clusters.

The cluster of advanced biotechnologies exhibits a predicted adoption timeline that spans from 2043 to 2051, indicating a rather extended period for assimilation. On the other hand, advanced digital technologies cluster reveals a more clustered timeline from 2041 to 2048, suggesting that this domain might experience a more simultaneous introduction of several technologies into full maturity. The cluster of micro-, nanotechnologies and nanobiotech anticipates its innovations to be mature between 2042 and 2048. In contrast, new energy and transportation has a broader distribution from 2035 to an outlier in 2063 for the teleportation of complex molecules, indicating varied acceptance and feasibility levels among its clusters. The policy innovation domain appears to be the nearest in terms of adoption, with many of its innovations predicted for mature use by the mid-2030s, emphasizing the immediate relevance and feasibility of policy adjustments. Finally, the financial and social innovations sector also expects its technologies to be embraced mainly in the mid-2030s, pointing towards an imminent need for these innovations in the agrifood landscape.

By studying this time distribution, stakeholders can gain a better understanding of where to channel their investments and resources, ensuring timely adoption and integration of these innovations in real-world scenarios. The emphasis on certain technologies, particularly those nearing maturity and adoption in the next decade, is a testament to the dynamic evolution of the agrifood sector and its constant striving for sustainability, efficiency and inclusivity.

3

Strategic foresight

Building on the results of the horizon scanning of emerging technologies and innovations on their perceived impact, timeline of emergence and achieving maturity and regional aspects, a strategic foresight was used to further identify the forces and events, driving and shaping this emergence. Contrasted and plausible scenarios of alternative futures related to the environment for emergence of agrifood technologies and innovations in the context of global agrifood scenarios (FOFA, FAO 2022) have been developed, to stimulate reflection and proactive decision-making. Scenario building process was embedded in the narratives of the 4 FOFA scenarios (FOFA, FAO 2022), then enriched through the horizon scanning results and through multi-stakeholder workshops and collective intelligence sessions.

DRIVERS OF AGRIFOODS SYSTEMS FOR EMERGENCE OF TECHNOLOGY AND INNOVATION

The future of food and agriculture: Drivers and triggers for transformation (FAO, 2022), undertook the task of identifying key drivers impacting these systems. Utilizing the expertise of international private sector professionals, academics, farmer organisations and international agencies via a Delphi survey, a prioritization of these drivers was made based on their global significance. Crucially, these drivers not only influence the traditional aspects of agrifood systems but also play a determining role in shaping the direction of emerging technologies and innovations.

Table 2 presents the global ranking of agrifood systems drivers based on a real-time Delphi question in which respondents were asked to select 5 key drivers for each of the 6 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 often 0.

Climate change, with a global normalized score of 1.0, underscores the urgency of sustainable and resilient farming practices, in particular nature-based solutions and ecosystem innovations. This has and will continue to push the envelope for innovations like drought-resistant crop varieties, precision agriculture and information and early warning systems using AI, realtime satellite imagery, and other technologies that can withstand unpredictable weather patterns. Energy storage technologies and quantum computing can create the basis for expanded analytics and resource efficiency.

Population and development dynamics, food and nutrition security, sustainable diets, scoring 0.78, implies a need for novel protein and micronutrient sources, paving the way for responsible use of synthetic biology and celluar agriculture, as well as healthy and nutritious food, produced through nature-based practices and ecosystem innovations. As urban centres grow, smart urban farming technologies, such as vertical farming- hydroponics and aeroponics, and innovations in supply chain management may gain traction to meet food demand without expanding land use. The driver of economic growth, structural transformation and the macroeconomic outlook with a score of 0.72 suggests that, as economies evolve, there will be a demand for tech-driven, as well as policy and social innovations. This can range from advanced machinery to agroecological solutions and finance and market technologies like blockchain for transparent, traceable and efficient agricultural trade.

Public investment in agrifood systems (0.64) hints at the role of public funding in spurring on STI. Innovations that might benefit from public funding include those in gene editing, post-harvest technology and waste reduction. With food prices (0.59) being

		NORMALISED SCORE* (higher value for more crucial drivers)					
Driver	Global ranking	Asia and 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	0.93	0.93	1.00	1.00
Population dynamics and urbanization	2	0.80	0.33	1.00	0.87	0.73	1.00
Economic growth, structural transformation and the macroeconomic outlook	3	0.80	0.93	0.73	0.93	0.20	0.80
Public investment in agrifood systems	4	0.33	1.00	0.33	0.67	0.87	0.80
Food prices	5	0.47	0.67	0.73	0.67	0.53	0.73
Innovation and science	6	0.73	0.80	0.73	0.93	0.07	0.47
Scarcity and degradation of natural resources	7	0.20	0.73	0.87	0.47	0.60	0.67
Geopolitical instability and increasing conflicts	8	0.40	0.67	0.33	0.33	0.73	0.67
Inequalities are widespread and deep-rooted	9	0.40	0.00	0.73	0.33	0.60	0.73
Consumption and nutrition patterns	10	0.33	0.80	0.07	1.00	0.40	0.13
Big data generation, control, use and ownership	11	0.53	0.53	0.27	0.87	0.00	0.20
Rural and urban poverty	12	0.33	0.00	0.60	0.13	0.53	0.60
Capital and information intensity of production	13	0.27	0.27	0.67	0.40	0.07	0.33
Epidemics and degradation of ecosystems	14	0.40	0.20	0.33	0.33	0.20	0.20
Uncertainties	15	0.07	0.00	0.20	0.20	0.60	0.47
Cross-country interdependencies	16	0.13	0.60	0.40	0.13	0.00	0.00
Input and output market concentration	17	0.00	0.33	0.00	0.33	0.00	0.13
The “sustainable ocean economies”	18	0.20	0.07	0.20	0.20	0.00	0.00

**Scores calculated based on a question in which respondents were asked to select 5 key drivers for each region, by order of importance. Normalised values, with 1 signifying drivers considered to be the most important by the respondents and 0 the least important ones.*

Table 2: Global rank of agrifood systems drivers

a significant concern, innovations in territorial value chains and consumer-to-food economy, as well as in predictive analytics to anticipate market fluctuations or AI-driven optimization of food storage and distribution to reduce costs might see a surge. The importance of innovation and science itself, scoring 0.58, is a testament to the need for continuous research and development in the agrifood systems, in particular on policy and nature-based solutions and ecosystem innovations. From gene editing for improved crop yields to Internet of Things (IoT) devices for real-time farm monitoring, the horizon for tech integration looks promising.

Drivers like big data generation and its control (0.33) emphasize the role of data in revolutionizing farming. Innovations might include advanced sensor networks for farms and analytics platforms that provide actionable insights for farmers. While drivers such as input and output market concentration (0.03) and the sustainable ocean economies (0.0) might be lower on the list, they too hold implications. For instance, innovations might emerge that focus on sustainable aquaculture or platforms that decentralize food markets.

In summary, the interface between the prioritized drivers and the agrifood systems is ushering in an era of policy, social and technological innovations. As challenges intensify, so too does the impetus for actionable solutions, ensuring a dynamic and evolving future for global agrifood systems.

INTERNAL TRENDS FOR EMERGING TECHNOLOGIES AND INNOVATIONS

As was explained in previous chapters, the trajectory for the development of agrifood systems is being significantly shaped by a new era of emerging technologies and innovations. They, in turn, are being influenced by several key trends which were already extensively described in previous FAO foresight work, specifically in The future of food and agriculture report. These trends, important to technology and innovation, but also shaping the future of food and the livelihoods of those depending on food and agricultural systems 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 an extremely 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 smart phone. The agrifood sector's stakeholders must stay abreast of these trends, ensuring that their strategies align with the evolving landscape of emerging technologies and innovations. Specific scores are presented below.

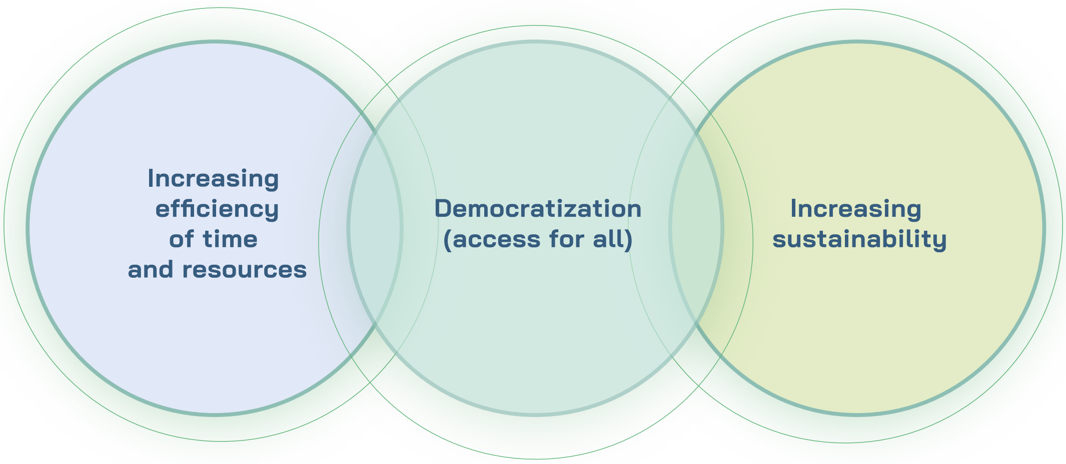


Figure 14: Top three internal trends in emerging agrifood technologies and innovations

Trend 9: Increasing efficiency of resources and time Score: 2.79

Efficiency remains a cornerstone for the future of agrifood systems. Emerging technologies and innovations that optimize resource usage and reduce time in agricultural processes are likely to gain prominence. This trend underscores the need for innovations that address wastage, optimize farm operations and accelerate food production without compromising on quality.

Trend 4: Democratization, allowing for accessibility for all. Score: 2.75

The move towards more democratic agrifood systems should prioritize technologies that ensure food accessibility for all. Emerging technologies and innovations that bridge the gap between producers and consumers, making food sources more available and affordable, will be pivotal.

Trend 8: Increasing sustainability of technologies and innovations Score: 2.60

Sustainable practices in the agrifood sector are no longer optional; they're imperative. Emerging technologies and innovations emphasizing sustainability – whether through reduced carbon footprints, sustainable farming techniques or eco-friendly packaging – will be at the forefront of agrifood advancements.

Trend 1: Increasing precision (for more precise output) Score: 2.50

Precision technologies in agrifood systems facilitate targeted interventions, reducing unnecessary inputs and enhancing outputs. This trend signifies a move towards technologies that allow farmers to apply exact measures be it in planting, irrigation or harvesting, leading to optimized yields and reduced waste.

Trend 6: Increasing the integration of technologies (fusion or combination of several types of technologies and innovations) Score: 2.35

The fusion of multiple technologies can bring about holistic solutions in the agrifood sector. Integrated systems, where AI meets drone technology or where biotech converges with digital platforms, will redefine how we grow, process and distribute food.

Trend 5: Increasing possibilities of real-time notification and interaction (allowing for observation during the actual time of occurrence) Score: 2.30

Real-time insights are set to revolutionize agrifood systems. Emerging technologies and innovations that offer instant notifications, whether about soil health, crop diseases or market demand, can empower stakeholders to swiftly make informed decisions.

Trend 7: Increasing universality (multipurpose, functionality valid for all) Score: 1.45

Multi-functionality in emerging technologies and innovations means tools and innovations that cater to a spectrum of agrifood needs. Such universal technologies, adaptable across various agrifood sub-sectors, will be integral in creating cohesive and streamlined systems.

Trend 2: Minimization, allowing for a reduction in size of particles or device. Score: 1.05

Compact and efficient designs in agrifood technologies, such as micro-sensors or nano-fertilizers, can bring about more precise, less invasive interventions in farming and food processing.

Trend 3: Personalization, allowing for specifications according to the individual needs. Score: 0.55

The agrifood sector will see a rise in tailored solutions. From personalized nutrition plans powered by AI to crops engineered for specific regional needs, catering to individual preferences and requirements will gain traction.

WILD CARDS AND TRIGGERS

In addition to external drivers of the agrifood systems and internal to technology and innovation trends, the Delphi has provided with the participants' perception on the triggers of change and wildcards for emerging technologies and innovations.

The triggers of change are hypothetical future, which can potentially affect the strength of currently observable drivers and the course of trend. The expert and multistakeholder community identified the following triggers :

- Governance and business environment related to agrifood emerging technologies in place
- Rapid acquiring of new skills and rise of human capital in place
- Removed barriers for technology adoption that involves improved mechanisms for intellectual property rights, knowledge flow and dissemination
- Societal consensus and ethical standards in place
- Achieving true circularity and sustainability

In the course of the Delphi survey, we also asked experts to come up with a number of 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 the context of agrifood systems, these wildcards can bring about sudden and intense shifts, leading to challenges or opportunities that stakeholders might not be prepared for. 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 in place to address unexpected shifts in the agrifood landscape.

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

1. Exacerbating of global conflicts and mass casualties
2. Discovery macromolecule of teleportation, and very cheap energy sources at 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 aging 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.

SCENARIOS FOR EMERGING AGRIFOOD TECHNOLOGIES AND INNOVATIONS

Five scenarios have been elaborated through a participatory and iterative process with different areas of professional knowledge (research institutes, farmer organizations, private sector, international agencies) and broader multistakeholder perspective (including civil society organizations). The scenarios are a selection of contrasted, coherent, plausible and alternative pictures of the future with a specific focus on technologies and innovations. The scenarios have benefited from the broader agrifood systems scenarios (FOFA. FAO, 2022) and the relation with FOFA scenarios is presented on the figure below. Each scenario has been shaped by using the previously identified key external agrifood systems' drivers, key internal trends to technology and innovation, triggers of change and wildcards. Each scenario is sustained by a set of drivers that affect different components and actors of the agrifood systems that are able to identify their needs, design, experiment, implement, control, manage, govern, adapt, reshape and use the new technologies and innovations.

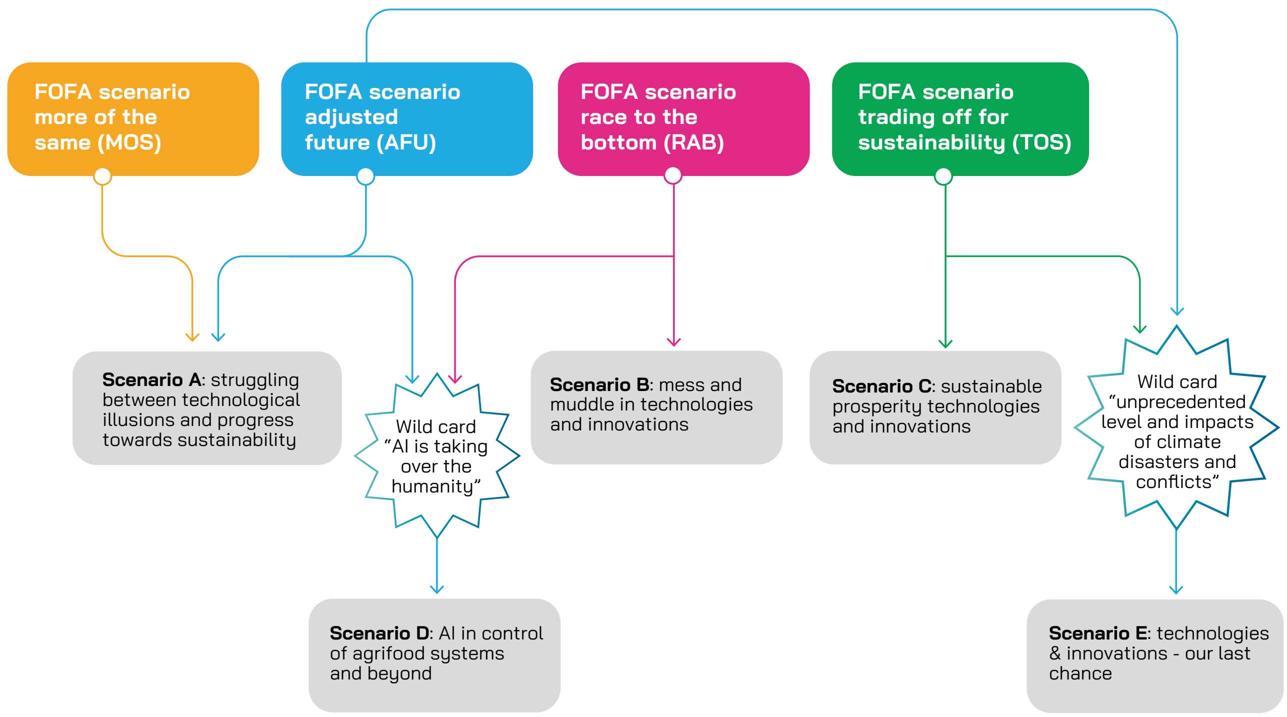


Figure 15: Link between FOFA agrifood systems scenarios and the scenarios of emerging agrifood technologies and innovations

The following narratives have been developed.

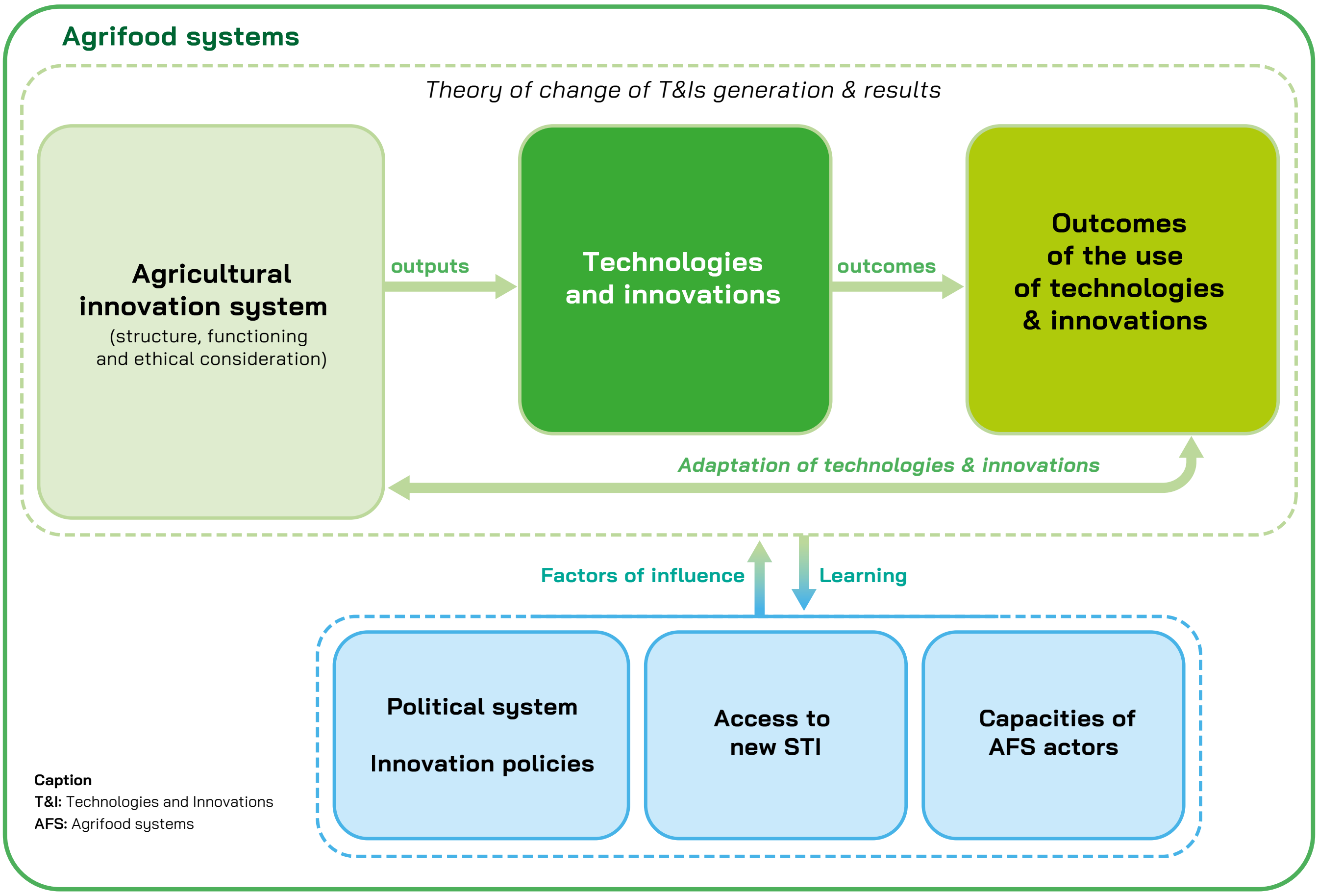


Figure 16: Conceptual diagram to represent and summarize scenarios

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, mostly due to a lack of strong policy engagement and challenging science–policy interface, and the availability of effective instruments to conduct relevant and inclusive monitoring, evaluation or impact assessment, as well as to 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 own investment strategies, while smaller or start-up companies with insufficient public support and dysfunctional business environments are reluctant to invest. With respect to 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 poor or insufficient when it comes to supporting sustainability transitions of agrifood systems. As a result, emerging technologies and innovations only partially address major challenges (climate change, disaster mitigation, inclusion), and this leads to technological disillusionment. As a result, misunderstandings persist and access to relevant information is impeded.

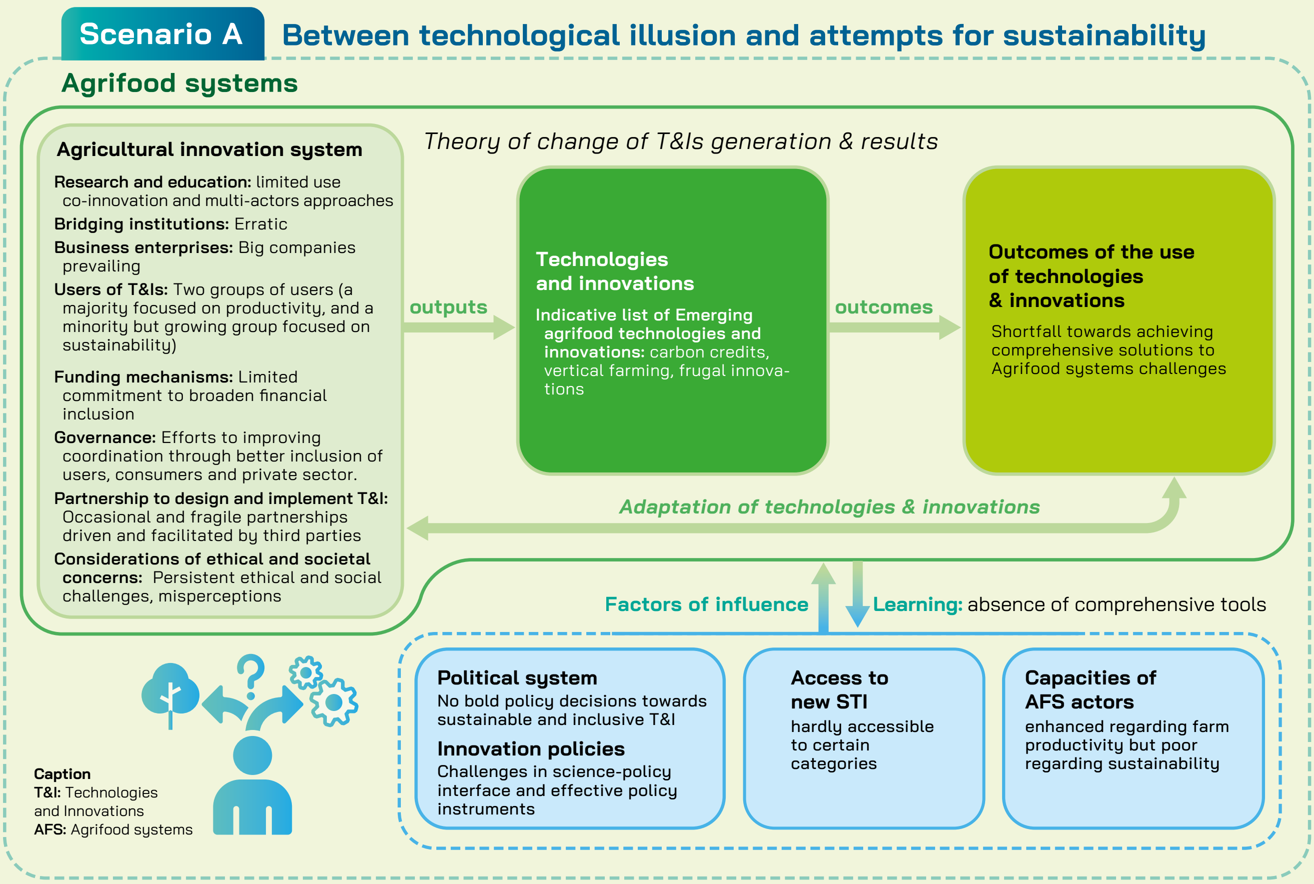


Figure 17: Overview of scenario A "Struggling between technological illusions and progress towards sustainability"

Scenario B: Mess and muddle in technologies and innovations

In 2050, technology and innovation systems are not 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 famers and food processors unable to access the benefits of innovation and technological progress. Research, societal and innovation agendas are disconnected from development challenges, 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 unfavourable business environment for the development and diffusion of 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. The funding of new technologies and innovations is driven by major financial interests from banks and insurance companies.

Start-up enterprises that seek to challenge this status quo find themselves faced with insurmountable business obstacles. The research, design and implementation of new technologies and innovations is carried out in silos and led exclusively by private interests, or through platforms of specially selected private companies at the exclusion of other stakeholders. There are no mandatory mechanisms to monitor technologies and innovations according to its performance, or their economic, social, environmental and cultural impacts. Research findings become intellectual property, and therefore are inaccessible. Technology and innovation then become difficult to develop, without open access knowledge platforms and a premium on any high-quality, relevant or reliable knowledge. Actors involved in the implementation and use of technology and innovation lack the relevant 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 are run rampant, further worsened by the limited access to scientific knowledge, information and networking platforms.

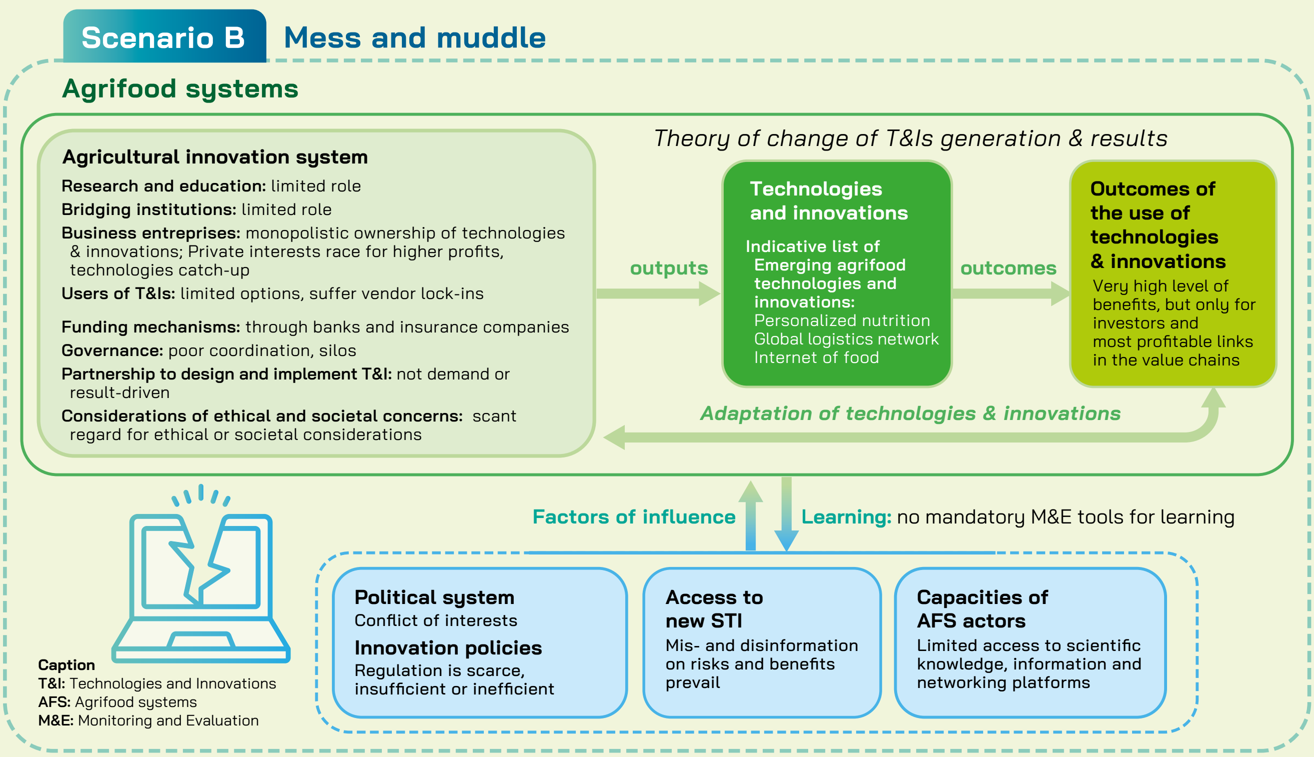


Figure 18: Overview of scenario B "Mess and muddle in technologies and innovations"

Scenario C: Sustainable prosperity of technologies and innovation

In 2050, innovation and technology development systems are driven by a focus on sustainability, one-health approaches and circularity in most economies. Technology and innovation develops according to responsibility, inclusivity and functionality. Governance is led by citizens and relies on fair and transparent dialogue with the private sector and civil society organizations, which are also engaged in global dialogues. Research and innovation agendas are perfectly aligned with development challenges. This is further supported by renewed public–private–users partnership funding, relying on accountability based on performances and results (outcomes and impacts), including crowd funding or specific funds allocated to smallholders. Multinational, local, small and start-up companies, along with research and farmers' organizations and food-processors, are all involved and actively support the design of technology and innovation oriented towards sustainability. Participatory and inclusive approaches are now mature and allows for a broad engagement in social and ethical national and global roundtables, enabling road map compliance. Innovation policy labs, where all types of stakeholders are a true 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 and inclusive, and managed through transparent and professional mechanisms. Actors benefit from updated and free access to human capital development programs for sustainable development.

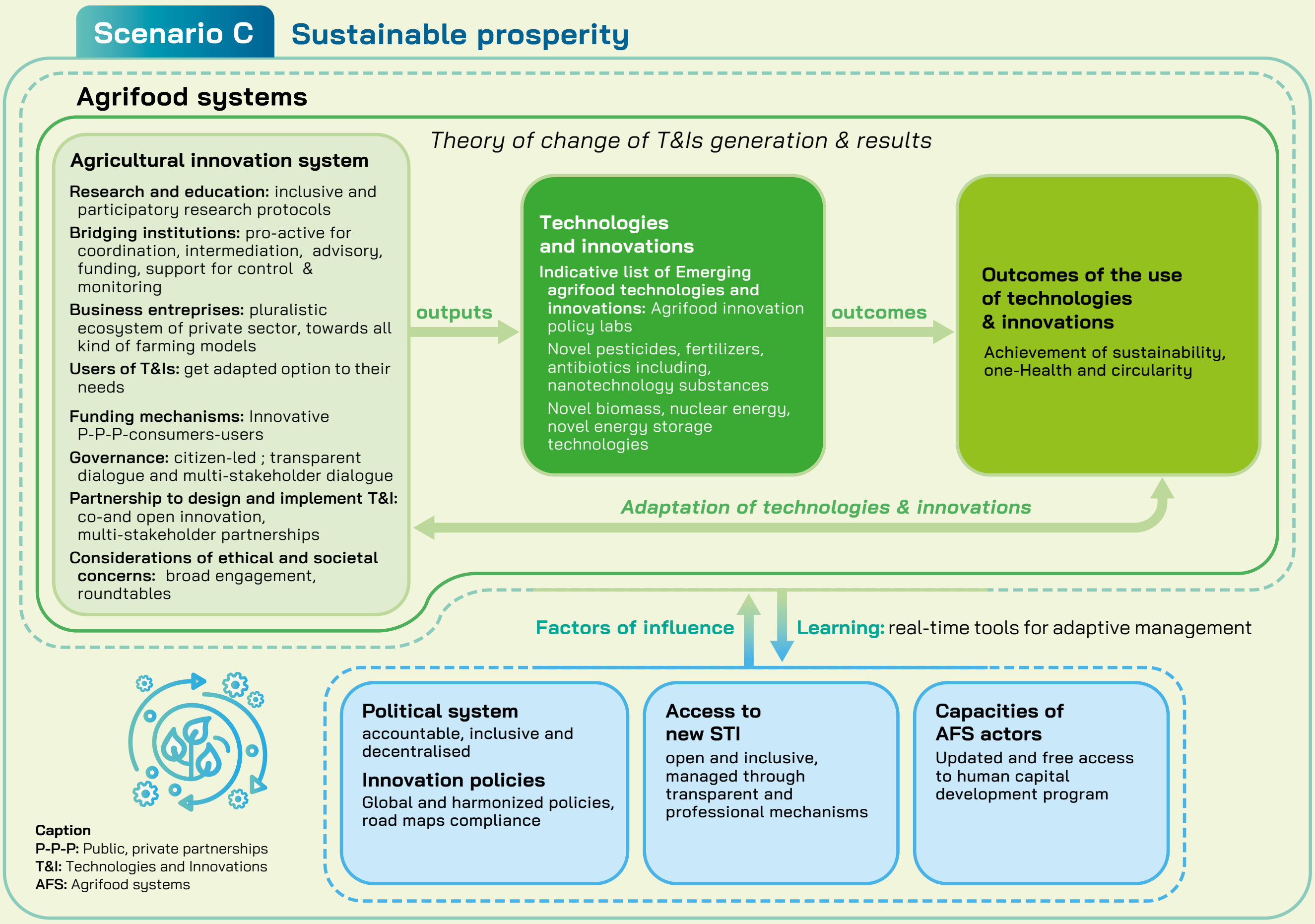


Figure 19: Overview of scenario C "Sustainable prosperity of technologies and innovations"

Scenario D: AI in charge of agrifood systems and beyond

In 2050 regulations increasingly favour automated decision-making in most aspects of life. Technology and innovation is mostly managed by autonomous artificial intelligence (AI) systems, without human involvement. Initial investments are made by AI-agritech companies. Key decision-making on agrifood systems, implementation and real-time optimization are also managed by AI. For instance, AI advices whether pursuing or switching from food production models, depending on agrifood systems capacities, available natural resources and, food demand and safety. The research and innovation agenda is aligned to 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 and results in serious problems around inclusion and equity.. This is partly due to the fact that the methods for developing AI systems are based on advanced country situations, and may not account for other contexts like living remote areas, disregarded value-chains or alternate farming models. Access to new knowledge, technology and innovation is automatically managed and rationalized by AI. Agrifood systems actors have restricted access to the type of knowledge, technology and innovation that they need for their daily life 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 dictated by AI. They send and receive advice from AI for real-time adjustments. The capacities of actors are weak in general, except for those actors in charge of designing and running the AI system. Besides this, cyber-crime is on the rise and poses a threat to actors in agrifood systems. Many fear the risk of ill-governance, as vested interests could steer the actions of AI and influence its decisions.

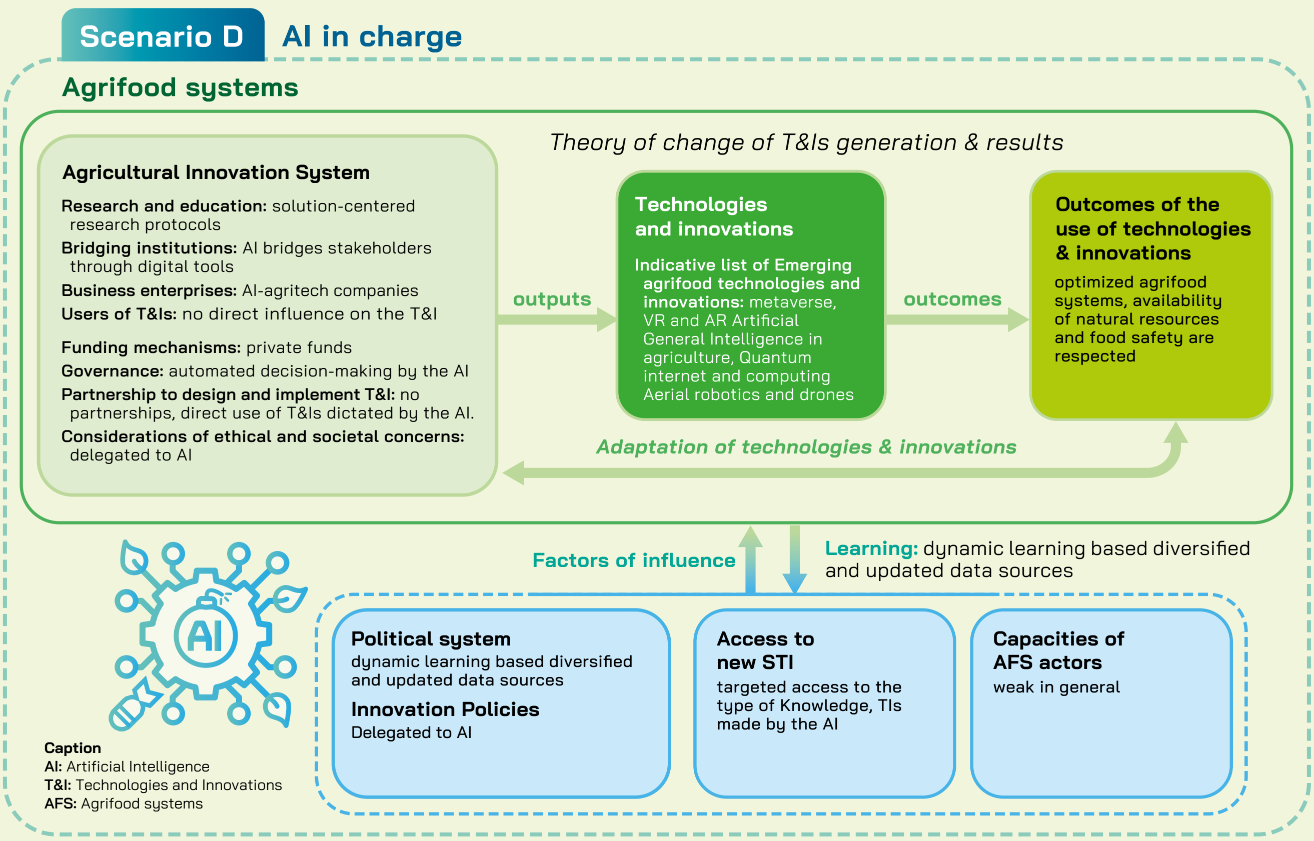


Figure 20: Overview of scenario D "AI in control of agrifood systems and beyond"

Scenario E: Technologies and innovations – our best last chance

In 2050, climate change, disasters and conflicts happen at a faster pace and with greater impact than ever before. In particular, this is a result of governments' inability to formulate and enforce viable and efficient policies and decisions that address numerous acute challenges, as well as their failed role as knowledge brokers and governance coordinators. However, to fill this void, non-state actors – private sector and civil society organizations (CSO) – have taken matters into their own hands. They are stronger than ever before, and actively cooperate in order to collectively address global catastrophe 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 around the world have elaborated a multitude of potentially game-changing solutions that offer high-level impact in short time frames. The private sector benefit from public emergency and recovery funds, along with private investments and capital funds created by major banks accessible through major companies and start-ups. Partnerships for the design and implementation of technologies and innovations is dominated by expert and leader opinion, which values their experiential knowledge as there is no time for "traditional" research protocol or peer-reviewed academic research, or for broad multistakeholders 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 that are developed and promoted within technology and innovation often poses a high level of uncertainty and comes at the cost of significant trade-offs, for example 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.

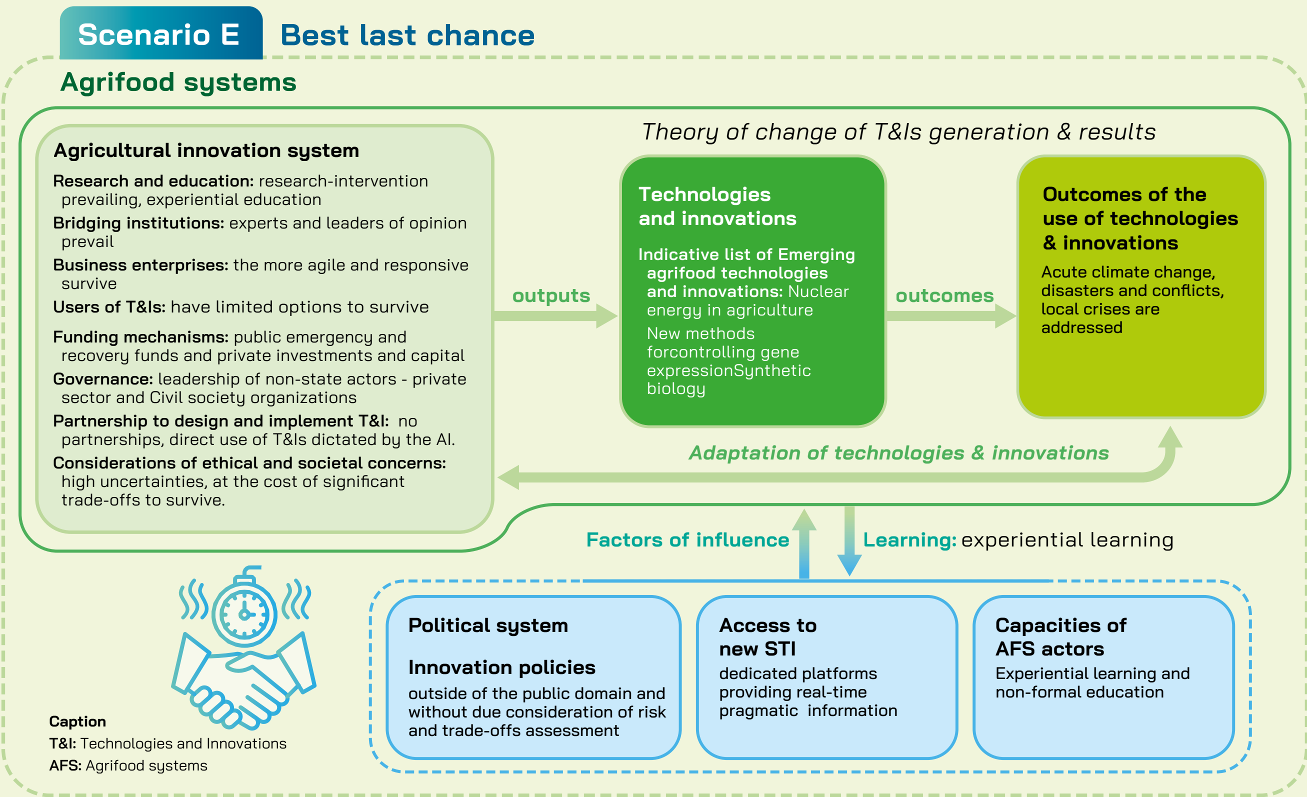


Figure 21: Overview of scenario E "Technologies and Innovations, our best last chance"

INSIGHTS FROM THE SCENARIOS ON EMERGING AGRIFOOD TECHNOLOGIES AND INNOVATIONS

The set of five scenarios is used to envision desirable and undesirable futures, as well as the features within the agrifood systems that enable such positive or negative aspects. Based on the scenarios, a back-casting exercise with the multistakeholder audience from the World Investment Forum 2023 has been conducted to determine the scenario that shows greatest similarity to the current reality, the most preferred scenario and the one that is the most undesirable. Based on the responses, actions have been identified to move from the current situation (Scenario A and Scenario E) to the desirable future (Scenario C) by avoiding features in Scenario B and Scenario D. Through a cross-cutting analysis, we reflect on some lessons derived from the scenarios:

- Governance and partnership for the design and implementation of technology and innovation are key to convey towards 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 contribute to strengthening social cohesion and equity. Accountability and monitoring, evaluation and learning mechanisms are key for successful transformative actions.
- The role of stakeholders may vary from one scenario to another (as designer of new technologies, implementers, solution providers, co-partner, regulator, gatekeeper, users etc.). However, co-innovation is deemed critical to accelerate the scaling up and out of the innovations. No player can be autonomous and totally independent, and the emergence and development of a technology or innovation requires the specific contribution of a diversity of players both upstream and downstream of the process.
- Scenarios may coexist, as they reflect plausible futures which can happen at regional or even national scale. They may also constitute different steps or phases of the development process.

4

Final considerations for strategic planning

Agrifood systems will only be able to meet all expectations if efficient and responsible technologies and innovations are available and accessible. Emerging technologies and innovations with this potential need to be identified and supported, and the conditions for their development and efficient use put in place. The main aim of this study was to explore emerging technologies and innovations in relation to the challenges of the agrifood systems of the future.

POLYCRISIS HINDERING AGRIFOOD SYSTEMS TRANSFORMATION

We are entering an age of polycrisis with unprecedented, escalating and intertwined challenges that affect our agrifood systems of today and tomorrow.

TECHNOLOGY AND INNOVATION CAN ACCELERATE THE TRANSFORMATION

Agrifood technologies and innovations can be part of the solution of accelerating the agrifood systems transformation to achieve more resilient, sustainable and inclusive patterns, if we succeed in merging the spatial and time gap between the emergence of a given technology or innovation from its ideation to its practical application and ensuring conducive environment to maximize the benefits and minimize challenges of the emerging impactful technologies and innovations.

FORESIGHT CONNECTS THE DOTS

Foresight approaches, while not a prediction, allow for using science-based and collectively informed methods that can help take action in the presence of novelty (lack of evidence), uncertainty and complexity, valid for most innovation domains, to achieve the most essential transformative outcomes in a shorter time.

TOP 20 TECHNOLOGIES AND INNOVATIONS IN FOCUS

Twenty top emerging agrifood technologies and innovations were identified as deserving special attention by decision-makers, and the broader multistakeholder community with their capability to address multiple challenges through the assessment of their relative advantage compared to technologies and methods being currently used. Those are:

- Nature-based and ecosystem innovations
- Artificial general intelligence in agriculture
- Agricultural innovation policy labs
- Energy storage technologies
- Social impact bonds
- Real-time satellite imagery, positioning systems and autonomous GIS
- 6–10G connectivity in agrifood systems
- Environmental biotechnologies
- Synthetic biology
- Ensuring access to science-based information on sustainability matters
- Internet of food
- Frugal innovation
- Digital twins
- Quantum internet and computing applied to agrifood systems
- Aerial robotics and drones
- New methods for controlling gene expression
- Global logistics network
- Territorial or landscape value-chain and food-to consumer economy policies
- Carbon credits in agriculture and aquaculture
- Nanomaterials for water technologies

THE SOLUTION IS NOT ONE

A given technology or innovation cannot address all future challenges that agrifood systems will face: it is not a silver bullet. Hence, technologies and innovations should be considered as a set of targeted solutions to be combined, including with traditional knowledge when relevant, to achieve impact.

NEED FOR MULTIPLE OPTIONS

Complex challenges such as inclusion of the most vulnerable and national and international governance are perceived to be better addressed by combination of technologies and innovations. This foresight came up with five key technologies and innovations that are perceived to have most impact on each of the eight agrifood systems challenges that can provide insights for priorities in planning of research programme, capacity development initiatives, policies and investments.

THE SOLUTION IS NOT ONLY TECHNOLOGICAL

The innovations centred around policy, nature-based solutions and data-driven technologies are perceived as the most impactful and are expected to be adopted sooner.

INCREMENTAL INNOVATION EMERGENCE PATHWAY IS PREFERED

The experts and agrifood multistakeholder community, which may prefer safer pathways to transformation, perceived that the majority of expected advancements in the agrifood systems for the next several decades will be based on refining and enhancing existing technologies rather than introducing entirely new paradigms.

DISRUPTIVE TECHNOLOGY AND INNOVATION CAN ACHIEVE TRANSFORMATIVE OUTCOMES FAST

However, they may require time to emerge as they could introduce more uncertainties as changes have to take place in many areas- infrastructure and investments, human and social capital, policy environment and mindsets. More futuristic concepts like teleportation and nuclear fusion in the agrifood sector are perceived as having a longer horizon before they become mature.

While artificial intelligence and synthetic biology hold great potential in revolutionizing the agrifood systems, their full-fledged adoption is still some years away.

NEED TO ASSESS DISRUPTIVE TECHNOLOGIES

Potentially powerful but disruptive technologies are perceived as having less potential impacts. Actually, these technologies are the ones that bring more uncertainty, which reveal the need to focus on ex-ante risk-benefit assessment frameworks to fully leverage their potential.

IMBALANCE between the emergent clusters of technologies and innovations and the clusters, perceived to be more impactful. From the identified 167 emerging technologies and innovations, the most numerous emerging technologies and innovations – 69 – belong to digital and biotechnology innovations, while the perceived most impactful ones – geospatial and policy innovations – account for 31, or more than two times less. This may signal less attention in research and investments for impact.

VENTURE CAPITAL PLAYS A ROLE in fuelling innovation for the agrifood systems, and this cannot be understated. Their investment in emerging technologies has the potential to unlock transformative solutions, providing the much-needed momentum for innovations to transition from concept to reality. The infusion of capital, expertise and networks that venture capital brings accelerates the pace at which these technologies can address pressing global challenges in the agrifood sector. However, it's worth noting that there are areas where investment priorities could benefit from a slight recalibration. Given the financial leverage or other forms of public aid for innovation in the form of e.g. corporate tax instruments or grants which are sometimes provided by public funding through science, research and development, venture capital could strategically align with these public initiatives. By doing so, they can ensure that both immediate and future agrifood challenges are addressed in tandem, maximizing the impact of every dollar invested. In essence, while venture capital's commitment to the agrifood sector is invaluable, a collaborative approach with public funding avenues might pave the way for an even more resilient and sustainable food system.

NEED TO SHORTEN THE TIME LAG BETWEEN RESEARCH AND INVESTMENT PHASES AND THE UPTAKE OF TECHNOLOGY AND INNOVATION

This can be achieved through PREPAREDNESS in terms of IMPACT, TIMELINE and PLACE (regional and country approach) translated in (i) conducive environment – infrastructure, capacities and human capital, policy incentives, repurposed research programmes, development initiatives and investments; (ii) quicken the paradigm of the linear technology transfer towards co-creation and towards more democratic and decentralized governance mechanisms; and (iii) investing in collaboration and multistakeholder partnership. To reduce the emergence phase of the technologies and innovations, taking into account the rising trend of co-innovation, a future option would be to gradually move away from regulating technologies and innovations as a function of state, towards co-creative ex-ante assessments or self-assessment by scientists and innovators in the presence of high ethical standards at the stage of inventing or conceiving the technology or innovation. To that end the assessment and monitoring, evaluation and learning mechanisms must be in place and gain societal trust.

COEXISTENCE OF DIFFERENT PATHWAYS OF CHANGE

New technologies and innovations may emerge from different pathways leading to different levels of involvement and forms of partnerships amongst stakeholders. Technology transfer may remain relevant for supporting disruptive innovations by targeting specific types of farmers and food-processors. Such approaches require sound diagnosis and impact assessments from R&D (either public or private led) to ensure the right innovation is being designed and disseminated to address localized challenges and ensuring they are fit for purpose. However, other pathways of change will coexist, especially for supporting incremental innovations to emerge. Such pathways refer to co-innovation process, where multistakeholders gather and experiment in an iterative and participatory manner, and adapt their practices step by step following loops of diagnosis, experiment, reflection, refinement and learning. Such pathways are particularly suited to nature-based and ecosystem innovations, innovation policy labs, frugal innovations, territorial value chains and consumer to food economy innovations. For these latest types of technologies and innovations, the initial problems and adequate solutions are not known in advance and require multistakeholder discussion and consensus building to be framed.

RECOMMENDATIONS

- **ALIGNING** research and innovation agendas with societal development challenges to ensure that new technologies and innovations will fulfil their role and expectations.

- **STRENGTHENING TECHNICAL AND FUNCTIONAL CAPACITIES** to innovate and ensure that the raising complexity and uncertainties within the agrifood systems are well understood, anticipated and managed by a wide range of stakeholders.

- **DEMOCRATIZING ACCESS** to science, technology and innovation to ensure that all, including the most vulnerable groups like smallholders, women, youth, indigenous peoples etc., can access easily and timely the proposed solutions.

- **CONTEXTUALIZING** the technology and innovation for availability and relevance. Beyond the traditional technology transfer paradigm, it is key to empower national, regional or local AIS actors to innovate and co-create adapted solutions relevant to their problems rather than be recipients of technologies conceived elsewhere.

- **MONITORING THE PERFORMANCE AND IMPACT** of emerging technologies and innovations, in combination with other factors and in the presence of appropriate open-access feedback mechanisms and monitoring, learning and evaluation tools can inform on benefits and challenges of emerging technologies and innovation regarding economic, agronomic, environmental, social but also cultural results or potential risks.

- **CO-INNOVATING** becomes crucial to act locally and scale up faster with bigger impact: no stakeholder alone can succeed in providing an adequate response to the challenges. New forms of inclusive partnerships and financing mechanisms must be developed with the public sector, industry, consumers, various farmer groups and agencies. This requires inclusive, context sensitive but also global governance mechanisms, in particular with respect to artificial intelligence.

- **ENHANCING INTERNATIONAL AND MULTISTAKEHOLDER COLLABORATION FOR GLOBAL SOUTH.** Many technologies and innovations have emerged already in other parts of the world but are not yet part of the transformative options in the Global South. Transformative partnerships, new governance and business models, repurposed investments, refocused research programmes and development support are part of the solutions.

- **CREATING CONDUCIVE ENVIRONMENTS** is a key factor in reducing the emergence phase of the technologies and innovations and ensuring a reorientation towards more sustainable, resilient and inclusive patterns. This includes policy incentives, repurposing of investments, refocusing of research programmes and developments assistance. Furthermore, there is a need to establish an efficient governance and coordination mechanism between stakeholders engaged at different levels and with different roles in the agrifood systems. To reduce the emergence phase of the technologies and innovations, taking into account the rising trend of co-innovation, a future option would be to gradually move towards co-creative ex-ante assessments or self-assessment by scientists and innovators in the presence of high ethical standards at the stage of inventing or conceiving the technology or innovation.

Annex 1. 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 agriculture sectors 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.

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