Food and Agriculture Organization of the United Nations

EXPLORING THE FUTURE LANDSCAPE OF NEW FOOD SOURCES AND PRODUCTION SYSTEMS

A foresight exercise

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by

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Abbreviations

3D	three-dimensional
3DFP	three-dimensional food printing
ACHIPIA	Chilean Food Safety and Quality Agency
AI	artificial intelligence
AIDS	acquired immunodeficiency syndrome
BPA	bisphenol A
BSG	brewers' spent grain
CAP	cold atmospheric plasma
CFSA	China National Center for Food Safety Risk Assessment
CP	cold plasma
DNA	deoxyribonucleic acid
EBI	electron beam irradiation
EFSA	European Food Safety Authority
EPA	United States Environmental Protection Agency
FAO	Food and Agriculture Organization of the United Nations
FDA	United States Food and Drug Administration
FSA	Food Standards Agency
FSAI	Food Safety Authority of Ireland
GFI	Good Food Institute
GM	genetically modified
GRAS	generally recognized as safe
HFCI	human–food–computer interaction
HiMOs	human-identical milk oligosaccharides
HIPEs	high internal phase emulsions
IoT	internet of things
JEMRA	Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment
LMIC	low- and middle-income country
ML	machine learning
NFPS	new food sources and production systems
RNA	ribonucleic acid
ROI	return on investment
SCP	single-cell protein
SFA	Singapore Food Agency
SIFBI	Singapore Institute of Food and Biotechnology Innovation
SMEs	small and medium-sized enterprises
STEEP	social, technological, economic, environmental, and political
UN	United Nations
WHO	World Health Organization

Chemical formulae

CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
H_2	hydrogen
TiO_2	titanium dioxide

Units of measurement

µm	micrometre
nm	nanometre

Executive summary

Agrifood systems are undergoing significant changes, in part due to new technological advances and scientific discoveries, as well as a recognized need to shift towards sustainability and resilience. New food sources and production systems (NFPS) are emerging worldwide in response to these changes, potentially altering the future food landscape in the next 5 to 25 years.

In light of this transformation, the Food and Agriculture Organization of the United Nations (FAO) Food Safety Foresight Programme conducted a multi-phase foresight exercise to explore potential food safety implications related to the growing NFPS space. Through expert consultations and a structured methodology combining a two-part Delphi survey and mind mapping, the exercise identified 44 emerging innovations across nine clusters expected to develop within the next 25 years.

The exercise revealed both opportunities and challenges associated with these innovations, highlighting the need for proactive preparation by food safety authorities and stakeholders to ensure the safe development and implementation of the innovations while protecting public health. Several steps were identified as necessary to achieve this: improving communication about NFPS safety implications, fostering technical advancement for safety assurance, developing tailored safety assessments, encouraging collaboration between regulators and industry, and harmonizing regulatory requirements while maintaining safety standards.

The findings also highlighted various social, technological, economic, environmental and political issues that need to be considered and addressed for the safe integration of these innovations into food systems. Continuous monitoring and assessment of emerging NFPS issues will be crucial, with further analysis needed on their long-term implications for food safety and public health.

Participants of the Food Safety Foresight Technical Meeting at FAO headquarters in November 2023.

1. Introduction

1.1 Foresight to identify emerging food issues

The environment in which our current agrifood systems operate is transforming rapidly in response to a myriad of global drivers of change and trends such as new scientific and technological advances, changing consumption patterns, growing geo-political instability, climate change and increasing scarcity of natural resources (FAO, 2022a). As global agrifood system actors grapple with these rapidly changing contexts, a reactive approach is no longer an option, especially amid a growing need for transformative processes that create more sustainable, inclusive and resilient agrifood systems. The Food and Agriculture Organization of the United Nations (FAO) uses forward-looking approaches such as foresight to proactively identify emerging issues and prepare for the associated benefits and risks. To this end, FAO has conducted a variety of global perspective studies and foresight exercises (FAO, 2017; FAO, 2018a; FAO, 2022a).

Food safety is integral to the production, distribution and consumption of food within agrifood systems, and therefore has far-reaching implications for public health, economic prosperity, and environmental sustainability. Applying foresight to food safety will assist stakeholders in ensuring that food safety stays relevant, reliable and robust, keeping pace with the changing global contexts. The FAO Food Safety Foresight Programme uses a variety of approaches, including horizon scanning, to actively monitor global drivers of change and trends and assess direct or indirect food safety impacts to support strategic preparedness on emerging food safety issues (FAO, 2022b).

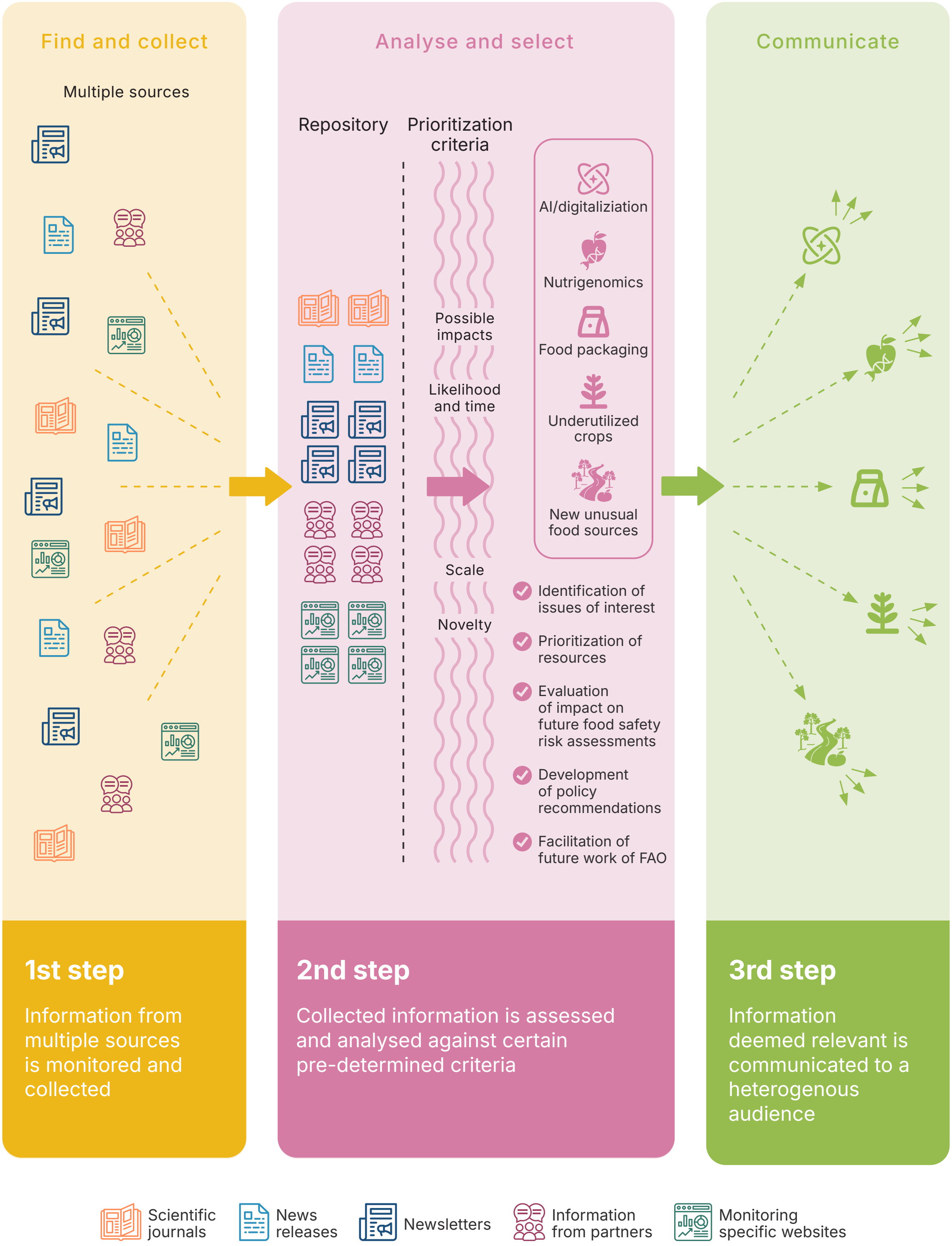
Horizon scanning is a foresight method in which various information sources are scanned or reviewed systematically in order to detect early signals of developments with potentially significant impacts in the future (Box 1). These developments include early weak signals, emerging issues and trends with potentially relevant impacts in the short-, medium- or long-term time horizons. Following scanning, a specific set of criteria is used to guide filtering and selection (FAO, 2022b).

Box 1. The FAO food safety horizon scanning methodology

New food sources and production systems were identified by the FAO Food Safety Foresight Programme as one of several key emerging issues with significant implications for future food safety using a three-step horizon scanning process (Figure 1). The process consisted of collecting, analysing and disseminating information about emerging social, scientific, technical, political, economic and environmental issues with expected implications for future food safety. A variety of information sources were scanned, including scientific journals, news releases, and other digital media as well as published documents from United Nations (UN) and non-UN organizations. Relevant information gathered was subsequently assessed according to various prioritization criteria, including their novelty, scale (local, national or global), and the likelihood and expected timescale of impacts on future food safety. Particular attention was given to the possible impacts of the trends on food safety and consumer health. The final step in the process was to effectively communicate the information to a diverse audience, aiding the development of strategic actions and policies by relevant stakeholders. The methodology and the full list of emerging issues identified through this process can be found in the report *Thinking about the future of food safety*.

Source: FAO. 2022. *Thinking about the future of food safety – A foresight report*. Rome. https://doi.org/10.4060/cb8667en

Figure 1. Overview of the horizon scanning methodology followed



Source: Adapted from FAO. 2022. *Thinking about the future of food safety – A foresight report*. Rome. https://doi.org/10.4060/cb8667en

1.2 New food sources and production systems (NFPS)

NFPS are undergoing rapid advances and gaining increased attention among stakeholders across the agrifood systems, in part due to growing global awareness of the environmental impacts of conventional agriculture. The term "new food sources" refers to any food sources not yet widely consumed globally, either because their consumption has historically been constrained to specific regions of the world, or because only recent technological innovations have made it possible to produce or process them (FAO, 2022b). Plant-based food products mimicking animal-based food products are an example of new food sources. At the same time, despite not being "new," edible insects and seaweed are also considered new food sources in the context of this publication, because their growing global expansion is new. "New food production systems", on the other hand, refer to new technological innovations or advancements in pre-existing food technologies involved in the production of new foods (FAO, 2022b). Cell-based food production is an example of a "new food production system".

1.3 Food Safety Foresight Technical Meeting: scope and objectives

A technical meeting was held at FAO headquarters in November 2023 to discuss the food safety implications of three NFPS in particular: plant-based food products, precision fermentation and three-dimensional (3D) food printing. "Plant-based" foods encompass a broad spectrum of foods made from plants. The meeting focused on the growing trend of creating plant-based food products that mimic animal-derived foods such as meat, seafood, fish, eggs and dairy products. While there is no internationally agreed definition of precision fermentation, for the purposes of the meeting, precision fermentation was defined as "the controlled cultivation of modified microbial cells to produce specific food products and ingredients" (FAO, 2024b, p. 35). Three-dimensional (3D) food printing is a form of additive manufacturing, where foods are constructed from pre-programmed digital models into 3D structures by adding materials (including food ingredients) layer-by-layer in a specific spatial arrangement. These areas were chosen based on their growing popularity in the NFPS space, their future potential for growth, and therefore, their relevance from a food safety foresight perspective. A more detailed overview and analysis of these three focus areas is provided in a dedicated report (FAO, 2024b).

A seller holds yams in a stall at the market. Kenya.

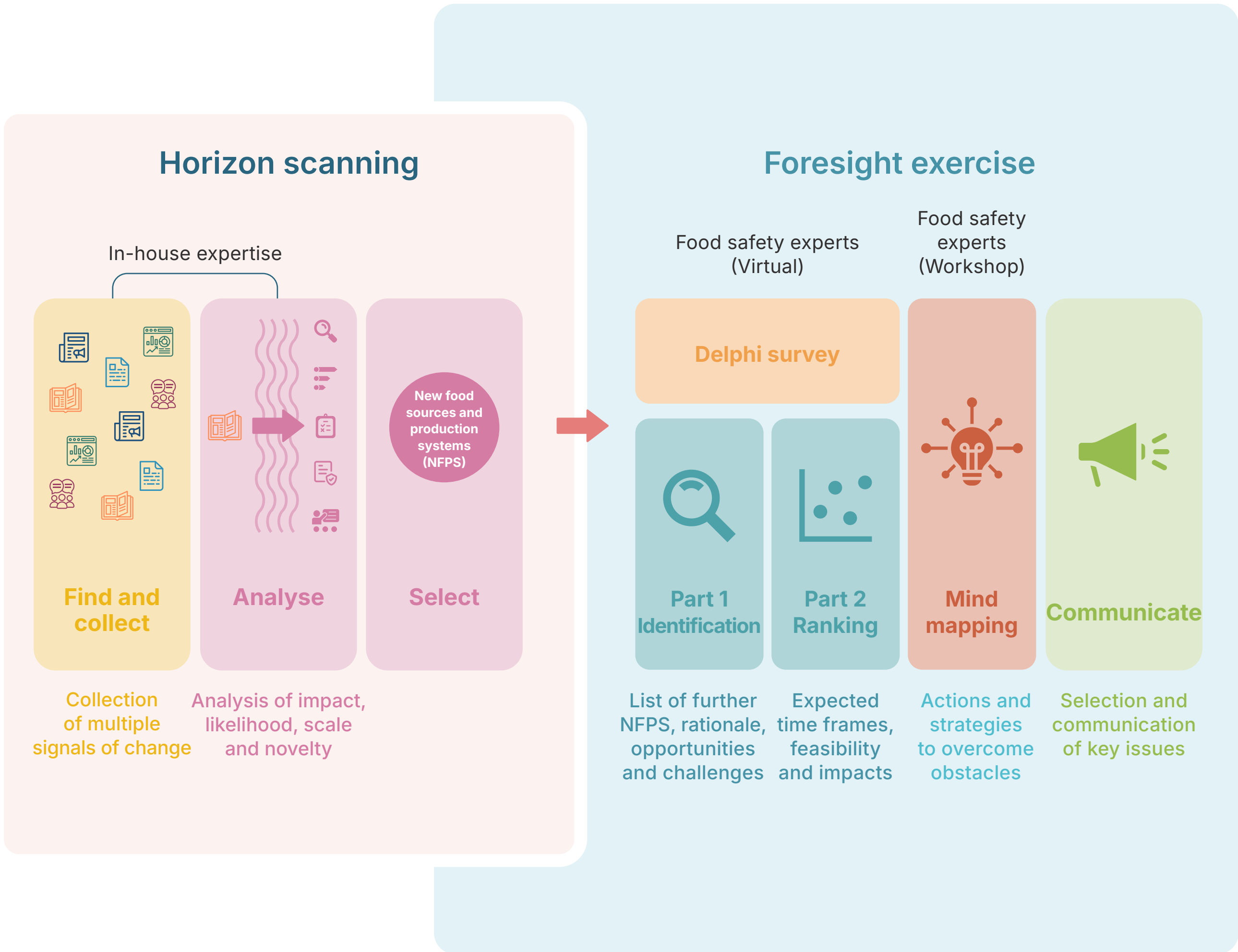
Experts discussing new and emerging food sources and production systems at the Food Safety Foresight Technical Meeting in November 2023.

2. FAO foresight exercise

In parallel to the technical meeting on the three focus areas, a structured multi-phase foresight exercise was conducted based on the outputs from the horizon scanning process, to further delve into the future NFPS landscape. The aim was to identify additional emerging NFPS innovations and discuss the readiness of the food safety community to navigate the issues they may bring (Figure 2). In the context of the exercise, "innovations" refer to any advancements in the agrifood space, including new food sources and novel raw materials and ingredients not yet widely implemented; advancements in technologies for new food production and processing methods; as well as other developments along the food chain from food production, processing, distribution, retailing, and consumption.

The foresight exercise used a mixed qualitative and semi-quantitative approach, divided into two phases – a two-part Delphi survey including ranking of outcomes (Annex 2 and Annex 3) and a mind mapping exercise (Annex 4). To ensure diversity – an essential component of a foresight exercise – the participating experts represented a range of geographical regions and professional backgrounds including academia, national food safety authorities, relevant UN agencies, non-governmental organizations and the private sector (Annex 1).

Figure 2. General workflow of the foresight exercise and its link with in-house horizon scanning



Source: Authors' own elaboration.

2.1 Delphi survey

The first phase of the foresight exercise consisted of an expert consultation through a Delphi survey. The survey was conducted anonymously in two rounds and was designed to aid experts in identifying additional key emerging innovations in the NFPS sector. The first round consisted of three questions. First, experts were asked to list emerging innovations in the NFPS space they believe to likely become prevalent in the next 5–25 years and explain the rationale for their choices (Annex 2). Second, they were asked to indicate some opportunities and challenges associated with the innovations, particularly for agrifood systems and food safety. And lastly, experts were asked to describe any emerging food safety-relevant issues they believe to be important in the context of NFPS but are yet to be fully addressed, including governance, infrastructure and related sectors like transportation.

The responses were combined into a list of 44 unique innovations and trends and then grouped into nine clusters based on themes identified in the survey (Figure 3).

Based on the outputs of the first round, the experts were then asked to rank the innovations on a Likert scale based on feasibility and impacts (Annex 3). For feasibility, the experts were asked if a certain innovation was likely to be realized, come to market, or find utilization in the food sector in the future based on a "business-as-usual" scenario, with the current landscape of technological innovations, regulatory frameworks and consumer preferences continuing as usual. They were asked not to consider the desirability of the innovations, that is, to disregard their own personal preferences of which innovations should come to market. The participants were further asked to point out the time horizons within which their most feasible innovations were likely to materialize. The three time horizons provided were 0–5 years (H1), 5–15 years (H2), and 15–25 years (H3).

For impacts, the experts were asked to consider the overall influence that an innovation could have on food systems, weighing both the related opportunities and challenges. Impacts would be considered beneficial (or high) if they brought benefits such as improved productivity, better food safety management, improved sustainability and social well-being, and reduced costs. Innovations would have adverse (or low) impacts if they brought mostly negative consequences, for example high environmental impacts, considerable food safety challenges and adverse effects on the livelihoods of producers. The experts were asked to consider if the benefits brought by the innovations outweighed the adverse impacts or vice versa.

The scores received for feasibility and impact per innovation were plotted on a matrix and further analysed (Figure 4). The time horizons estimated for the various innovations can be found in Figure 5.

Figure 3. List of the NFPS innovations identified through the Delphi survey

Cluster 1: Valorization of agrifood by-products and waste/circular economy

1. New sources (corn husks, brewers' spent grain, cassava leaves) of nutrients
2. New sources (oil cake/meal, rice bran) of bioactive compounds (antioxidants, peptides) and fibre
3. Novel growth media from consumer waste
4. Wastewater as source of fit-for-purpose water and nutrients for crops

Cluster 2: New production technologies

5. Fermentation techniques
6. Molecular farming
7. Food printing
8. Reverse food manufacturing and multiscale food structuring approach
9. Cellular agriculture
10. Liquid oil structuring (oleogels, emulsion gels, bigels, high internal phase emulsions)
11. Controlled environment agriculture

Cluster 3: New food sources and food ingredients

12. New sources of fats and oils (Brazil: macaúba, tucumã and babaçu)
13. Underutilized/orphan crops
14. Cultured human milk
15. Edible bird's nest
16. Single-cell proteins
17. Nanotechnology
18. "Hybrid" food products
19. Edible insects
20. Protein-based sweeteners

Cluster 4: Digitalization and data-based technologies

21. Artificial intelligence in food production and food safety
22. Big data and the internet of things
23. Digital food twins
24. Distributed ledger technologies (such as blockchain)

Cluster 5: Food safety/quality control

25. Cold plasma
26. Irradiation
27. Biopesticides
28. Bacteriophages for pathogen control
29. Novel methods for food tracking

Cluster 6: Genetic engineering, gene editing and synthetic biology

30. Bioengineered microalgae
31. Gene-edited plants, including minor crops
32. New foods enabled by synthetic biology
33. DNA-based barcodes for food authentication

Cluster 7: Personalized nutrition/nutraceuticals/food as medicine

34. Nootropic foods
35. Microbiome-focused foods
36. Edible vaccines
37. Nutrigenomics and nutrigenetics

Cluster 8: Food packaging

38. Nanotechnology in food packaging
39. Recycling and reuse of food packaging/utilization of valorized materials in food packaging

Cluster 9: Further emerging trends

40. Reduced added salt and sugar food products/push for sugar alternatives
41. Sustainable food products/renewable energy solutions to new production technologies
42. E-commerce
43. Multi-sensory integration to enhance food-related experiences
44. Evolving human–food–computer interaction

Source: Author's own elaboration.

Figure 4. Matrix of the impact and feasibility outcomes for all innovations identified in the survey

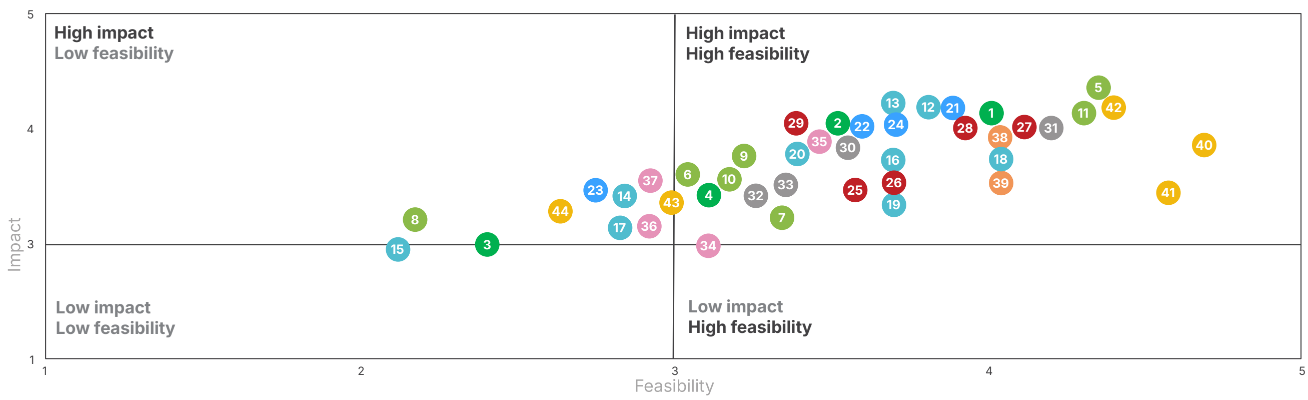
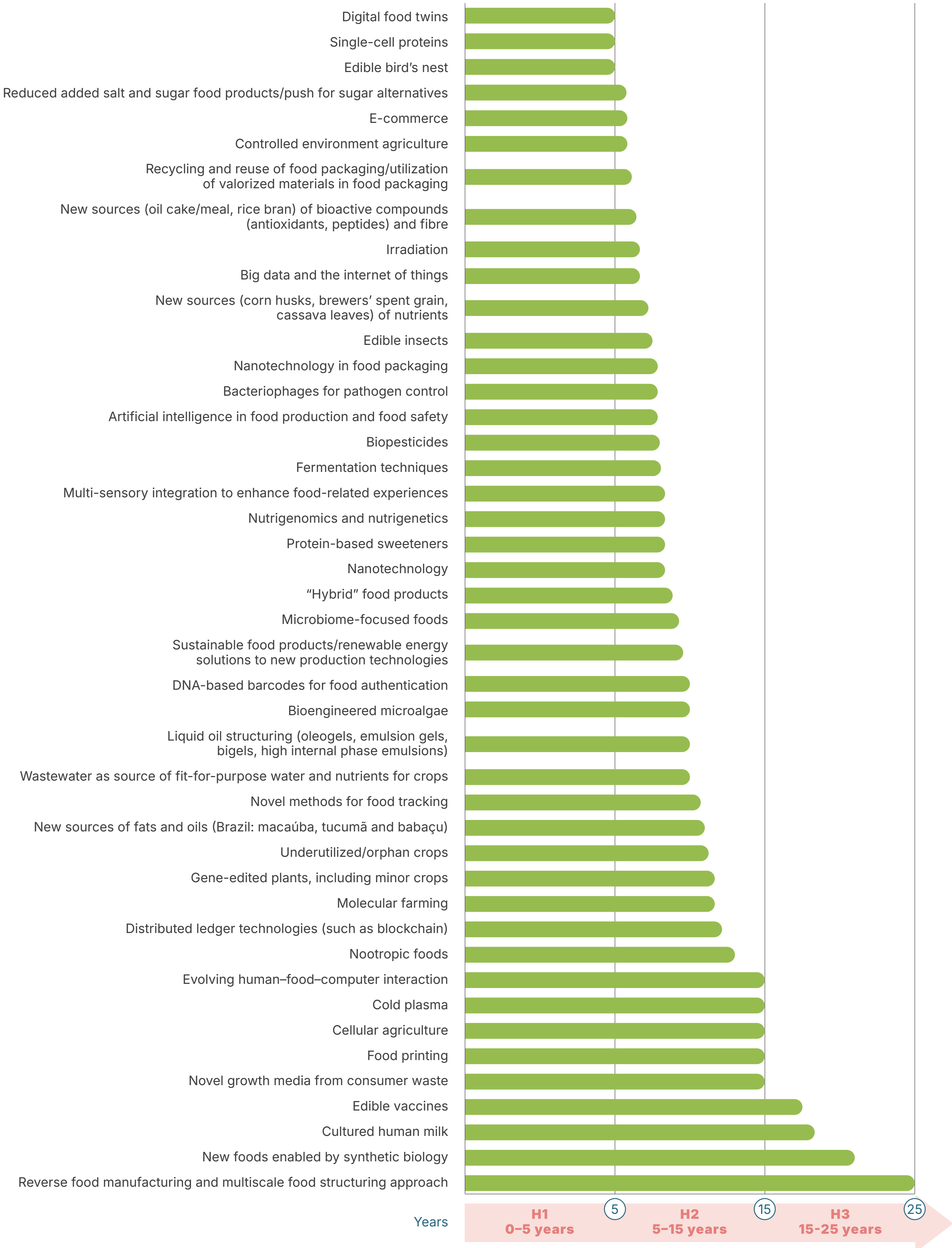


Figure 5. Expected time horizons of the various innovations identified



2.2 Forty-four emerging food innovations

The 44 emerging innovations described below were those identified by the experts as likely to become available and prevalent in the future NFPS space within the next 25 years. The descriptions are not exhaustive and are intended to summarize the inputs provided by the experts without going into detail on the associated food safety risks and opportunities. It is also important to note that the analysis did not focus on nutritional aspects, which were considered outside the scope of this study.

2.2.1 Innovation cluster: Valorization of agrifood by-products and waste/circular economy

1 New sources (corn husks, brewers' spent grain, cassava leaves) of nutrients

Agricultural by-products are emerging as a valuable resource for nutrient intakes, particularly for proteins and fats. In addition to macro- and micro-nutrients, anti-nutrients (e.g. phytates, oxalates, tannins) that might affect nutrient bioavailability and metabolism in the human body, as well as bioactive compounds beneficial to human health and disease prevention, such as antioxidants and phytochemicals, need to be considered in these food products. An innovative two-step technology allows for the conversion of agricultural waste, such as corn husks, into gases that are then fed to microbes. These microbes "brew" complex lipids, which have potential applications as ingredients in various food formulations, including plant-based products and cell-based foods (Morrison, 2023). Brewers' spent grain (BSG), a by-product of the brewing process, is often used as animal feed or discarded. However, due to its protein content (Lynch, Steffen and Arendt, 2016), some companies are actively developing methods to upcycle BSG into protein concentrate for use in a range of food products (Nyhan *et al.*, 2023). Similarly, cassava (*Manihot esculenta*) cultivation generates a substantial volume of leaves, which are typically underutilized. Efforts are underway to harness these leaves for food and nutrition applications, turning waste into a valuable resource.

A cassava field in the Central African Republic.

2 New sources (oil cake/meal, rice bran) of bioactive compounds (antioxidants, peptides) and fibre

Rice bran, the primary by-product of rice processing, is produced in vast quantities globally and contains nutrients and bioactive compounds (Spaggiari *et al.*, 2021). Despite its potential, rice bran remains underutilized in the food industry (Spaggiari *et al.*, 2021). Similarly, it has been reported that oil cake/meal, the main by-product left after oil extraction from seeds, is rich in bioactive compounds and fibre. This makes it a promising resource for both food and feed applications (Sá *et al.*, 2021). While upcycling such food manufacturing side streams offers significant potential in food circular economy, food safety considerations and assessment would be necessary to identify potential hazards (e.g. cumulated mycotoxin on soybean residues or BSG) and develop innovations to reduce these hazards (Yeo *et al.*, 2024).

3 Novel growth media from consumer waste

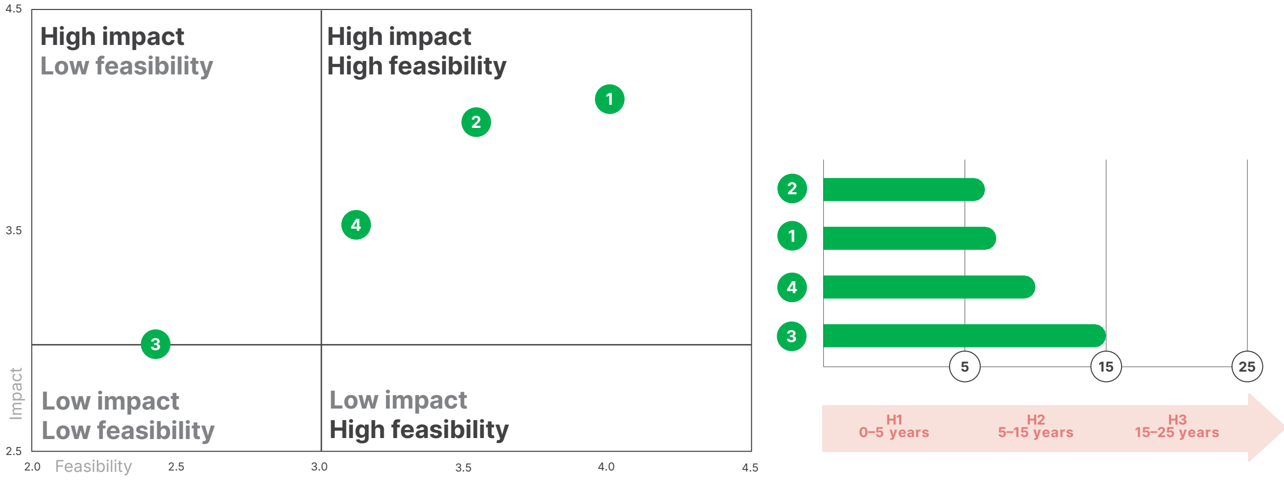
Food side streams or by-products from consumers can be used as ingredients in growth media for microbes, fungi or plants. For example, consumer fruit and vegetable waste can be processed and used to grow ureolytic and carbonic anhydrase producing bacteria (Mwandira *et al.*, 2024). Repurposing waste in this way is one approach being explored to improve the circularity of agrifood systems by diverting potentially useful materials from landfills.

4 Wastewater as a source of fit-for-purpose water and nutrients for crops

Water availability and quality are increasingly pressing concerns, particularly in the context of climate change (Jones, Bierkens and van Vliet, 2024). Wastewater represents a potentially valuable resource that, when properly treated, can be repurposed for agricultural applications (Mishra, Kumar and Kumar, 2023). The Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment (JEMRA) regularly assesses the microbial quality of water for food production, particularly for use in fresh produce, dairy, fish and fishery products (FAO and WHO, 2021, 2023a, 2023b). Additionally, the treated by-product of the wastewater treatment process, known as sewage bio-solids, can serve as an alternative nutrient source for crops (Healy *et al.*, 2017). With rising costs in the global fertilizer market driven by factors such as inflation, geopolitical conflicts and supply chain disruptions, sewage bio-solids may represent a cheaper alternative to fertilizer.

Woman working in cassava production in the Central African Republic.

Figure 6. "Valorization of agrifood by-products and waste/circular economy" innovation cluster: Feasibility/impact matrix and time horizons



Cluster 1: Valorization of agrifood by-products and waste/circular economy

1. New sources (corn husks, brewers' spent grain, cassava leaves) of nutrients
2. New sources (oil cake/meal, rice bran) of bioactive compounds (antioxidants, peptides) and fibre
3. Novel growth media from consumer waste
4. Wastewater as source of fit-for-purpose water and nutrients for crops

Experts expected new nutrient sources and new sources of bioactive compounds to be highly beneficial for future food safety, feasible, and likely to occur within the next 5 years (Figure 6). In the intermediate future (5–15 years), the use of wastewater as a source for fit-for-purpose water and nutrients for crops was expected to gain momentum and, when carefully managed and controlled, was deemed beneficial for food safety. The application of novel growth media from consumer waste was considered beneficial but only feasible within the next 15 years.

2.2.2 Innovation cluster: New production technologies

5 Fermentation technologies

Biomass, gas and precision fermentation represent innovative fermentation techniques expected to scale up in the coming years. Biomass fermentation technology enables the production of large quantities of protein-rich food by leveraging the rapid growth and high protein content of specific microorganisms (Teng *et al.*, 2021). In this process, the microorganisms themselves become a direct source of alternative proteins. Gas fermentation

Fermenting tanks at an Italian winery.

is a biotechnological process where microorganisms convert gaseous substrates, such as carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and hydrogen (H_2) into, among other things, proteins for food or feed (Marcellin *et al.*, 2022). Unlike traditional fermentation methods that rely on sugars or organic materials, this process utilizes carbon-rich gases as the primary feedstock. The technology has already progressed to a semi-commercial scale in certain applications (Forward Fooding, 2024). Precision fermentation is a cutting-edge technology that involves using genetically modified microorganisms, like yeasts, to produce specific functional compounds that can replace animal-derived products, among others. This method is particularly valuable for creating new and conventional proteins by incorporating non-standard amino acids – either through chemical synthesis or genetic modifications (FAO, 2024b).

6 Molecular farming

Molecular farming in general is a biotechnological technique that involves genetically modifying plants to produce specific proteins, enzymes or other bioactive compounds typically derived from non-plant sources such as animals or microorganisms (Schillberg and Finnern, 2021). Plant molecular farming has been applied to non-food or medicinal plants to produce pharmaceuticals, such as antibodies, vaccines and medicinal proteins (Long *et al.*, 2022). New research is underway to apply this technology to food crops, such as rice, wheat, maize and soybean to produce nutraceuticals and functional food (Long *et al.*, 2022). Molecular farming effectively transforms plants into bio-factories, leveraging their natural growth processes to produce complex molecules that would otherwise be sourced from animals or created through alternative biotechnological methods.

7 Food printing

Food printing, and 3D food printing (3DFP) specifically, involves using "food inks" – solutions of food ingredients or cells – to create spatially organized, compartmentalized structures that can closely mimic complex food products, such as meat cuts with alternating layers of fat and muscle (Wen *et al.*, 2023). This technology can be applied in domestic kitchens and on an industrial scale, with several plant-based alternatives to meat and seafood already nearing market readiness (Trager, 2023; Wen *et al.*, 2023).

8 Reverse food manufacturing and multiscale food structuring approach

Unlike traditional food manufacturing, which processes raw materials, reverse food manufacturing refers to the molecular engineering of food ingredients below the 100 µm range, allowing for precise control over the composition and 3D structure of the final product (Aguilera, 2005). Structural elements that influence food properties and qualities include meat fibers, small particulate material in powders, starch granules, protein assemblies, plant cells and cell walls, oil droplets, gas bubbles, and colloidal particles (Aguilera, 2005). Among other applications, food structuring is used in molecular gastronomy, innovative plant-based foods and meat alternatives, and in the development of nutraceuticals (Aguilera, 2022). By designing food at this detailed level, reverse food manufacturing can make use of the effect of microstructure on the properties of foods. For example, microstructure can affect taste and texture and provide distinct functional benefits (Aguilera, 2005). Similar to 3D food printing, it enables precise adjustments to sensory properties, which could help manage energy intake and influence consumption behaviour. An example of a novel application of the food structuring approach is the conversion of CO_2 into single-cell protein (Xu *et al.*, 2021). Using renewable energy, for example, gaseous CO_2 can be converted into nutrient-rich single-cell protein flour through a probiotic production process utilizing hydrogenotrophs (Xu *et al.*, 2021). In the future, this protein flour could be used to create "air-based protein", reducing the need for conventional protein production such as from agriculture. However, it is unclear whether this process might impact the digestibility of these single-cell proteins.

9 Cellular agriculture

Cell-based food is produced by cultivating animal cells in a controlled laboratory environment to create food products that are comparable to meat, seafood and other animal-derived products (FAO and WHO, 2023c). The product resulting from this cellular agriculture can be harvested and processed in ways that resemble the taste, texture, and nutritional profile of the conventional counterpart (FAO and WHO, 2023c). Cellular agriculture, more broadly, can furthermore encompass the production of cell-based foods through the cultivation of plant cells and cultured microbes for the production of food ingredients (FAO, 2024b; FAO and WHO, 2023c).

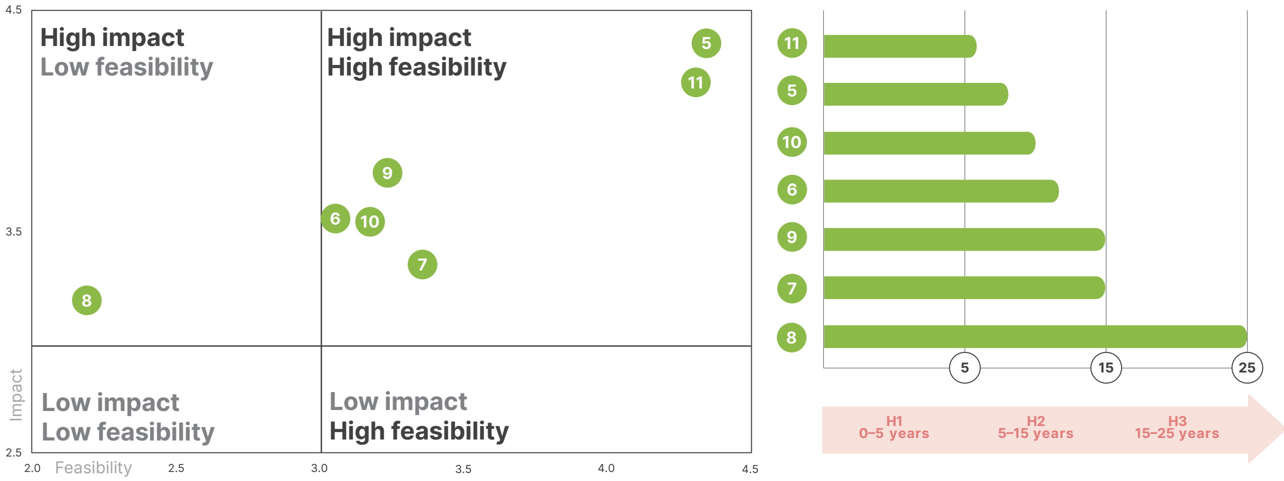
10 Liquid oil structuring (oleogels, emulsion gels, bigels, high internal phase emulsions)

Liquid oil structuring involves transforming liquid vegetable oils into solid-like fats, such as oleogels, emulsion gels, bigels, and high internal phase emulsions (HIPEs), using various techniques. This process employs plant-based structuring agents to create fats that mimic the texture and functionality of traditional solid fats (Guo, Cui and Meng, 2023). These techniques are used to modify the physical properties of oils, enabling them to function similarly to solid fats in various food applications.

11 Controlled environment agriculture

Controlled environment agriculture is a method of growing crops within fully managed indoor spaces, where factors such as light, temperature, humidity, and nutrient supply are precisely regulated (Ragaveena, Shirly Edward and Surendran, 2021). This farming approach allows for the cultivation of various crops, including vegetables, herbs and fruits, independent of external weather conditions or seasonal changes. The infrastructure for indoor farming can be established in diverse locations, ranging from urban centres to more remote or unconventional sites like repurposed buildings.

Figure 7. "New production technologies" innovation cluster: Feasibility/impact matrix and time horizons



Cluster 2: New production technologies

5 Fermentation techniques
6 Molecular farming
7 Food printing
8 Reverse food manufacturing and multiscale food structuring approach
9 Cellular agriculture
10 Liquid oil structuring (oleogels, emulsion gels, bigels, high internal phase emulsions)
11 Controlled environment agriculture

Expert opinions on feasibility and impact of these innovations were that fermentation, whether biomass, gas or precision fermentation, and indoor farming beneficially impacted food safety and were likely to substantially advance within the next 5 years (Figure 7). Molecular farming and liquid oil restructuring, while considered feasible and likely to have a net positive impact on food safety, were expected to develop more slowly, becoming relevant in the next 5–15 years. Food printing was expected to develop further in the next 5–15 years with a limited impact from a food safety point of view if monitored and controlled appropriately. Reverse food manufacturing and cell-based food were considered to be in very early stages of development, expanding only in 15–25 years, however with a predicted overall benefit to the agrifood space.

2.2.3 Innovation cluster: New food sources and food ingredients

12 New sources of fats and oils (Brazil: macaúba, tucumã and babaçu)

In the exploration of alternative sources of fats and oils for food production, species from Brazil's diverse flora such as macaúba (*Acrocomia aculeata*), tucumã (*Astrocaryum aculeatum*) and babaçu (*Attalea speciosa*) have been identified (Gallon, 2021). Macaúba is a palm species known for its high oil yield, making it a potential source for both edible oils and industrial applications such as biodiesel (Navarro-Díaz *et al.*, 2014). Tucumã, a palm species native to the Amazon, contains valuable bioactive compounds with evidenced benefits for human health. Furthermore, tucumã and its by-products provide potential opportunities for biofuel production and alternative packaging (Machado *et al.*, 2022). Babaçu, found predominantly in the northeastern regions of Brazil, is harvested for its versatile oil, which is extracted from the seeds and used in both food and non-food products due to its high nutritional value (Fakhouri, da Silva and Velasco, 2021). These native Brazilian plants are examples of the sources being explored around the world to diversify sources of fats and oils.

A man holds grains of teff in a market in Addis Ababa.

© FAO/Eduardo Soteras

13 Underutilized/orphan crops

Underutilized or orphan crops refer to plant species that are traditionally grown in specific regions or by specific communities but have not been widely commercialized or integrated into mainstream agriculture. These crops demonstrate resilience to local environmental conditions, and hold significant cultural value (Talabi *et al.*, 2022). Examples of orphan crops include finger millet (*Eleusine coracana*), jojoba (*Simmondsia chinensis*), and teff (*Eragrostis tef*) (FAO, 2024; Talabi *et al.*, 2022). Despite their potential as a food source, they are generally overlooked in global food production and research efforts, leading to under-exploitation of their benefits (United States Department of State, 2024). However, it is important to investigate the nutrient contents, bioavailability, anti-nutrient properties, and pharmacological properties of these underutilized plants.

14 Cultured human milk

Cultured human milk refers to human milk produced in a laboratory by culturing mammary epithelial cells obtained from donated breast milk or tissue, capable of producing milk, in an environment that closely mimics the mammary gland. Cultivation has enabled the mammary cells to secrete proteins, oligosaccharides and fats structurally similar to those found in human breast milk (Turrell, 2024). Alternatively, human-identical milk oligosaccharides (HiMOs) can be produced by precision fermentation and have been approved in some countries for use as food ingredients across a wide range of food categories for the general population (Bode *et al.*, 2016). HiMOs can also be synthesized through chemical or enzymatic synthesis, however the currently preferred method is via microbial production (Bensimon and Lu, 2024; Gan *et al.*, 2023). Biochemical production of HiMOs focuses on reproducing those human milk oligosaccharides that are most abundantly found in natural breast milk, or those that represent the three principal classes of human milk oligosaccharides (core structures, fucosylated or sialylated) (Phipps *et al.*, 2018). Although chemically identical to their natural counterparts, their metabolism in infants is yet to be fully analysed.

15 Edible bird's nest

Edible bird's nests are a traditional delicacy in Southeast Asia, consumed for centuries, particularly in countries like China, Malaysia and Indonesia. These nests are produced by swiftlets (*Aerodramus maximus* and *Aerodramus fuciphagus*) using their hardened saliva to construct the nests (Daud *et al.*, 2021). Recently, glycopeptides from converted edible bird's nests glycoproteins have been applied in the development of novel food products and beverages (Benjakul and Chantakun, 2022).

16 Single-cell proteins

Single-cell proteins (SCPs) refer to dry cells of microorganisms, which contain valuable amino acids and fatty acids, nucleic acids, minerals and vitamins (Koukoumaki *et al.*, 2024). Recent studies have explored the potential of various microorganisms including bacteria, microalgae, yeasts and filamentous fungi to produce SCPs (Koukoumaki *et al.*, 2024). SCP production involves the rapid growth of microbial cells on a wide range of substrates, including industrial and agriculture waste, side-streams or by-products (Koukoumaki *et al.*, 2024). SCPs are attracting interest from the food industry as an alternative protein source.

17 Nanotechnology

Nanotechnology is increasingly being applied in the food industry including the use of nanoparticles, which can encapsulate nutrients to enhance their bioavailability, improve the flavour and texture of foods and extend the shelf life of food products (Cruz-Lopes, Macena and Guiné, 2021). By manipulating food at the nanoscale, these innovations have the potential to produce foods that are more nutritious, palatable, and durable. For instance, nanoparticles can be used in functional foods to deliver vitamins, minerals, and other nutrients, or in packaging to preserve freshness (see section 2.2.8).

18 "Hybrid" food products

Hybrid foods are created by combining various food technologies or blending traditional food products with innovative ingredients. These products, which often consist of plant-based ingredients supplemented with a small portion of harvested or cultivated animal cells, are already entering the market or are on the verge of doing so (McNamara, 2024). The appeal of hybrid foods to consumers often lies in their ability to replicate the flavour, smell, and mouthfeel of traditional food sources, making them more acceptable to a broader audience.

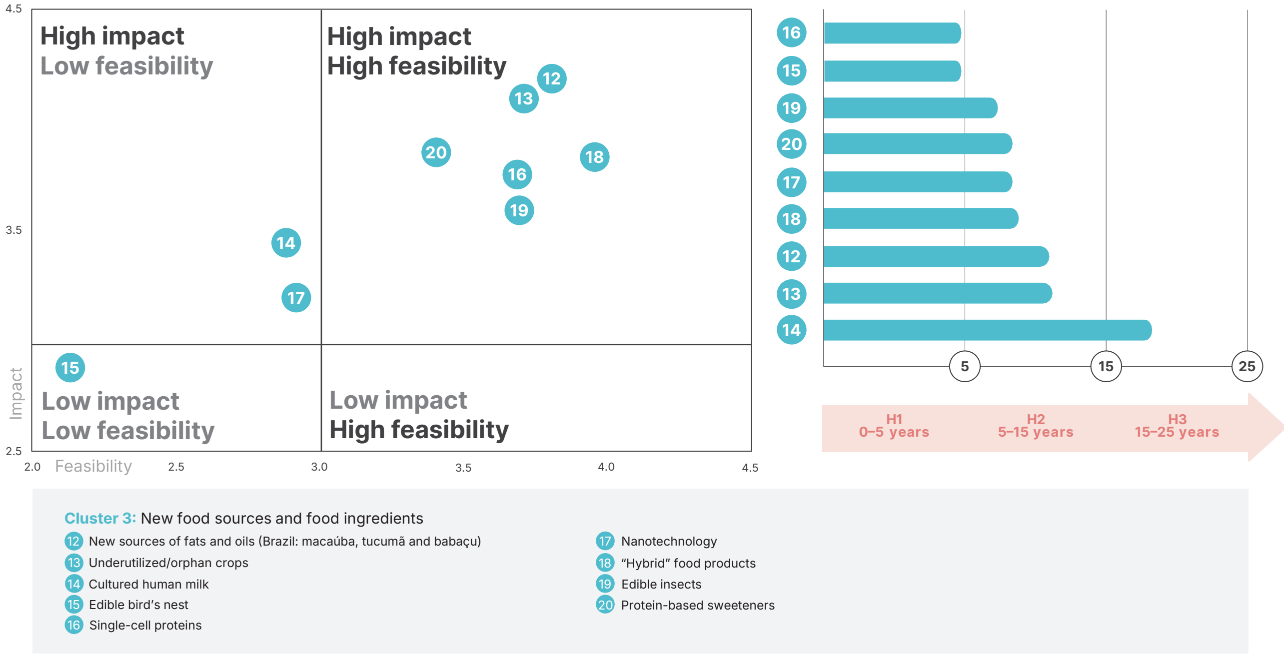
19 Edible insects

Edible insects are increasingly recognized as a valuable source of high-quality protein and essential micronutrients, providing a sustainable alternative to traditional livestock farming (FAO, 2021). With a rich nutrient profile that includes amino acids, vitamins and minerals, insects offer a versatile ingredient for various food products. However, further research is needed to investigate their digestibility and nutrient absorption. Several countries have already authorized the use of certain insects as a food source, acknowledging their potential to enhance food and feed security, particularly in the context of a growing global population (Stroka, Robouch and Goncalves, 2021).

20 Protein-based sweeteners

Protein-based sweeteners, primarily derived from plants, are gaining attention as promising alternatives to sugar. To date, eight sweet-tasting proteins have been identified, including miraculin, monellin, thaumatin, mabinlin, pentadin, curculin, brazzein and neoculin (Zhao *et al.*, 2021). However, some of these proteins present challenges such as low sweetness intensity or poor thermostability (Zhao *et al.*, 2021), which can limit their application in the food industry. Recent advancements in protein engineering and recombinant technology are being explored to enhance the properties of these sweet proteins, making them more viable for widespread use as sugar substitutes.

Figure 8. "New food source and food ingredients" innovation cluster: Feasibility/impact matrix and time horizons



Based on the discussions at the meeting, aside from cultured human milk and nanofoods, the innovations of this cluster were considered both feasible and beneficial overall (Figure 8). The implementation and development of cultured human milk and nanofoods, while beneficial, were considered less likely to fully expand into the mainstream. Edible bird's nests, SCP, hybrid food products, edible insects and protein-based sweeteners are for the large part already being utilized and were expected to develop further within the next 5 years. New fat and oil sources, underutilized crops and cultured human milk, on the other hand, were expected to develop more slowly, with more widespread application of these innovations in the 5 to 15-year time frame.

2.2.4 Innovation cluster: Digitalization and data-based technologies

21 Artificial intelligence in food production and food safety

Artificial intelligence (AI) is increasingly being applied across various aspects of food production, manufacturing, packaging, food traceability and supply chain optimization. These technologies are also used to enhance product efficiency, improve sensory outcomes, and reduce experimental costs in research and development. AI is instrumental in forecasting climate changes and pest outbreaks, contributing to more efficient agricultural practices (Thakkar *et al.*, 2023).

AI algorithms enable forecasting for crop management, pest management, fertilizer use, and disease management. The technology can also help to optimize food product characteristics, packaging sizes and distribution, thus making food systems more responsive and efficient (Thakkar *et al.*, 2023). In addition, AI is used to identify allergens, pathogen presence and specific concentrations to predict food safety risks and analyse real-time data from production lines to ensure food quality (Thakkar *et al.*, 2023). AI can be used to support food traceability through the integration of blockchain technology to enhance transparency and accountability in the supply chain.

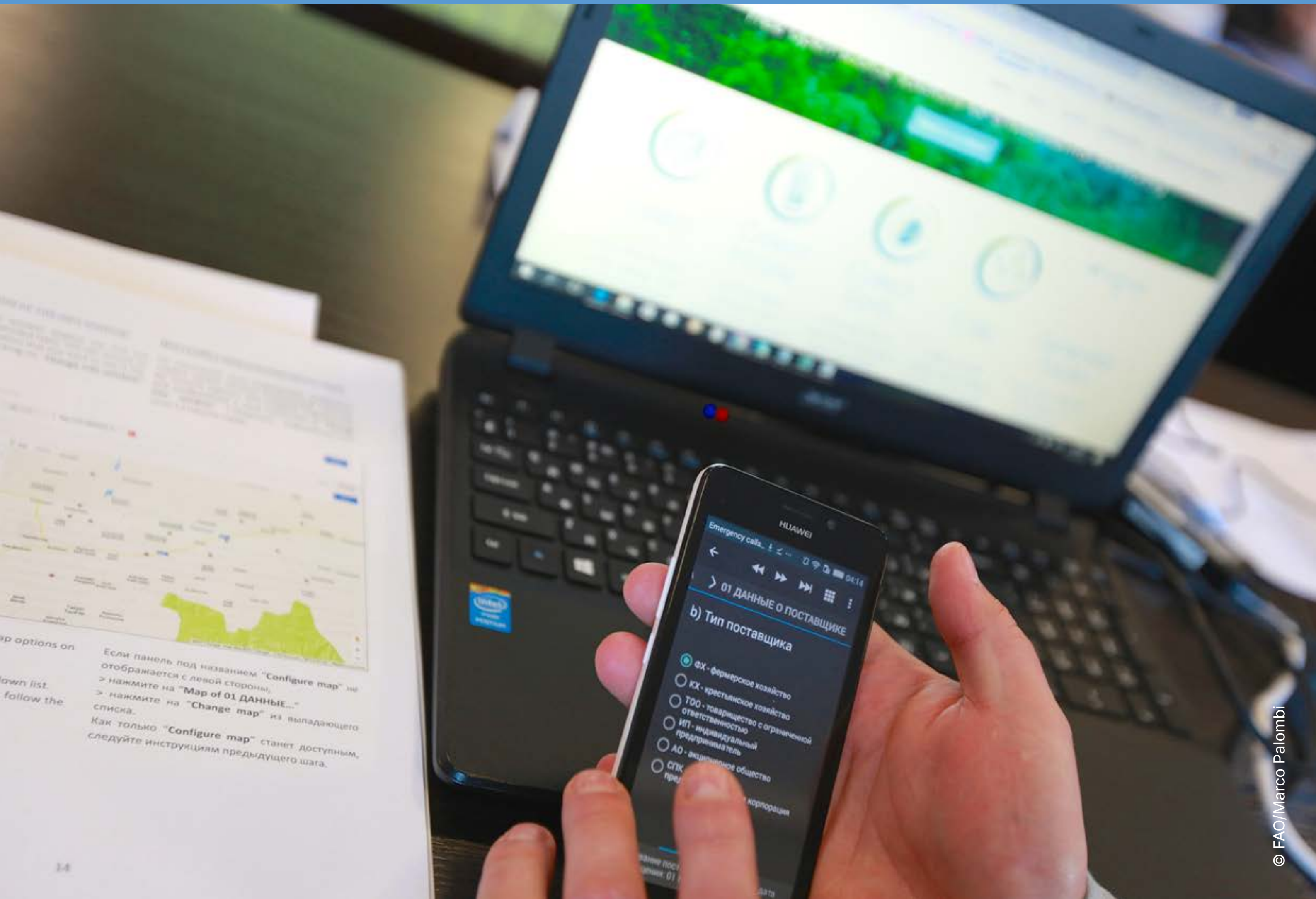
22 Big data and the internet of things

The internet of things (IoT) refers to software, devices with sensors, and other technologies that exchange data with other devices over the Internet. IoT offers significant opportunities for the future of agrifood systems and can be combined with AI. These technologies have many applications in the food supply chain, such as enabling real-time monitoring of food products and enhancing food traceability, which can drive more efficient food production and distribution networks (Jagtap *et al.*, 2021). For example, farmers can monitor data on soil temperature and moisture detected by sensors to facilitate precision fertilization programs (Zhang, ed., 2015). IoT provides large amounts of potentially valuable data, "big data", which requires advanced data-processing software.

23 Digital food twins

Digital food twins offer a dynamic way to simulate and monitor food systems by creating a virtual environment that accurately represents the physical characteristics and behaviour of food as it evolves over time. Unlike traditional mathematical models that rely on continuous data collection, digital food twins can replicate real-time changes in food during processing, transportation, storage, and cooking. This enables food manufacturers to observe and predict how food will behave, allowing them to adjust conditions to maintain optimal quality (Cabeza-Gil *et al.*, 2023; Datta *et al.*, 2022). Despite the energy requirements, this technology has the potential to conserve resources in food production, enhance processing development, and improve the design and development of new manufacturing equipment, ultimately accelerating time-to-market.

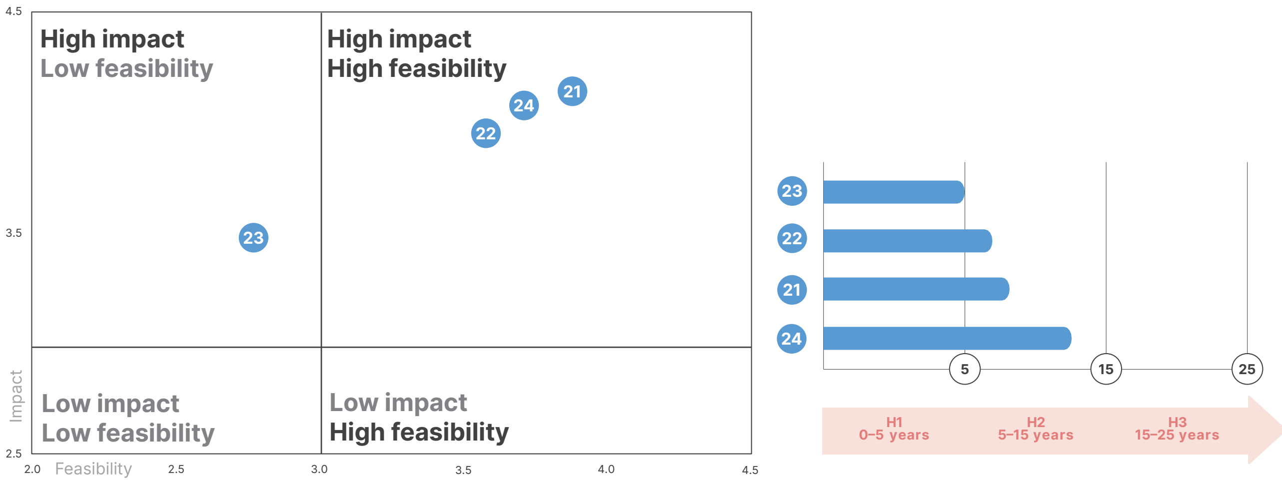
Milk producer learning how to apply digital technologies to various aspects of dairy management in Kazakhstan.



24 Distributed ledger technologies (such as blockchain)

Advancements in distributed ledger technologies, particularly blockchain, combined with real-time food monitoring via IoT devices, are offering new technologies to assist with food traceability (Tang *et al.*, 2024). These technologies can be used by food companies to provide more comprehensive end-to-end traceability, and by consumers to access detailed information about the origin and quality of their food through smart labels and stand-alone food grading devices.

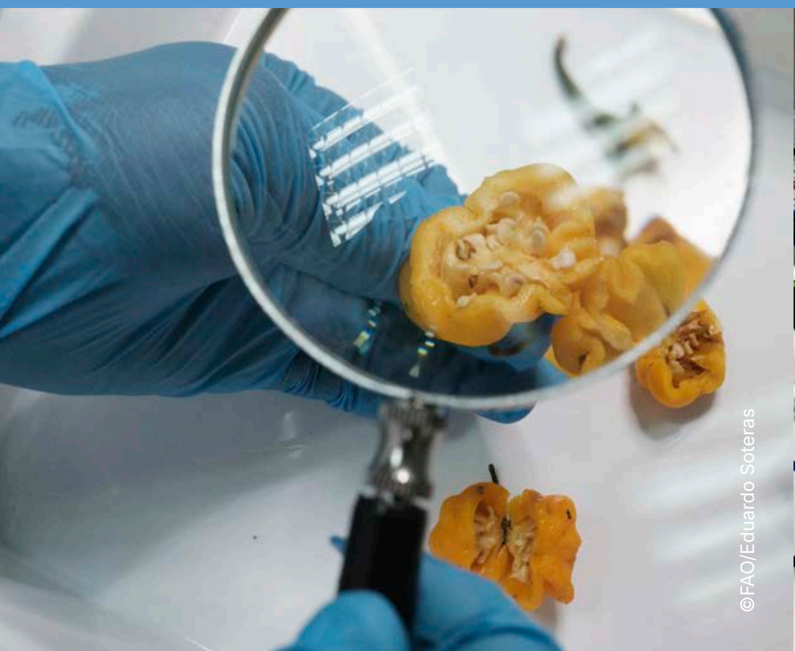
Figure 9. "Digitalization and data-based technologies" innovation cluster: Feasibility/impact matrix and time horizons



Cluster 4: Digitalization and data-based technologies
21 Artificial intelligence in food production and food safety
22 Big data and the internet of things
23 Digital food twins
24 Distributed ledger technologies (such as blockchain)

With the exception of digital food twins, experts agreed that the innovations described above were likely to expand and have a beneficial impact on the future agrifood space (Figure 9). Digital food twins were not deemed very feasible, despite having a potentially large overall beneficial impact on food safety. AI, big data, IoT and digital food twins were expected to gain momentum in the next 5-year time horizon, while the application of distributed ledger technologies such as blockchain in the agrifood sector considered to become more widespread in 5–15 years.

Technician inspects vegetables in a pesticide laboratory.



©FAO/Eduardo Soteras

Scientist analysing the protein content of a cell-based food product.

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2.2.5 Innovation cluster: Food safety/quality control

25 Cold plasma

Cold plasma (CP) refers to "partially ionized gas maintained at low temperatures" created by subjecting gases to an electrical field, which ionizes the gas and produces plasma (Harikrishna *et al.*, 2023). In the food industry, CP is employed for a variety of purposes. CP can be directed onto the surface of food or packaging materials, where plasma-created reactive species can lyse the cell membranes of microorganisms, extending shelf life (Harikrishna *et al.*, 2023). CP can also modify protein structures found in treated foods and decrease cooking time on grains such as black gram (*Vigna mungo*). Additionally, it can be applied in nutrient and bioactive compound extraction, pesticide decontamination and food waste processing (Khumsupan *et al.*, 2023).

26 Irradiation

Although irradiation is not a new technology, ionizing radiation, such as gamma rays, is gaining wider acceptance as a method for controlling foodborne pathogens, particularly in raw and ready-to-eat products (Bandyopadhyay *et al.*, 2020). Exposing food to controlled doses of ionizing radiation reduces or eliminates the presence of harmful pathogens. This technology is particularly useful for foods for which other forms of pathogen control, such as the use of chemical preservatives or high-temperature treatments, are less effective. In addition to gamma irradiation, electron beam irridation (EBI) is a technology increasingly applied by the food industry for microbial decontamination of crops or food through treatment with low-dose ionizing radiation (Lung *et al.*, 2015). EBI can also extend the shelf life of fruits and vegetables by regulating ripening rate (Lung *et al.*, 2015). In line with these technologies, quantum dots are emerging as novel food safety assessment tools, which enable real-time detection and quantification of a range of contaminants, including pathogens, heavy metals, and pesticides (Ma *et al.*, 2024).

27 Biopesticides

While there is no harmonized definition of biopesticides, they include naturally occurring substances and organisms, as well as synthetic versions of naturally derived compounds, used to protect plants from pests and diseases (European Commission, 2022). Biopesticides offer environmentally friendly pest control alternatives. The shift from familiar chemical pesticides, with well-defined application rates and schedules, to biopesticides may require significant adjustments in agricultural practices. For example, microbial biopesticides require different storage conditions depending on the microbe used, thereby requiring changes in storage and transportation practices compared to those used for chemical pesticides (Ayilara *et al.*, 2023).

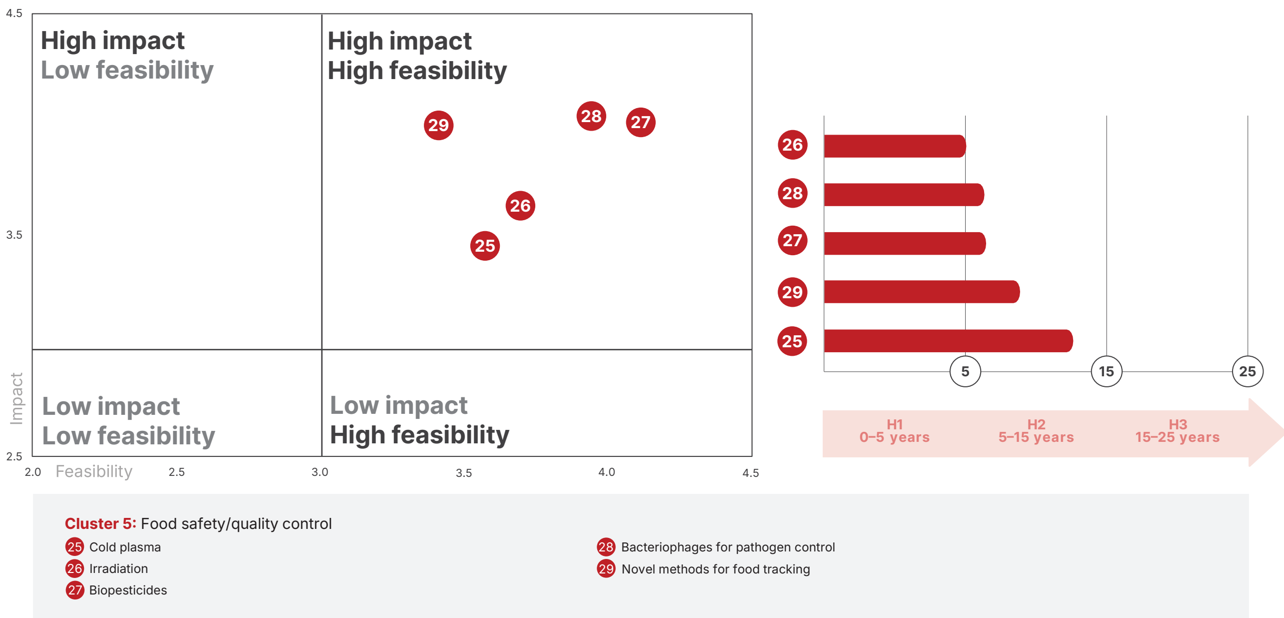
28 Bacteriophages for pathogen control

Bacteriophages, viruses that naturally infect and replicate within bacteria, have emerged as a potential tool for decontaminating and eliminating bacterial pathogens from food sources. Unlike broad-spectrum antibiotics, bacteriophages specifically target harmful foodborne bacteria without affecting beneficial bacteria, representing a potential alternative for controlling pathogens in the food industry. Recent innovations include incorporating bacteriophages into food packaging films or using them as food or feed additives to combat antimicrobial resistance (Wagh, Priyadarshi and Rhim, 2023).

29 Novel methods for food tracking

In response to growing food safety concerns due to the increasing complexities of agrifood systems, food producers are exploring the use of novel tracking methods, such as DNA-based methods relying on synthetic or naturally occurring DNA sequence tags to track food (Zografos and Farquar, 2019). Using a complex tagging scheme, specific DNA tags are sprayed onto food or food products enabling the identification of the multiple origins of the food across the distribution chain, including the producer, packer and other points of distribution (Zografos and Farquar, 2019). In the food industry, this technology can significantly enhance food traceability, which often relies on packaging that is discarded, preventing significant time lapses between contamination detection and product recall, for example.

Figure 10. "Food safety/quality control" innovation cluster: Feasibility/impact matrix and time horizons



Experts at the meeting agreed that all the innovations in the "food safety and quality control" cluster were highly feasible, with beneficial impacts on future food safety. The application of radiation, biopesticides and bacteriophages was expected to fully expand within the next 5 years. Cold atmospheric plasma and tracking devices for detecting food fraud, on the other hand, were considered more likely to fully roll out in 5–15 or more years with respect to their widespread implementation.

2.2.6 Innovation cluster: Genetic engineering and synthetic biology

30 Bioengineered microalgae

The genetic engineering of microalgae offers the potential to enhance their metabolic capacity, enabling higher accumulation of desired biomolecules (Kumar *et al.*, 2020). This bioengineering approach can significantly expand the applications of microalgae in various industries, including food, nutraceuticals, and biofuels (Carrasco-Reinado *et al.*, 2019). However, unlike for bacteria, yeast, and fungi, the technology required for bioengineering of microalgae is still largely underdeveloped, and thus, no genetically modified microalgae are currently on the market.

31 Gene-edited plants, including minor crops

Gene-editing technologies, a sub-domain of synthetic biology described below, enable precise modification of genomes. Gene-editing of plant genomes is being explored and applied to enhance a wide range of crop characteristics. These include nutritional enhancement, improved food safety, increased resistance to diseases, weeds and pests, and greater climate resilience (Pixley *et al.*, 2022). Gene-editing plant technologies are being applied to both major and orphan crops, the latter being particularly important for food security in low- and middle-income countries (LMICs) (FAO, 2022c). These technologies allow for the direct editing of genes in both select breeding or commercially available varieties, bypassing the need for lengthy backcrossing processes and accelerating the development of more resilient and nutritious plant varieties. However, long-term research is important to address potential food safety concerns.

32 New foods enabled by synthetic biology

Synthetic biology is paving the way for the creation of entirely new foods, as it enables the production of molecules that have never been part of the human diet. These include non-canonical nucleotides, amino acids, peptides and de novo-designed proteins, with novel functions such as acting as biosensors in food (Quijano-Rubio *et al.*, 2021). Unlike traditional genetically modified organisms, synthetic biology enables the engineering of organisms with entirely novel traits by inserting complex metabolic pathways or other extensive genetic modifications. Through synthetic biology, it is possible to create new foods and ingredients for use as nutraceuticals or sweeteners, for example (Barnum, Endelman and Shih, 2021; Xu *et al.*, 2022). Synthetic microorganisms could also be developed to enhance the traits of other species. For example, synthetic soil microbes can be engineered to speed up plant growth, or gut microbes and probiotics can be designed for therapeutic purposes in humans (Chua *et al.*, 2017; Ke, Wang and Yoshikuni, 2021).

Microalgae production in the United Arab Emirates.

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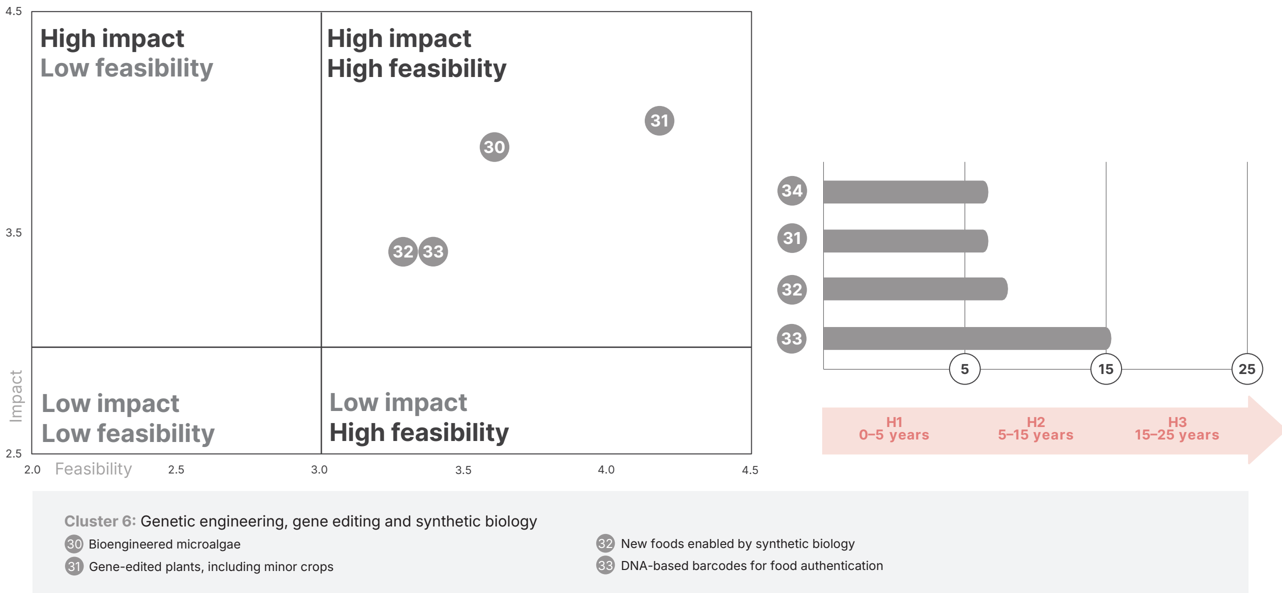
A reactor for microalgae at ETH Zürich, Switzerland.

© FAO/Mario Heller

33 DNA-based barcodes for food authentication

DNA barcoding is a classification method which utilizes DNA sequences to trace back to organisms belonging to a particular species (Dawan and Ahn, 2022). This species identification can be applied to food authentication and traceability. The process relies on specific DNA sequences, typically chloroplast and mitochondrial DNA, to identify plant and animal species, respectively (Barcaccia, Lucchin and Cassandro, 2016). DNA barcodes can withstand various food processing conditions without degrading, ensuring the integrity of the system throughout the food's lifecycle (Galimberti *et al.*, 2013).

Figure 11. "Genetic engineering and synthetic biology" innovation cluster: Feasibility/impact matrix and time horizons



Overall, experts considered the widespread application of genetic engineering in the agrifood system both feasible and beneficial to food safety and expected it to fully develop in 5–15 years, with the exception of synthetic biology, expected in the more distant time horizon (25 years).

2.2.7 Innovation cluster: Personalized nutrition/nutraceuticals/food as medicine

34 Nootropic foods

Nootropics are compounds that are known or believed to have the ability to enhance cognitive functions such as memory, motivation, concentration and attention (Suliman *et al.*, 2016). Nootropics can be synthetic, such as amphetamines, or natural "food-derived" and herbal. Due to a growing interest in identifying drugs with fewer side-effects, attention has shifted in recent years to the discovery, characterization and use of nootropics from natural sources, in particular for the treatment of age-related cognitive decline. It has been reported that food-based nootropics include a variety of substances such as *Ginkgo biloba*, *Panax ginseng*, and *Moringa oleifera* (Onaolapo, Obelawo and Onaolapo, 2019). Another nootropic, *Rhodiola rosea*, has been shown to have neuroprotective properties (Qu *et al.*, 2009). Other plants have been shown to enhance, preserve and restore memory including the Ayurvedic herb ashwagandha (*Withania somnifera*) (Onaolapo, Obelawo and Onaolapo, 2019). In addition to these, natural compounds like quercetin, L-glutamine, L-theanine (present in green tea, *Camelia sinensis*), L-tyrosine, L-taurine, and acetyl-L-carnitine have been increasingly used for their nootropic effects (Onaolapo, Obelawo and Onaolapo, 2019).

35 Microbiome-focused foods

Future personalized dietary interventions may increasingly focus on gut microbiome dynamics to enhance individual health and potentially extend the life span of an individual (Fontaine *et al.*, 2024; Low *et al.*, 2021). One novel approach involves using next-generation supplements designed to support gut health, such as synbiotics – a mixture of probiotics and prebiotics primarily derived from non-digestible fibre-rich foods (Gomez Quintero, Kok and Hutkins, 2022). Postbiotics are substances produced in the gut as microbes break down fibre, which are deemed beneficial for human health. Diets that promote the production of postbiotics are gaining increased attention due to their potential health benefits to consumers (Vinderola, Sanders and Salminen, 2022).

Moringa (*Moringa oleifera*) tree leaves in the United Republic of Tanzania, Zanzibar.

Chinese green tea (*Camelia sinesis*) in a tea shop in Rome.

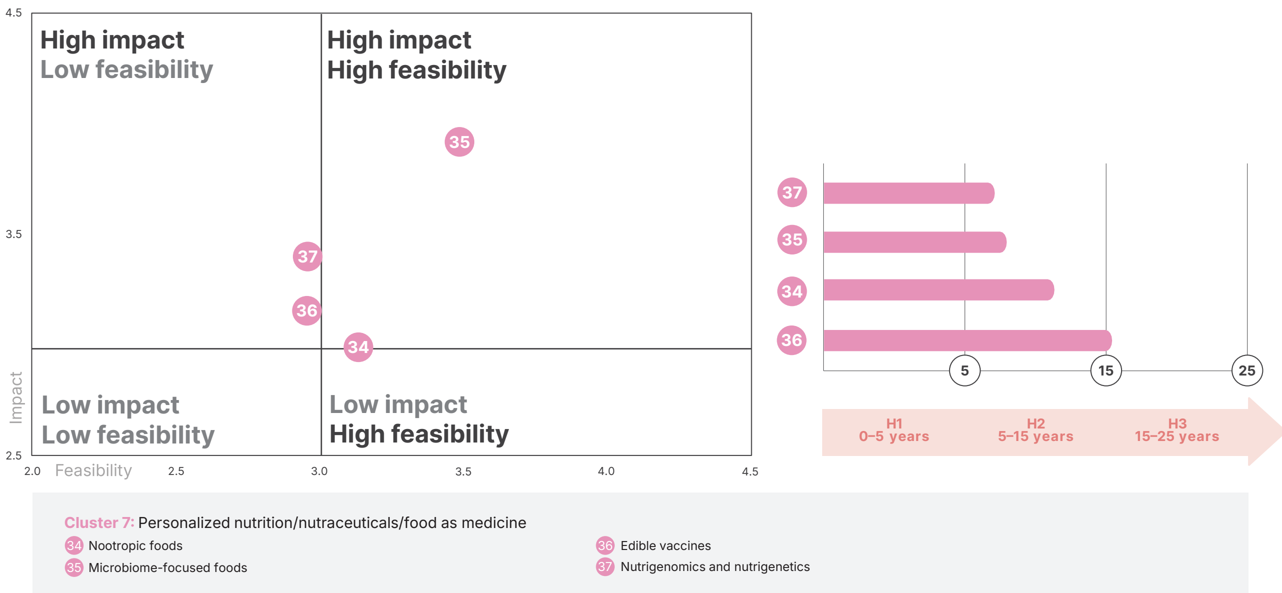
36 Edible vaccines

Ribosomal DNA technology, particularly *Agrobacterium*-based transformation of plant cells, can be applied to produce edible vaccines (Naik, 2022). Through this technology, commercial crops and other plants can be modified genetically to express antigens capable of causing an immune response against a range of diseases, including measles, hepatitis B, diphtheria, tetanus, acute gastrointestinal illness, acquired immunodeficiency syndrome (AIDS), anthrax, and cholera (Naik, 2022). Additionally, second-generation edible vaccines are being developed, which incorporate multi-subunit antigen proteins, enabling them to target multiple diseases simultaneously (Naik, 2022).

37 Nutrigenomics and nutrigenetics

Nutrigenetics explores the interactions between inherited genomes and nutrition, including the combined effect of one's inherited genome and nutrition on health. Nutrigenomics is broader in scope, encompassing all aspects of nutrient-gene interactions, including how dietary components impact the genome, proteome and metabolome (Mead, 2007). Nutrigenetics and nutrigenomics can shed light on the observed variation of the effects of nutritional interventions on specific subpopulations. This knowledge enables the creation of diets tailored to an individual's genetic predisposition, possibly optimizing health outcomes (Kohlmeier, 2013). This technology, including the potential for AI technology, is being used to develop highly personalized food products and diet plans in some high-income country contexts (Rosenn, 2023).

Figure 12. "Personalized nutrition/nutraceuticals/food as medicine" innovation cluster: Feasibility/impact matrix and time horizons



The experts expected the occurrence and use of nearly all the innovations in the cluster to substantially increase in the next 5–15 years. Microbiome-focused probiotics, postbiotics and symbiotics were considered to be feasible and to have positive implications for future food safety. Nootropic foods, on the other hand, were regarded as presenting a safety risk. Furthermore, as these vaccines are regulated as medicine, food safety risks were not deemed relevant.

2.2.8 Innovation cluster: Food packaging

38 Nanotechnology in food packaging

Nanotechnology refers to the fabrication, manipulation and production of materials at nanoscale (1–100 nm), which exhibit different properties than their micro- or macro-scale counterparts (Cruz-Lopes, Macena and Guiné, 2021). A variety of nanomaterials are being developed for use in food packaging, including nanocellulose, nano starch, chitosan nanoparticles and carbon nanotubes (Ashfaq *et al.*, 2022). Organic and inorganic particles are typically incorporated into packaging polymers to improve the flexibility, strength and durability of packaging (Ashfaq *et al.*, 2022). Furthermore, nanosensors-based smart packaging allows food conditions to be monitored during storage and transport (Cruz-Lopes, Macena and Guiné, 2021).


© FAO/Luis Tato

Preparing dried mangoes in Kenya.

39 Recycling and reuse of food packaging/utilization of valorized materials in food packaging

The recycling and reuse of food packaging involve collecting used packaging materials, processing them to remove contaminants and then reforming them into new packaging products. This process can include both traditional materials, like plastics, and innovative valorized materials – by-products or waste from other processes that are repurposed into packaging solutions. For example, fruit and vegetable by-products can be used in the production of biopolymers, offering an alternative to non-biodegradable synthetic polymers. Due to their high concentration of fibrous proteins, such as starch and cellulose, food processing by-products such as husks, seeds, leaves and gums (for example, corn husks, mango kernels and potato peels) can be recycled as value-added packaging films and coatings (Karimi Sani *et al.*, 2023; Kumar Gupta *et al.*, 2024).

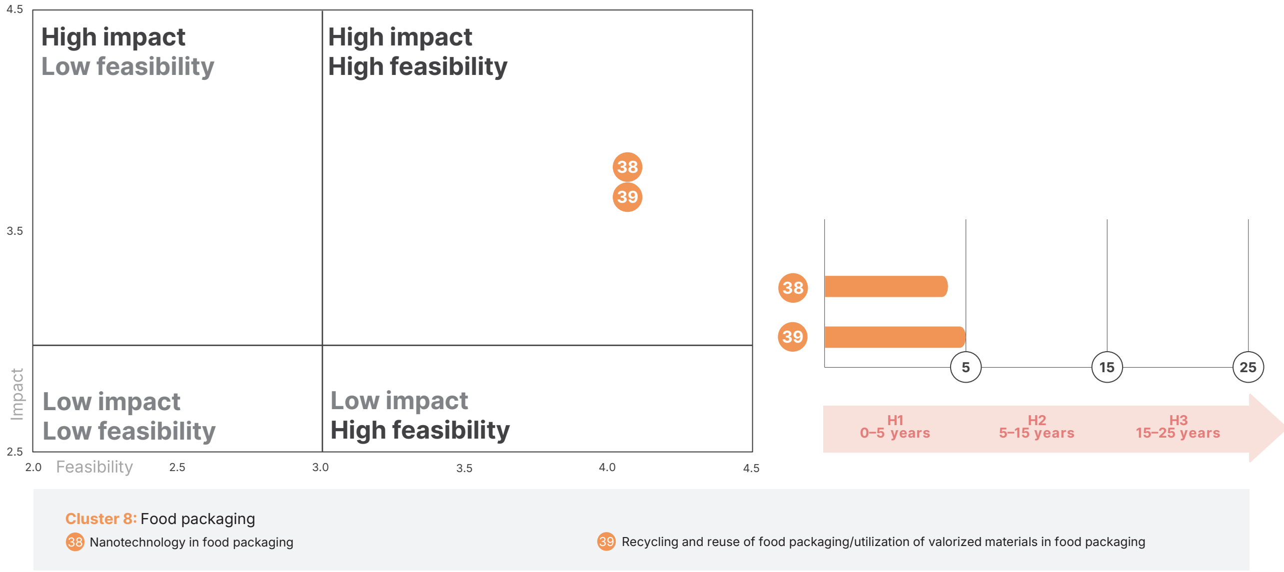
Sweetcorn in husks in a market in Türkiye.


© FAO/Robin Hammond

Peeling potatoes for cooking in Papua New Guinea.


© FAO/Russell Wai

Figure 13. "Food packaging" innovation cluster: Feasibility/impact matrix and time horizons



Innovations in food packaging were regarded by the experts as feasible with current scientific and technical knowledge and tools, making it likely that they will become widespread within the next few years. Novel food packaging was considered to have a net beneficial impact on the future agrifood systems as well as food safety.

2.2.9 Innovation cluster: Further emerging trends

40 Reduced added salt and sugar food products/push for sugar alternatives

There is growing interest in developing food products with less added salt and sugar in response to increasing consumer awareness of the potential health risks associated with excessive consumption of these ingredients. Reducing salt and sugar in foods is an initiative aimed at addressing critical public health issues such risk of unhealthy weight gain and diet-related noncommunicable diseases in adults and children. To meet this demand, there is a growing interest in ingredients that mimic sweetness, allowing for the reduction of added sugars (McKenzie and Lee, 2022). However, removal or reduction of the sugar present in food products may not be the only way to address overconsumption. Inulosucrase, for example, can convert sugars into non-digestible dietary fibres (Ni *et al.*, 2018). Enzymes added to food products could mitigate the negative effects associated with excessive sugar amounts in these products. Despite the growing interest in non-sugar sweeteners, their use as a means of achieving weight control or reducing the risk of noncommunicable diseases is currently not recommended as there is no clear consensus on whether non-sugar sweeteners are effective for long-term weight loss or maintenance (Rios-Leyvraz and Montez, 2022; WHO, 2023).

41 Sustainable food products/renewable energy solutions to new production technologies

Global energy demand is expected to double by 2035, driven by population growth, technological development, urbanization and climate change, which will in turn increase the price of energy and food (International Energy Agency *et al.*, 2010; Majeed *et al.*, 2023). Adopting renewable energy sources and better energy management practices can help prevent this increase in costs. Furthermore, as competition for carbon-neutral foods intensifies, it is likely to spur research and innovation across the entire food production process, from farm to table, creating more opportunities for the development of sustainable agrifood systems relying on renewable energy sources. Several renewable energy sources can be used in agricultural production, including solar, biomass, wind, and geothermal energy (Majeed *et al.*, 2023).

42 E-commerce

The rapid spread of e-commerce has transformed the food industry, offering consumers unprecedented convenience and access to a wide range of products with just a few clicks. In recent years, meal delivery services, online grocery shopping, drone delivery, and direct-to-consumer models have gained increasing attention (Schnieder, Hinde and West, 2022; Tyrväinen and Karjaluoto, 2022). This growth in e-commerce has also led to the proliferation of dark or "ghost" kitchens, which operate exclusively for takeout and delivery, bypassing the traditional dine-in experience (Hakim *et al.*, 2023). Consumers expect the same level of safety from products ordered online as those purchased in physical stores, which requires food manufacturers, distributors and delivery services to implement robust quality control measures.

A visitor using a virtual reality headset at FAO headquarters in Rome.

A cell-based meat roll.

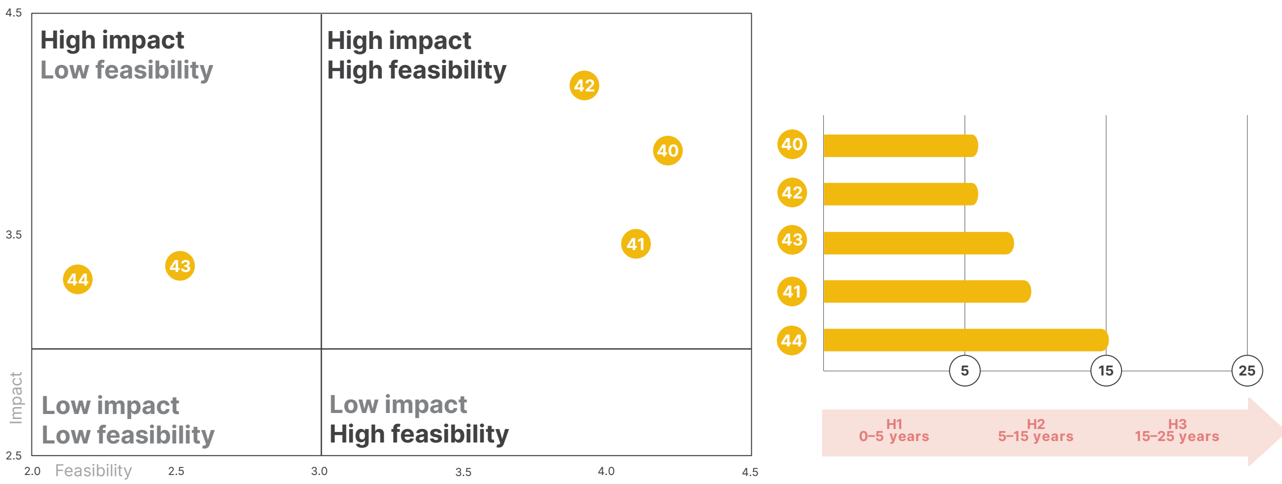
43 Multi-sensory integration to enhance food-related experiences

Recent discoveries show that food perception is a multi-sensory experience which involves sight, hearing, taste, touch and smell (Lin *et al.*, 2022; Spence, 2018). Characteristics of food such as its colour or odour can affect the perception of other sensory attributes such as taste (Spence, 2022). The colour and brightness of the surrounding ambient lighting while eating has been shown to influence the quantity of food that people consume. For example, blue lighting decreases the amount of food consumed by men (Cho *et al.*, 2015). Furthermore, colours in the interior of coffee shops have been shown to influence expected sensory properties of the coffee itself (Motoki, Takahashi and Spence, 2021). The application of a multi-sensory approach is being actively explored in food science and gastronomy to enhance sensory experiences and influence eating behaviour.

44 Evolving human–food–computer interaction

The rapid advancement and widespread use of digital technologies are transforming the way people interact with food (Choi, Foth and Hearn, 2014; Deng, 2021). Human–food–computer interaction (HFCI) encompasses innovative concepts like digital gastronomy, where tools such as 3D printing and smart appliances enhance culinary creativity as well as food experiences in the metaverse, such as virtual dining and cooking (Velasco *et al.*, 2023). HFCI aims to revolutionize food by making it more personalized, enjoyable and sustainable, with the potential to improve health, reduce waste and offer new ways of experiencing food.

Figure 14. "Further emerging trends" innovation cluster: Feasibility/impact matrix and time horizons



Cluster 9: Further emerging trends
- 40 Reduced added salt and sugar food products/push for sugar alternatives
- 41 Sustainable food products/renewable energy solutions to new production technologies
- 42 E-commerce
- 43 Multi-sensory integration to enhance food-related experiences
- 44 Evolving human–food–computer interaction

Experts agreed that e-commerce, which gained notable momentum during the COVID-19 pandemic, was overall beneficial for agrifood systems without posing significant threats to food safety if well-monitored within the next 5 years. Sustainable food products made with renewable energy solutions were expected to become more widespread in the intermediate future but will likely bring substantial benefits to future agrifood systems and food safety. Multi-sensory approaches to gastronomy to enhance food-related experiences were expected to see a major rise in popularity in the near future with potentially beneficial implications for food safety. Due to its relative infancy, however, it was associated with low feasibility. HFCIs, while difficult to expand, were expected to contribute to enhanced food safety in the next 5–15 years.

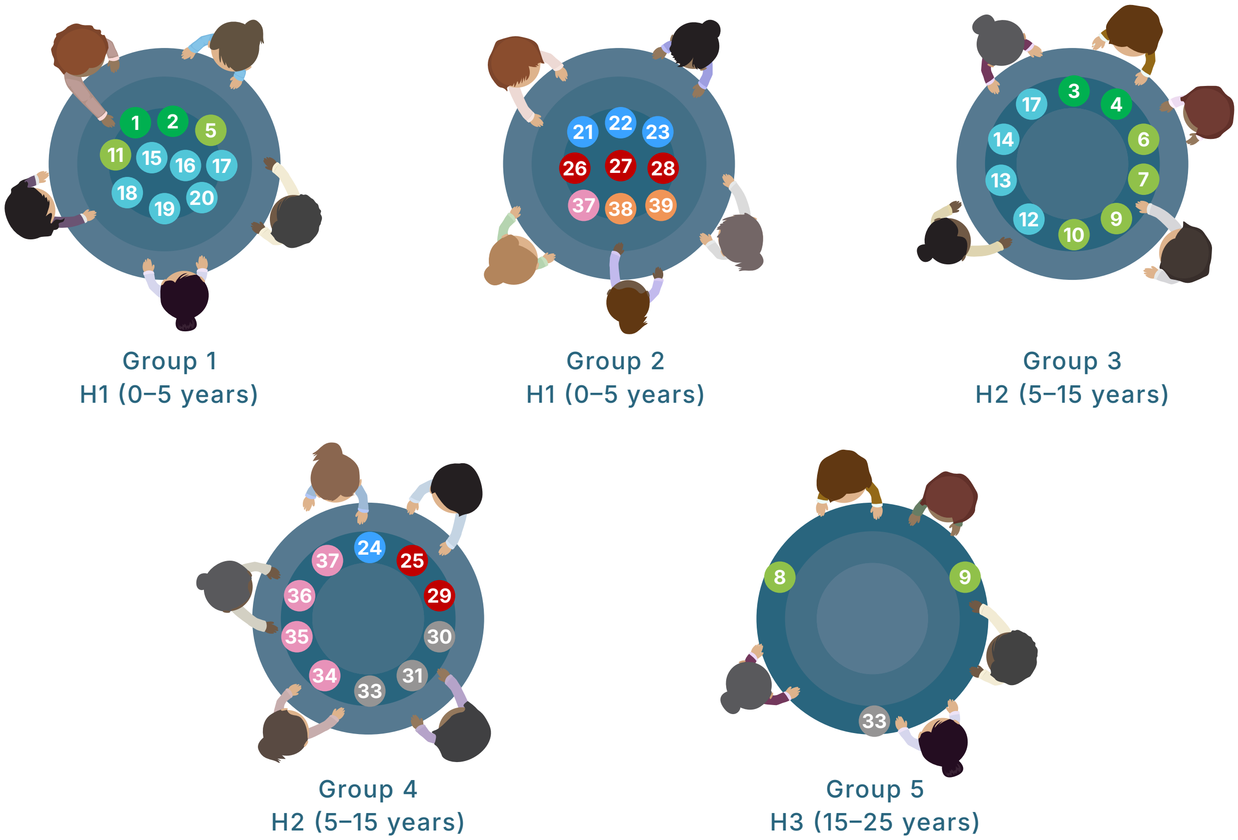
Experts take part in the mind mapping exercise at the Food Safety Foresight Technical Meeting at FAO headquarters.

2.3 Mind mapping

In the second phase of the foresight exercise, the overall preparedness of the food safety community to address the challenges and seize the opportunities associated with the identified innovations was explored using a mind mapping approach. The experts were randomly assigned into five groups to discuss various innovations based on expected time horizons (Figure 14), with each group asked to consider the following questions:

1. What would be the necessary steps (including possible regulations, research, collaboration between specific stakeholders, appropriate communication strategies, etc.) needed to realize the benefits and avoid the challenges of the innovations in their designated time horizons?
2. What could be stumbling blocks that stand in our way and where could they arise from (considering social, technological, economic, environmental, and political, or STEEP, concerns as a framework)?

Figure 15. Innovations discussed per group based on the various time horizons



1. New sources (corn husks, brewers' spent grain, cassava leaves) of nutrients
2. New sources (oil cake/meal, rice bran) of bioactive compounds (antioxidants, peptides) and fibre
3. Novel growth media from consumer waste
4. Wastewater as source of fit-for-purpose water and nutrients for crops
5. Fermentation techniques
6. Molecular farming
7. Food printing
8. Reverse food manufacturing and multiscale food structuring approach
9. Cellular agriculture
10. Liquid oil structuring (oleogels, emulsion gels, bigels, high internal phase emulsions)
11. Controlled environment agriculture
12. New sources of fats and oils (Brazil: macaúba, tucumã and babaçu)
13. Underutilized/orphan crops
14. Cultured human milk
15. Edible bird's nest
16. Single-cell proteins
17. Nanotechnology
18. "Hybrid" food products
19. Edible insects
20. Protein-based sweeteners
21. Artificial intelligence in food production and food safety
22. Big data and the internet of things
23. Digital food twins
24. Distributed ledger technologies (such as blockchain)
25. Cold plasma
26. Irradiation
27. Biopesticides
28. Bacteriophages for pathogen control
29. Novel methods for food tracking
30. Bioengineered microalgae
31. Gene-edited plants, including minor crops
33. DNA-based barcodes for food authentication
34. Nootropic foods
35. Microbiome-focused foods
36. Edible vaccines
37. Nutrigenomics and nutrigenetics
38. Nanotechnology in food packaging
39. Recycling and reuse of food packaging/utilization of valorized materials in food packaging

2.4 Readiness, actions and stumbling blocks

2.4.1 Key factors influencing readiness

Scaling up and implementation of technologies

The experts found that the technology for the NFPS innovations considered to become relevant in the next 5 years, such as precision fermentation and indoor farming, is already largely established, suggesting that these technologies primarily require scaling up and implementation. For novel technologies used for food safety and quality control, such as radiation and bacteriophages, scaling up may be hampered by potential issues with the supply chain, such as standardization requirements, if demand increases significantly.

Regarding digital innovations expected in the coming years, large companies were considered ready for scaling up digital technologies on the market. However, the readiness of smaller and medium-sized businesses remains unclear. Digital innovations could potentially turn into a service provided by specialized companies to smaller players. Improvements in data collection and analysis were considered to enable the full realization of the potential of digital innovations. Removing barriers to AI training was regarded as a potential way to expand digital technologies. Digital technology in general was stressed to be outside the scope of LMICs, where access to these innovations and awareness regarding their application may be missing, resulting in slower technology diffusion. A wide adoption of smartphone technology may partially mitigate this problem.

The technology for some innovations expected within the next 15 years, such as cell-based human milk, was considered at a very early stage in research and development. Similarly, decentralized detection devices, such as handheld devices for detecting DNA, are expected to continue to develop and their applicability to improve.

Public awareness and misinformation

Insufficient communication on the innovations in the NFPS sector in all time horizons was identified by the experts as a factor hindering consumers' clear understanding of the innovations and their related issues. For the innovations relying on agrifood by-products and waste, for example, communication is missing on their implications for the sustainability of agrifood systems and food safety. This is complicated by mis- and disinformation due to a lack of scientific data. The science behind innovations such as nutraceuticals, for example, is still in development and the claims by companies are not always supported by scientific evidence. Limited consumer acceptance resulting from missing communication on potential risks and benefits may affect the adoption and use of technologies.

Issues around the consequences of insufficient information on data quality were also raised, particularly in terms of hampering the development of effective policies and regulations. Unequal distribution of data among stakeholders (large companies often have large data sets that are not made public) may exacerbate market imbalances.

Tailored food safety risk assessments

Societal readiness for many of the NFPS innovations was linked to the knowledge and availability of tailored food safety assessments. A strong interest in and willingness to implement molecular farming exists in developed countries. However, an assessment is needed to understand the agricultural practices required to ensure that food crops expressing novel allergens are adequately managed to avoid the contamination of commodity crops. The level of stewardship needed for plant molecular farming is expected to be greater than that required for conventional or other genetically modified crops. Cold plasma is already at the research stage for non-thermal antimicrobial use, however potential risks associated with the generation of biogenic amines also needs to be assessed for this innovation. In contrast, adequate risk assessment processes were found to already be in place for food production systems relying on genetic engineering. Similarly, bacteriophages are currently already being implemented for pathogen control and the use of several are generally recognized as safe (GRAS) in the United States of America.

2.4.2 Actions needed to realize opportunities and avoid challenges

A range of necessary steps needed to realize the benefits and avoid the challenges of the innovations in their designated time horizons were identified. The key actions are presented below.

Improve communication on NFPS and related issues

- **Use effective communication to enhance consumer acceptance of new foods.**
    - Implement education and communication strategies at national and international levels to raise awareness about new food sources and new ways of producing food. Designate entities responsible for communication with consumers and stakeholders.
    - Ensure proper labelling on foods containing new ingredients.
    - Establish formal communication channels around received submissions for NFPS products and reviews alongside partnerships with social influencers.
    - Communicate about new products and their safety characteristics early in the development stage
    - Pay attention to framing; avoid terms like "wastewater" that may deter consumers.
- **Guide the agrifood industry and local/national authorities on NFPS.**
    - Create guidance documents for industry stakeholders on the optimal use of NFPS and on product labelling.
    - Inform local and national authorities of recommended safety standards for NFPS.
    - Ensure regulatory oversight of the messaging for the NFPS innovations.

Foster technical and scientific advancement

- **Fill knowledge gaps through research and knowledge sharing.**
    - Promote research to fill relevant knowledge gaps.
    - Increase data literacy across the agrifood chain and support data generation and sharing.
    - Encourage systems-thinking approaches.
    - Increase access to knowledge for regulatory bodies on the nature and use of NFPS such as new food ingredients in other contexts. Conversely, developers should have the opportunity to consult regulatory risk professionals early on to ensure the safety of their products in development.
- **Promote sustainable practices and technologies with societal benefit.**
    - Select fit-for-purpose solutions to increase the sustainability of the NFPS innovations.
    - Identify technologies with the greatest potential to aid society in the event of disasters.
    - Encourage governments to identify the best technologies achieve future goals and implement regulations to encourage their development.

Develop and optimize safety assessments

- Refine digital technologies for the risk assessment of NFPS innovations, including possible impacts on the human microbiome.
- Redesign food production and treatment processes to adapt to food safety requirements, functionality and intended use.
- Promote the development of methods for the detection of toxicity (e.g. nanotoxicity).
- Implement case-by-case assessments and regulatory systems for NFPS.
- Coordinate work between competent environmental and food safety authorities to improve food safety control.
- Ensure stewardship and adequate supervision for NFPS innovations to ensure food safety and increase consumer confidence.

Encourage collaboration and provide incentives

- Facilitate the formation of partnerships with conventional food industries to explore alternative livelihoods and increase transparency and knowledge sharing.
- Facilitate regulatory collaboration between the government and industry, especially small manufacturers, to identify the main technologies to prioritize.
- Involve food professionals in other areas of regulation, such as education and funding.
- Provide strong incentives to encourage the development of innovations that have yet to gain widespread popularity.

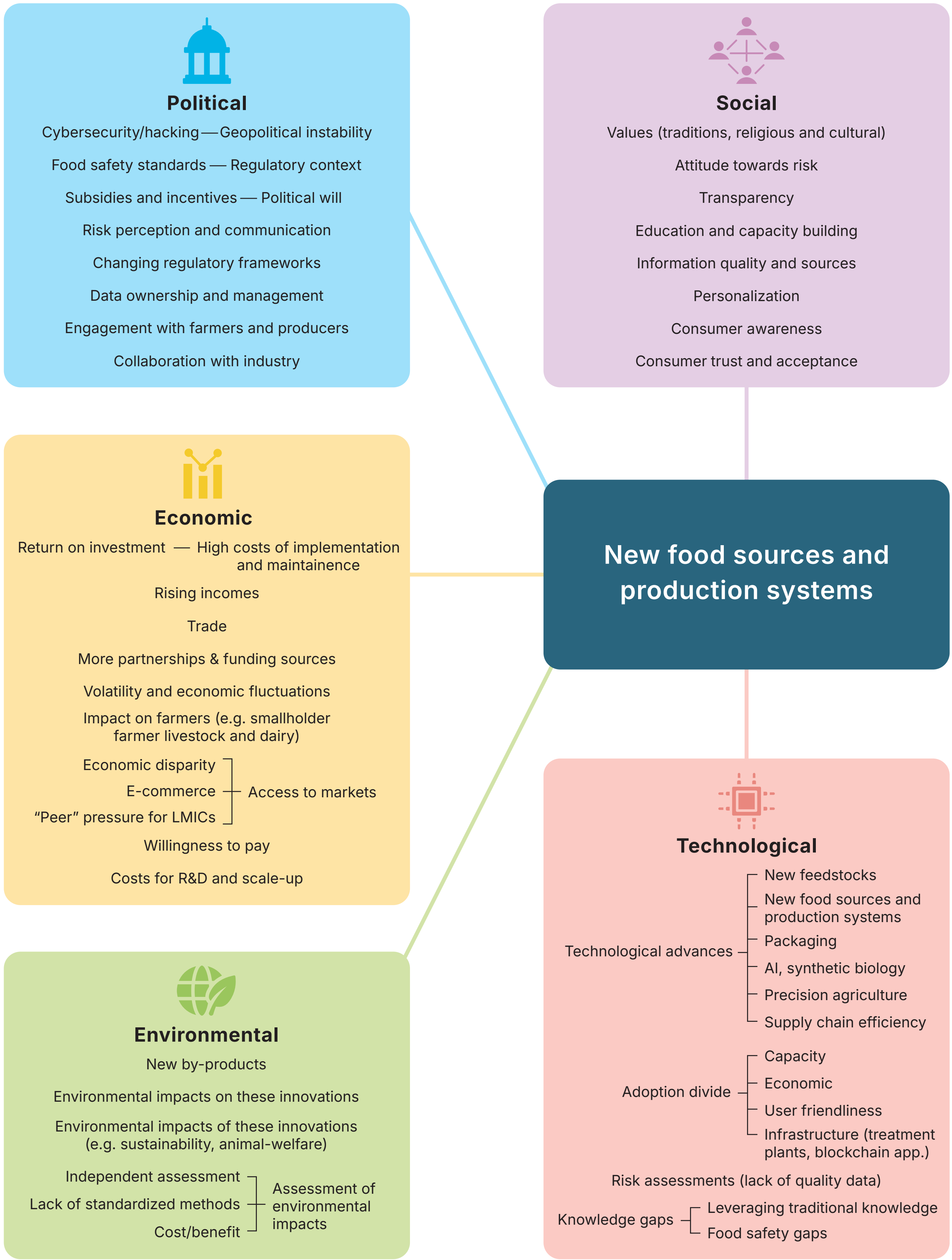
Harmonize regulatory requirements

- Harmonize risk-benefit assessments for the NFPS innovations.
- Establish minimum common submission requirements across regulatory bodies, for example, at Codex Alimentarius level.

2.4.3 Obstacles

Taking the necessary actions to seize the opportunities and address the challenges associated with NFPS innovations is not always easy. Several overarching social, technological, economic, environmental and political themes were identified as potential obstacles to taking the actions required for the safe development and implementation of these innovations. The list of obstacles to action is non-exhaustive, however, several key factors were identified (Figure 16) and are briefly described in this section.

Figure 16. Key social, technological, economic, environmental and political themes that influence the development and implementation of the NFPS



Children taking part in Junior World Food Day, FAO headquarters, Rome.

Social obstacles

The attitude of consumers, in particular consumer acceptance, trust and awareness, was identified as a key social barrier to innovation in the NFPS space. Acceptance of innovations by consumers can be influenced by traditions, beliefs, customs and cultural norms. Resistance to change may lead to a lack of readiness or willingness to accept innovations. Mistrust can result from fears or negative perceptions around a given innovation, which may be amplified through social media, some experts argued. Furthermore, mistrust and fear from industry towards regulatory bodies can prevent the development of NFPS innovations. Risk aversion is often a stumbling block when it comes to uptake of new innovations in the market. The lack of awareness among consumers, industry and governments or authorities may arise from insufficient knowledge related to the existence of certain NFPS technologies. Furthermore, what constitutes fully sustainable food production practices is often subjective and the need of agrifood systems to transition towards a modern and more sustainable model is not fully understood by all stakeholders. Limited consumer acceptance and understanding of innovations in general, especially those related to food safety control, influence their scalability with potential disadvantages for the consumers themselves as modern solutions in this field could improve the safety of food products.

The lack of both corporate and consumer knowledge in the area of NFPS is a major obstacle to innovation. Mis- and disinformation exacerbate knowledge gaps, posing significant additional barriers to innovation. Often, mis- and disinformation are caused by a paucity of or limited access to data, or poor data quality, resulting in a lack of preparedness for some of the NFPS innovations and contributing to a confused picture of these innovations among consumers. For example, consumers may lack information on the exact ingredients used in foods (e.g. in hybrid products) or the safety of certain NFPS products. Low scientific literacy can contribute to the lack of understanding, particularly of the risks and benefits of novel technologies. At the same time, the lack of information may stem from insufficient collective knowledge about the effects of an innovation.

Technological obstacles

Technological obstacles include a lack of awareness of the technologies themselves, access to the technology, a lack of sufficient resources, little corporate knowledge and engagement with relevant stakeholders, and insufficient training to operate and maintain them. Furthermore, there are often prohibitive costs to develop certain technologies, as well as intellectual property right issues. Large companies may store large datasets that are not available to the general public. This limits the amount of available data for analysis, thereby reducing the quality of the insights that can be obtained.

Capacity building can contribute to enhancing technological know-how. Learning how to optimally develop, maintain, and operate some of these technologies is essential if they are to become prevalent in society. Crop management techniques can also be learned to prevent unwanted cross-contamination. The technologies at later stages of development can offer valuable lessons learned, which can be applied to further advance the technology. Research is needed to enhance the usability of new technologies and to assess their safety risks. Risk assessments of the NFPS innovations are often inconclusive due to the lack of quality data. A very important aspect of food safety assessments – the quantitative assessment of the actual or anticipated human exposure of a food hazard – is especially challenging in the case of NFPS. This is due to the uncertainty surrounding the possible amount of new food sources likely to be out on the market presently or in the near future, and even to a lack of present data on this, as many new food sources are so new that there is no sufficient accumulation over time to make sound conclusions. In some cases, traditional knowledge of certain foods or production systems that are not "novel" in a given region can be leveraged to minimize these data gaps and ensure the safety and health of consumers.

Many of the NFPS identified in this exercise represent significant scientific and technological advancements, including AI, synthetic biology and precision agriculture. Key obstacles for their implementation include a substantial existing divide in their adoption. Global economic disparities among countries lead to unequal access to new technologies, causing significant downstream effects such as long-term unequal distribution of the innovations. This puts further pressure on countries that already have limited resources and lack the capacity to implement various technologies. Often, the necessary infrastructure for a particular innovation is missing in certain countries or regions of the world, preventing their adoption. Some innovations, such as molecular farming or the development of nutraceuticals, are also not a priority in some LMICs where food security remains of primary concern.

Microscopes used for microscopic examination of bacteria, fungi, or microorganisms at the Joint Kazakh-Chinese Laboratory for Biological Safety, Kazakh Agrotechnical Research University (KazATRU).

Economic obstacles

Economic barriers for innovators in the NFPS sector include prohibitively high costs of research and development, scale-up, costs related to the regulatory requirements associated with enforcement and monitoring of new foods, and a low or uncertain return on investment. Furthermore, high costs are associated with the maintenance and management of the innovations, including high energy costs for data storage and measures against hacking into data-based technologies, for example. Some innovations are not yet economic or cost-effective thereby posing a large financial risk to industry, for example in the case of increasing the use of underutilized crops. When the status-quo is more financially stable and profitable, there might be a greater avoidance of taking risks.

A stockfish, dry shrimp and cheese are displayed on sale in a stall at the municipal market in São Paulo.

To overcome the lack of (access to) funds, more partnerships and additional funding sources are required. This is of particular importance when it comes to shifting traditional food industries and production practices towards exploring alternative livelihoods. Smallholder livestock and dairy farmers, for example, may be greatly impacted by the changing food and agrifood system landscapes and require support in order to remain economically viable. E-commerce presents an interesting opportunity to empower food producers, providing a unique direct access to local markets.

Rising incomes provide an opportunity both for supply and demand of novel NFPS, as they may increase consumers' willingness to pay for the innovations. However, global economic fluctuations, price volatilities and economic cycles impact the timing and scaling of innovations. Furthermore, missing consolidation of industry and trade can hinder innovation, as food safety regulations are often used as non-tariff barriers to trade.

Another stumbling block is the perception that NFPS are to replace existing technologies or traditional practices. The transition of conventional agriculture sectors towards innovative alternatives may be linked with concerns regarding potential job loss of large sections of the populations working in this sector. Countries with limited economic resources are also put under increasing pressure to keep up with global innovations in order to stay competitive.

Environmental obstacles

Environmental barriers can significantly block development, implementation, and maintenance of innovations in the NFPS sector. On the one hand, the climate affects technologies. For example, extreme weather events can destabilize the energy supplies required to run energy-intensive technologies. On the other hand, the technologies themselves can have both beneficial and negative effects on the environment and climate. For example, new food sources bring new and possibly more types of waste and by-products which may negatively impact the environment. Likewise, novel technologies require raw materials, energy and other resources, contributing to the further depletion of natural resources. However, the environmental footprint of innovations could be lower compared to conventional agrifood production. Independent, objective and harmonized environmental impact assessments are needed to analyse the true costs and benefits of a given NFPS. This issue is exacerbated by the fact that the long-term consequences of environmental changes on agrifood systems are largely still unknown.

Almond saplings planted as part of agroforestry initiatives to decrease pressure on natural forest, Afghanistan.

Political obstacles

Political obstacles to the actions identified for the success of NFPS opportunities include a lack of political will and insufficient incentives for change, among others. Governments could provide incentives, for example, to reuse and recycle food packaging via specific regulations and support the production of wastewater for treatment of crops via subsidies or funding the development of necessary infrastructure. A common regulatory approach with respect to the safety recommendations of NFPS is also missing. Harmonization of risk assessments would further help ensure the food safety of certain innovations, for example by considering the possible presence of potential hazardous metabolites or anti-nutrients in underutilized crops or biogenic amines following the use of cold plasma, or the safety of novel growth media from waste.

Governments can play a key role in data ownership and management to ensure oversight and preparedness for rapid technological advances. Regulatory preparedness and oversight are essential to prevent public health risks. A lack of oversight may partly stem from the absence of sufficient collaboration between environmental and food safety authorities. More collaboration and knowledge exchange between regulators, industry and consumers are important to ensure transparency. Working in silos, hierarchical structures and limited public engagement are among possible causes for the insufficient preparedness of governments for future developments in the NFPS sector. Regular government engagement with farmers and producers, particularly smallholder farmers, is necessary to raise awareness and increase the preparedness of both governments and producers for these developments. Governments should also work to bridge the divide between traditional food producers and NFPS stakeholders, as well as between consumers of traditional and novel foods, fostering a more inclusive and sustainable food system.

Finally, in recent decades there has been a significant increase in global polarization and potential for conflict. Resulting geopolitical instability poses a real threat to the development and implementation of NFPS innovations. This issue is exacerbated by new forms of emerging weapons and hybrid threats, such as hacking, infrastructure disruption and increased risk of cybersecurity breaches.

Opening of the Summit of the Future, UN Headquarters, New York.

FAO Director-General Qu Dongyu arriving at the Summit of the Future at UN Headquarters in New York City.

©FAO/Roberto Schmidt

3. Conclusions and way forward

New food sources and production systems (NFPS) is a rapidly advancing sector influencing the future agrifood landscape with implications for future food safety. Through the participatory foresight approach outlined in this report, numerous NFPS innovations expected to develop or scale up within the next 25 years were identified and explored.

Forty-four NFPS innovations and trends emerged from the foresight exercise, grouped into nine clusters: the valorization of agrifood by-products and waste/circular economy; new production technologies; new food sources and food ingredients; digitalization and data-based technologies; food safety/quality control; genetic engineering, gene editing and synthetic biology; personalized nutrition/nutraceuticals/food as medicine; food packaging; and further emerging trends. This exercise shed light on emerging NFPS, detailing key actions needed to fully realize their potential. To enhance societal preparedness, and that of food safety authorities specifically, stumbling blocks that lay in the path towards action were mapped out and discussed.

Continuous monitoring and assessment of new and emerging issues related to NFPS will be necessary to keep pace with the speed of industry advancements. To that end, several areas identified in this foresight exercise have already been earmarked for future work by FAO with a number of publications in the pipeline (food safety in personalized nutrition with a focus on food supplements and functional foods; the terminology around precision fermentation; and the food safety implications of the use of wastewater in the agrifood sector).

While this foresight report touches on some nutritional implications, its primary focus was on food safety. Therefore, it should not be regarded as a comprehensive or fully up-to-date review of the nutritional aspects of NFPS.

Moving forward, more detailed analyses on the food safety aspects of selected innovations could be carried out, for example through technical briefs, and more comprehensive reviews of the nutritional considerations could be undertaken, some aspects of which are currently underway. Furthermore, concrete step-by-step roadmaps could be co-designed with experts to indicate the precise roles of national governments, food safety authorities, producers, consumers, and all other stakeholders across the agrifood system, local to global, to showcase the timeline of milestones required to successfully integrate the identified innovations in a safe and effective manner.

More analysis is needed to explore the food safety consideration of the full range of emerging NFPS likely to significantly advance in the long term given changing consumption patterns, extreme weather events, increasing resource scarcity and recent disruption from generative AI and geopolitical instability. In light of these challenges, stakeholders across the agrifood sector are working to build the resilience of agrifood systems, recognizing the urgent need for innovative solutions.

The results of this exercise revealed implications of the NFPS innovations beyond food safety, affecting all dimensions of society, which in turn can have additional beneficial or adverse impacts on food safety. In the future, the full range of impacts of these innovations across the agrifood system and even into other areas of society could be further analysed. Foresight methodologies, such as the futures wheel, provide a framework for studying the diversity of impacts of a given change. A futures wheel helps to explore the wide range of possible first, second, third (and higher) order impacts of a given innovation. Downstream secondary and tertiary effects are often overlooked but provide valuable insights into the full range of consequences a single change to any system can cause. Furthermore, recognizing the interconnectedness of food safety, nutrition, and other considerations such as environmental sustainability, it will be essential to address these aspects holistically to fully understand and manage the broader implications of these innovations.

In addition to a futures wheel, scenario building is a valuable qualitative method for identifying the range of consequences associated with the implementation of the identified innovations. Furthermore, technology assessments can help showcase the differences between the effects of a single innovation viewed in isolation as opposed to the cross-effects that occur as multiple innovations come to market simultaneously. Future scenario work could also include the development of cost-benefit scenarios which include social and environmental costs, to provide a general analysis of the economic, social and environmental feasibility of NFPS innovations.

While the future is largely uncertain, foresight exercises such as these can help explore some of the vast possibilities in the agrifood space and proactively prepare, to the best of our ability, for what is to come.

A high school student learning about agriculture and art with recycled materials in Azerbaijan.

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Annexes

Annex 1: List of participants

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Annex 2: Delphi survey part 1

The future landscape of new food sources

Objective and scope of the exercise

While the Food Safety Foresight Technical Meeting focuses on the food safety implications of three new food sources and production systems (i.e. *plant-based food products, precision fermentation, and 3D printing of food*), it will be remiss to not take a step back and look more broadly at the new foods landscape while imagining how the space may evolve in the future. Therefore, the scope of this exercise is to collectively explore the question of:

What will be the likely global landscape of new food sources in the future?

To do this we will use foresight which is a set of approaches that help explore, imagine and anticipate the future in an open but structured way. It can help identify and explore challenges and opportunities emerging from multiple signals and drivers of change shaping the future. Therefore, it can help inform decisions and act as a trigger for developing strategic options in a context full of unknowns.

Overall, the **objectives of this exercise** are (1) to identify a list of key emerging innovations in the new food sources space *apart from those listed in the 2022 FAO foresight publication*[1] *or covered by this meeting;* (2) to describe the opportunities and challenges associated with the innovations, both from food systems and food safety perspectives; (3) to broadly explore the various steps needed to realize the opportunities and circumvent the challenges identified.

Structure of the exercise and related timelines

The foresight exercise will be conducted in **two** phases:

Phase I: will primarily focus on objectives 1 and 2. This will be conducted via a Delphi survey that will be held virtually, in two parts. This exercise is part 1 of the Delphi survey. Part 2 of the Delphi survey will involve ranking of the various responses received through Part 1.

Phase II: will focus on objective 3 and will be conducted via a mind mapping exercise during the physical meeting in Rome where the responses from Phase I will be described and discussed in more details.

Guiding notes

Explanations on terms used

For the purpose of this foresight exercise the meaning of some terms, as generally understood, are described below:

Food systems: includes all the elements (environment, people, inputs, processes, infrastructure, institutions etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food. It also encompasses the outputs of these activities, including their socio-economic and environmental impacts[2].

New food sources: may imply those that have not been widely consumed, either because their consumption has been historically restricted to certain regions in the world or they have recently emerged in the global retail space thanks to technological innovations. They can also be considered new within the framework of existing Codex standards. New food production systems reflect advancements in pre-existing food technologies or novel innovations that are involved in producing some of the existing or new food sources that are finding their way into the mainstream[1,3].

Innovations: in the context of this exercise innovations refer to any and all advancements made in the food sector that impact how the new food sources space may evolve in the future. This includes new food sources, including novel raw materials and ingredients not yet considered, advancements in technologies for new food production and processing methods, as well as other developments along the food chain from food production, processing, distribution, retailing, and consumption.

Overarching drivers influencing food systems and food safety:

To help you answer the questions below we have attempted to set the stage by compiling a (non-exhaustive) list of drivers that are currently influencing (positively or negatively) our agrifood systems, and therefore also has implications for food safety.

- Global population is growing (estimated to reach 10.9 billion by 2100), with most of this growth in Africa and Asia. However, certain regions of the world will see a population decline, such as Europe (from 746.4 million in 2022 to 588 million by 2100).
- Demand for arable land and water will only increase, contrasting with the need to grow more food with less resources.
- Greenhouse gas emissions and biodiversity loss are projected to increase, particularly in Africa and Latin America.
- Climate change, without appropriate mitigation measures in place, will continue to lead to incidences of extreme weather events that are of incremental severity and frequency and are harder to predict and prepare for.
- By 2050 almost 70 percent of the global population are expected to live in cities. Migrations from rural to urban areas, from conflict zones, disaster-prone areas are on the rise globally
- Investments in the agrifood sectors are increasing, but investments in high-income countries is five times than what it is in sub-Saharan countries.
- Food systems are en route to becoming more technology-intensive, but adoption of these advances would continue to be heterogenous if issues related to digital divide are not resolved.
- Steadily growing consumer demands for food quality, diversity, and year-round availability, in addition to rapid technological advancements are increasing the complexity of governance of food safety and agrifood systems.

Foresight exercise questions

Note to the participants: This foresight exercise is looking for new and latest information in the new food sources space and views of future paths and trends. Therefore, while answering these questions, please take into account what has already been published and written about current NFPS. For instance, please do not mention innovations that have already covered been by the current meeting or have been described in the 2022 FAO food safety foresight[1].

1. Based on what you have read/analysed/detected what are the emerging innovations in the new food sources space that you think may have the potential/are likely to become available/prevalent in the future (next 5–25 years), and why?

No	Name of innovation	Rationale

2. What are some of the opportunities and challenges, for food systems in general and food safety in particular, associated with these innovations? Please describe them.

No	Name of innovation	Rationale

3. Are there any emerging food safety-relevant issues that you think are important in the context of new food sources but are yet to be captured and addressed? These issues can be broad (innovations, food safety governance, infrastructure and capacity, communication strategies, even related sectors like transportation and cold chain, etc). If so, please list and describe below. We have provided one as an example.

1 **FAO.** 2022. *Thinking about the future of food safety*. Rome. https://doi.org/10.4060/cb8667en

2 **FAO.** 2018. *Sustainable food systems: Concept and framewor*k. Rome.

3 **FAO and WHO.** 2021. *New food sources and food production systems: need for Codex attention and guidance?* Joint FAO/WHO Food Standards Programme. Codex Alimentarius Commission, forty-fourth session.

Annex 3: Delphi survey part 2

The future landscape of new food sources

Objective of this exercise

This Part 2 will explore the feasibility and impacts of the innovations that have been identified in Part 1 of the exercise.

By feasibility we are asking if a certain innovation is likely to be realized/come to market/find utilization in the food sector in the future based on a "business-as-usual" scenario, i.e. the current landscape of technological innovations, regulatory frameworks, consumer preferences, etc. continues as usual. In doing so, we also ask you not to consider the desirability of the innovations, for instance, your own personal preferences of what innovations should come to market.

By impacts we mean the overall influence that the innovation can have on food systems considering both the related opportunities and challenges. These impacts can be beneficial, as they bring improved productivity, better food safety management, improved sustainability and social well-being, and reduced costs, etc. Innovations can also have adverse impacts, e.g. bring negative externalities like high environmental impacts, considerable food safety challenges, badly affect the livelihoods of producers, etc. Therefore, we ask that you consider if the benefits that the innovations bring outweigh the adverse impacts or vice versa.

Please note that some innovations can have a high beneficial impact but low feasibility due to various factors, such as, consumer perceptions not likely to change in its favor or too many difficulties in establishing proper value chains, that hinder bringing such innovations into the market.

Foresight exercise questions:

Feasibility

1a. Through this question we seek to find out if an innovation is feasible, and if so, how feasible. Therefore, considering the list of innovations identified, please rank them in terms of feasibility from the order of least feasible to most feasible.

Innovation	1 (least feasible)	2 (somewhat feasible)	3 (likely feasible)	4 (strongly feasible)	5 (most feasible)

1b. Through this question we seek to find out the time frame within which your top ranked innovations are feasible. Therefore, considering only the innovations you have marked in 1a as strongly feasible and most feasible, please categorize them into the likely time frames of occurrence, i.e. if you see your top ranked innovations coming to market/finding utilization in the food sector within 5 years, 15 years or longer.

Innovation	1 (least feasible)	2 (somewhat feasible)	3 (likely feasible)	4 (strongly feasible)	5 (most feasible)

Impacts

2. Considering the list of opportunities and challenges associated with the innovations, can you rank the identified innovations based on their overall impacts on food systems in general and food safety in particular? For innovations for which no opportunities or challenges are provided, please refer to the rationale included instead to form your response.

Innovation	1 (least feasible)	2 (somewhat feasible)	3 (likely feasible)	4 (strongly feasible)	5 (most feasible)

Annex 4: Mind mapping questions

We have covered the feasibility and impact aspects of the innovations gathered, now if we do want the innovations to be realized the time frames indicated, let's talk about whether we as the food safety community are ready to tackle the challenges and optimize the benefits that come with them, i.e. **what is our preparedness?**

1. **What are the steps needed** to realize the benefits and avoid the challenges of the innovations in their designated time horizons? Let's think in terms of some key areas, some examples are:

    - Regulatory system and tools
    - Research and development
    - Communication and collaboration
    - Etc...

2. What could be the **stumbling blocks that can blind-side us?** Where can they arise from?

    Let's think in terms of:

    S social

    T technology

    E economic

    E environmental

    P political

    For instance: Are we considering all stakeholders? Are we thinking about unintended consequences for the stakeholders?

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