Food and Agriculture Organization of the United Nations

Thinking about the future of food safety

A foresight report

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Foreword

Agrifood systems span the different dynamic and interlinked stages of agricultural production, processing, distribution, up to the consumption of food, with each step comprising numerous processes, value chains, multiple stakeholders and their interactions. The UN 2030 Agenda for Sustainable Development flags the need for sustainable food production systems and resilient agricultural practices that provide healthy and affordable diets as well as tackle poverty, protect human rights and restore ecosystems. Food safety is a central part of such a system.

In order to cultivate agrifood systems that are resilient, sustainable and equitable in the face of economic, social, and environmental challenges, there are growing efforts underway to transform agrifood systems to ensure that the rising global population has access to food that is nutritious, ***safe*** and affordable.

To make this transformation happen, tools like foresight, which comprises forward-looking approaches, will be needed to identify and navigate the major global drivers, related trends and other issues that may emerge in the future, bringing varying impacts on agrifood systems. This will enable better preparedness and help to put into place appropriate strategies and policies to take advantage of future opportunities and to manage potential risks. Foresight also provides the means of looking at issues holistically, from a multisectoral point of view, which is inherent in a food systems way of thinking.

This publication, which is intended for a broad audience, explores several cross-cutting issues as identified through the FAO food safety foresight programme. Climate change, which is a defining challenge of our times, also has repercussions on food safety that can affect our health and well-being. As the emphasis on sustainability increases, the concept of circular economy is gaining attention in various sectors, including food and agriculture. How the circular economy may bring benefits in addition to potential food safety risks is discussed using, as an example, the recycling of plastics, another key issue of our time. Growing awareness of depletion of natural resources and adverse environmental impacts from food production is propelling the exploration of new sources of food and different ways of producing food, for instance, edible insects, plant-based meat alternatives and cell-based food. Such new foods are receiving increased attention making it important to determine any potential food safety risks while acknowledging the benefits that they might bring. With urbanization growing rapidly, farming within urban spaces to reduce the distance that food travels between farm and table is gaining traction. The food safety considerations of intra-urban farming methods, such as vertical farming, are therefore discussed in this report. To ensure that food safety competent authorities continue to develop and enforce standards, guidelines and policies that keep food supply chains safe, it is important to recognize the need to keep pace with the latest scientific endeavours, from technological innovations to advances in the field of microbiome, both of which are also described in this publication.

Finally, the ongoing drive to assure food security, reduce poverty and malnutrition, avoid food contamination issues and manage foodborne illness outbreaks, protect biodiversity, advocate for sustainably produced food, and address animal welfare concerns will continue to throw up challenges and calls for innovation which promises to shape the way in which we produce and consume food in the decades to come. In order to be prepared for both the opportunities and challenges, we need to be proactive in driving concrete action and truly forward-looking changes as agrifood systems transform to meet the Sustainable Development Goals

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Acronyms

ADI	Acceptable daily intake
AI	Artificial Intelligence
AIoT	AI-powered IoT (Artificial Intelligence of Things)
AMR	Antimicrobial Resistance
ARfD	Acute Reference Dose
CDC	Center for Disease Control
CSFE	Corporate Strategic Foresight Exercise
DA	domoic acid
DLT	Distributed ledger technologies
dw	dry weight
EAS	Electronic article surveillance
FAO	Food and Agriculture Organization of the United Nations
FBS	fetal bovine serum
GAP	Global Action Plan
GCCP	Good cell and tissue culture practice
GHG	Greenhouse gas
GHP	Good hygiene practices
GMP	Good manufacturing practices
HACCP	Hazard analysis (and) critical control point
IBD	Inflammatory bowel disease
IoT	Internet of Things
IMTA	Integrated Multi-Trophic Aquaculture
iPSCs	induced pluripotent stem cells
IPCC	Intergovernmental Panel on Climate Change
IFAD	International Fund for Agricultural Development
JECFA	Joint FAO/WHO Committee on Food Additives
JMPR	Joint FAO/WHO Meeting on Pesticide Residues
kg	kilogram
LMIC	Low- and middle-income country
ML	Maximum level
ml	millilitre
MRL	Maximum residue limit
MUL	Maximum use level
mADI	microbiological Acceptable Daily Intake
μg	microgram
mg	milligram
NCFU	National food crime unit
NCD	Non-communicable disorders
OECD	Organisation for the Economic Co-operation and Development
OIE	World Organisation for Animal Health
PAH	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
PTWI	Provisional tolerable weekly intake
PTX	palytoxin
RFID	Radio frequency identification
SDG	Sustainable Development Goal
SMIC	Système et Matrice d' Impacts Croisès (Cross impact systems and matrices)
SWOT	Strength, weaknesses, opportunities and threats
TSA	Time series analysis
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WFP	World Food Programme
WHO	World Health Organization

Executive summary

At the 1996 World Food Summit, the Heads of State and Government reaffirmed the right of everyone to have access to safe and nutritious food, consistent with the right to adequate food and the fundamental right of everyone to be free from hunger (World Food Summit, 1996). To achieve this commitment, agrifood systems will need to be transformed to sustainably deliver safe and nutritious food for all. The Food and Agriculture Organization of the United Nations' (FAO) Strategic Framework focuses on this transformation through achieving four pillars: *better production*, *better nutrition*, a *better environment*, and a *better life* (FAO, 2021). To "realize our shared vision for a better world" (UN Food Systems Summit, 2021) and to be better prepared to mitigate potential shocks and disruptions, we need to develop and maintain a deep understanding of the future opportunities, challenges and threats to our agrifood systems. The FAO food safety foresight programme is geared towards the proactive identification, evaluation and prioritization of emerging trends and drivers within and around agrifood systems that can have food safety implications (**Figure 1**). This will lead to improved and timely strategic planning to better manage potential risks and be ready to take advantage of new opportunities.

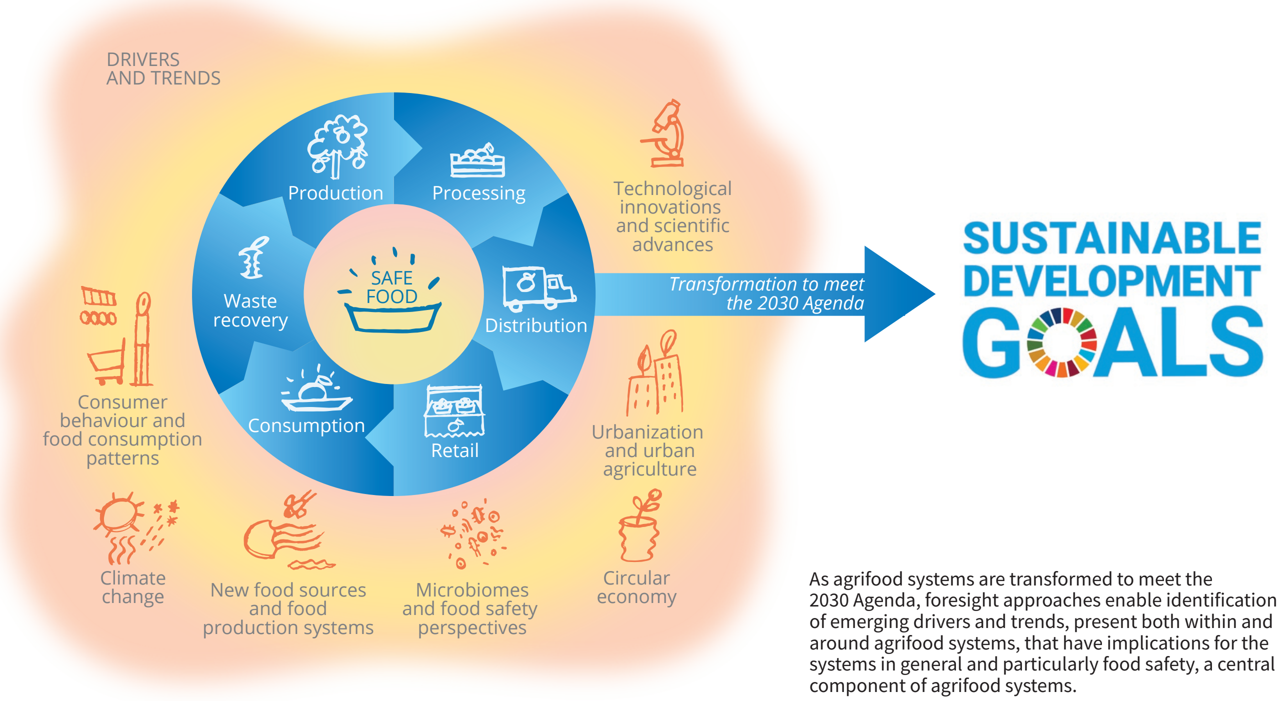
This publication explores a selection of the most relevant drivers and trends identified through the FAO food safety foresight programme. The methodology applied is described in the introductory chapter, while the remainder of the publication consists of a compilation of short briefs describing emerging areas. The briefs are not meant to be exhaustive reviews, but rather provide a concise overview of the topics of interest in terms of *what* they are, *why* they are important from a food safety perspective, and *how* to take stock of the issues moving forward. While for some of the drivers and trends the food safety implications are apparent, for others these may not be as obvious. An overview of the various drivers and trends discussed in the publication is given below.

- Climate change – increasing temperatures, changing precipitation patterns, greater frequency of extreme events, and others – is disrupting our production capabilities to produce enough nutritious food to feed the rising global population. In this report we outline some of the multi-faceted impacts of climate change on various food safety hazards (both biological and chemical). An increased preparedness to address the impact of climate change on food safety will not only benefit food security, but also will help foster resilience in agrifood systems.

- Today, consumer behaviours are shifting in response to a multitude of factors, such as climate change, a focus on improving health especially amid the ongoing pandemic, concerns about the impact of food production on environmental sustainability, rising incomes, amongst many others. These shifts are driving changes in the food purchasing and consumption habits of consumers. Such changes can also be accompanied by potential food safety risks, which will need to be evaluated in order to protect the health of consumers. Some trends in changing consumer demands are discussed in this publication together with the food safety implications associated with them.

- New food sources and food production systems are increasingly being explored with the goal of achieving improved environmental sustainability and/or nutritional benefits. The word 'new' here applies to recently discovered techniques and materials as well as to food that has been historically consumed in specific

Figure 1. Major drivers and trends relevant to agrifood systems and food safety



As agrifood systems are transformed to meet the 2030 Agenda, foresight approaches enable identification of emerging drivers and trends, present both within and around agrifood systems, that have implications for the systems in general and particularly food safety, a central component of agrifood systems.

regions of the world but has recently materialized in the global retail space. In this regard, this report discusses the food safety implications for:

- Farming of *edible insects*, for both human food and animal feed, has gained considerable interest globally owing to numerous potential nutritional, environmental and economic benefits. Likewise, production of *seaweed or macroalgae* is also rising globally, especially offshore in integrated operations that combine seaweed production with other aquaculture activities, such as farmed shellfish. Market demand for *jellyfish* as a food source that is high in protein content is also expected to grow. As these new food sources make inroads into new markets, thorough assessment of food safety hazards is needed to establish appropriate hygiene and manufacturing processes as well as relevant regulatory frameworks.
- As consumer diets are slowly shifting to include fewer animal-based food products, *plant-based alternatives* to animal derived products (meat, dairy, eggs, and seafood) are gaining popularity. There are certain unique food safety aspects associated with plant-based alternatives which are discussed in the publication.
- *Cell-based food* production technology is an evolving area, with various methodologies now well characterized and sufficiently matured to initiate production and commercialization of cell-based food products in some parts of the world. Key considerations for this growing sector are discussed in this report, including several potential food safety hazards that have been identified and documented in literature.

- Amid rapid urbanization, growing food in urban spaces is gaining attention in the face of global food security concerns and rising urban populations. While urban agriculture entails producing food within and around cities and towns, in this report we focus on agriculture activities carried out within urban areas, or *intra*-urban agriculture. Several different types of urban farms of varying scales, commercial and non-commercial, can be found in different parts of the world, from backyard gardens and community farms to innovative indoor vertical farming approaches (hydroponic, aquaponic, or aeroponic systems). Some key food safety aspects of agriculture within urban areas are discussed as well as the need for establishing mechanisms for good governance and appropriate regulatory frameworks specific to urban food systems.

- Technological innovations have greatly helped progress our ability to detect contaminants in food and assist in outbreak investigations, improve predictive analytics to identify potential risks, and enhance traceability of food supplies. The food sector is undergoing rapid evolution in terms of food packaging, new technologies (such as nanotechnology), and new methods for producing food (such as 3D printing) – all of which need careful evaluations of the benefits and threats they bring from a food safety perspective. Application of automation, Artificial Intelligence, big data, and Blockchain technology have the potential to enhance food safety management in the shifting landscape of agrifood systems, but can also raise concerns with regard to equitable access adoption and data privacy. In addition, scientific advancements are also bound to transform food safety risk assessments and it is paramount for food safety and trade that the global community is prepared to follow such progress.

- Microbiomes in agrifood systems and along the food chain are not isolated and can interact with each other. The human gut microbiome is exposed to microorganisms and compounds present in the diet. The potential of food additives, residues of veterinary drugs, food and environmental contaminants to induce changes in the gut microbiome, and any possible consequences to the host health are increasingly being considered for food safety risk assessments. New knowledge in this area will also inform decisions on whether and how to revise chemical risk assessment and regulatory science processes. Furthermore, there are specific concerns related to the transfer of antimicrobial resistance (AMR) from food organisms to the gut microbiome or the increase of AMR resulting from exposure to antimicrobials or low-level veterinary residues.

- The concept of circular economy is promoted to address concerns about environmental sustainability of food production, depletion of natural resources, and others. In contrast to a linear concept, circular economy emphasizes a systems-based approach that encompasses activities and processes geared towards sustainable management of materials within a closed loop system. While this concept holds promise for the agrifood systems, there are various unique food safety aspects that need to be considered before it is made fit-for-purpose for applications in the various quarters of the food sector. These specific food safety implications are explored by focusing on the use and re-use of plastics in the food sector.

- Food fraud is a complex issue that tends to evoke strong consumer responses and can have potential food safety implications. While the current narrative around the issue focuses on the trend of ever-increasing food fraud instances arising from opportunists taking advantage of the complicated nature of agrifood systems, the foresight brief on this topic attempts to re-center the discussion on increased awareness and the concept of *trust* built within food control systems. The brief also provides a snapshot of regulatory strategies that can be used to address food fraud and retain trust in agrifood systems.

The agrifood systems must be, and sometimes already are, transformed to allow an ever increasing and ever more urban population to access safe and nutritious food. How agrifood systems evolve and transform over the coming decades will have profound global implications for our health and socioeconomic wellbeing as well as for the environment. The global awareness, capabilities and capacities to manage food safety need to stay in-tune with this progression to ensure that the growing world population are adequately fed. Food safety will continue to face challenges from both within and outside agrifood systems. Foresight provides a mechanism to proactively identify and navigate these challenges as well as emerging opportunities. This publication showcases a selection of emerging areas of interest, as identified through the FAO food safety foresight programme, and is targeted at a broad audience – from policymakers, researchers, food business operators, private sector to all of us, consumers as food safety is everyone's business

1.
Introduction

W**ith the global population** set to reach 9.7 billion by 2050 (UN, 2019), the pressure on agrifood systems to nourish the world (FAO, 2018) has never been higher, while at the same time staying within planetary boundaries (Rockström *et al.*, 2020). With less than a decade remaining to achieve the 2030 Agenda (UN, 2015), the transformation of agrifood systems remains central to meeting the Sustainable Development Goals (SDGs). However, the environments within which food suppliers, producers, manufacturers and retailers operate within the agrifood systems are changing at an ever increasing rate. The global agrifood system is a complex space with numerous interdependent and interconnected features comprising many actors, relationships and processes as well as difficult to predict events. As these complex links between the farm-to-fork continuum and various environmental and socioeconomic factors become increasingly more evident, agrifood systems are being asked to evolve rapidly in response. This rapid evolution rests on the ability of agrifood systems to sufficiently anticipate, absorb and adapt to perturbations within and around the systems as well as to minimize the perturbations generated by the agrifood systems themselves on other systems. All of these complexities in turn affect the long-term needs of the current and future populations for sufficient, affordable, ***safe*** and nutritious food.

Throughout the world, in simple terms, food is kept safe by the collective efforts of all the relevant actors in the food supply chain: national authorities by establishing relevant guidelines and standards, food producers by adopting good practices, business operators by complying with regulations, and the consumers by being aware of safe food handling practices. This shared responsibility forms the basis of the slogan adopted for the annual World Food Safety Day, "Food safety is everyone's business" (FAO and WHO, 2021). As agrifood systems evolve and respond to various challenges – climate change, globalization, resource depletion, growing inequalities, geopolitical instabilities, e-commerce, amongst many others – food safety needs to keep pace with these changes. Policies, guidelines, standards and regulations related to food safety need to be kept up to date or further developed to reflect the changing needs within the current system. Managing critical food safety deficiencies will foster the efficiency and resilience of agrifood systems and ultimately help achieve food security while ensuring global public health.

To keep pace with the changing dynamics, a shift from a reactive to a proactive approach is needed in food safety management. A structured, futures-thinking approach like foresight can be used to provide a better understanding of the various drivers and trends, under the evolving global context, to promote preparedness for future challenges or showcase avenues for optimizing opportunities (**Box 1**).

Box 1.
FAO's corporate foresight work

From the early 1960s FAO has carried out long-term analyses of the prospects of food security and agriculture with the publication of *Provisional indicative world plan for agricultural development- A synthesis and analysis of factors relevant to world, regional and national agricultural development* (FAO, 1969), which looked at the major issues that would confront the global agricultural sector in the 1970s. Since then, FAO has continued to study and analyse the evolution of agrifood systems within the broader socioeconomic and environmental contexts, which has helped inform analysts and policymakers about the global and regional developments in food and agriculture.

More recently, FAO published *The future of food and agriculture – Trends and challenges* in 2017 with the purpose of increasing understanding of the nature of challenges that the agrifood systems do, and will continue to, face into the twenty-first century. The report identified 15 global trends and 10 challenges that need to be taken in account to achieve food security and sustainable development in the future (FAO, 2017). Building on this publication, FAO released *The future of food and agriculture – Alternative pathways to 2050*, which analysed the global challenges for the future of food and agricultural systems and explored through a quantitative foresight exercise, based on global socioeconomic models, how tackling the challenges – or leaving them unaddressed – will affect the sustainability of agrifood systems (FAO, 2018).

In order to analyse the current and emerging challenges and opportunities to move the global agrifood systems towards realizing the 2030 Agenda, a new Corporate Strategic Foresight Exercise (CSFE) is currently underway. This CSFE comprises internal expert surveys, external consultations as well analytical work carried out by various FAO technical departments. A flagship report in the series *The future of food and agriculture* based on CSFE's findings is being developed. The development of the New Strategic Framework of FAO (FAO, 2021), which is the programmatic document that defines the work of the Organization and reflects the context of major global and regional challenges in the areas of FAO's mandate, was guided in part by the various socioeconomic and environmental drivers (**Table 2**) identified through the CSFE.

Corporate foresight work, that also contributes to the foresight efforts of the whole UN systems through the informal Strategic Framework Network of the UN High Level Committee on Programmes, catalyses the contributions of and constitutes the context for specific foresight activities within the Organization, including those aimed at addressing global food safety concerns

Table 1. Different definitions of foresight

Definition	*Reference*
Foresight comprises "approaches to informing decision-making, by improving inputs concerning the longer-term future and by drawing on wider social networks than has been the case in much 'futures studies' or long-range planning".	Miles, Keenan and Kaivo-oja, 2002
Foresight is the "act of inventing, examining, evaluating, and proposing possible, probable, and preferable futures".	Bell, 2003
Foresight is "a process of visioning alternative futures through a combination of hindsight, insight and forecasting".	Kuosa, 2012

What is foresight?

While there are various definitions of foresight in published literature (see **Table 1** for some examples), in simple terms it involves taking a systematic, medium- to long-term view of the future to appropriately guide present-day decisions.

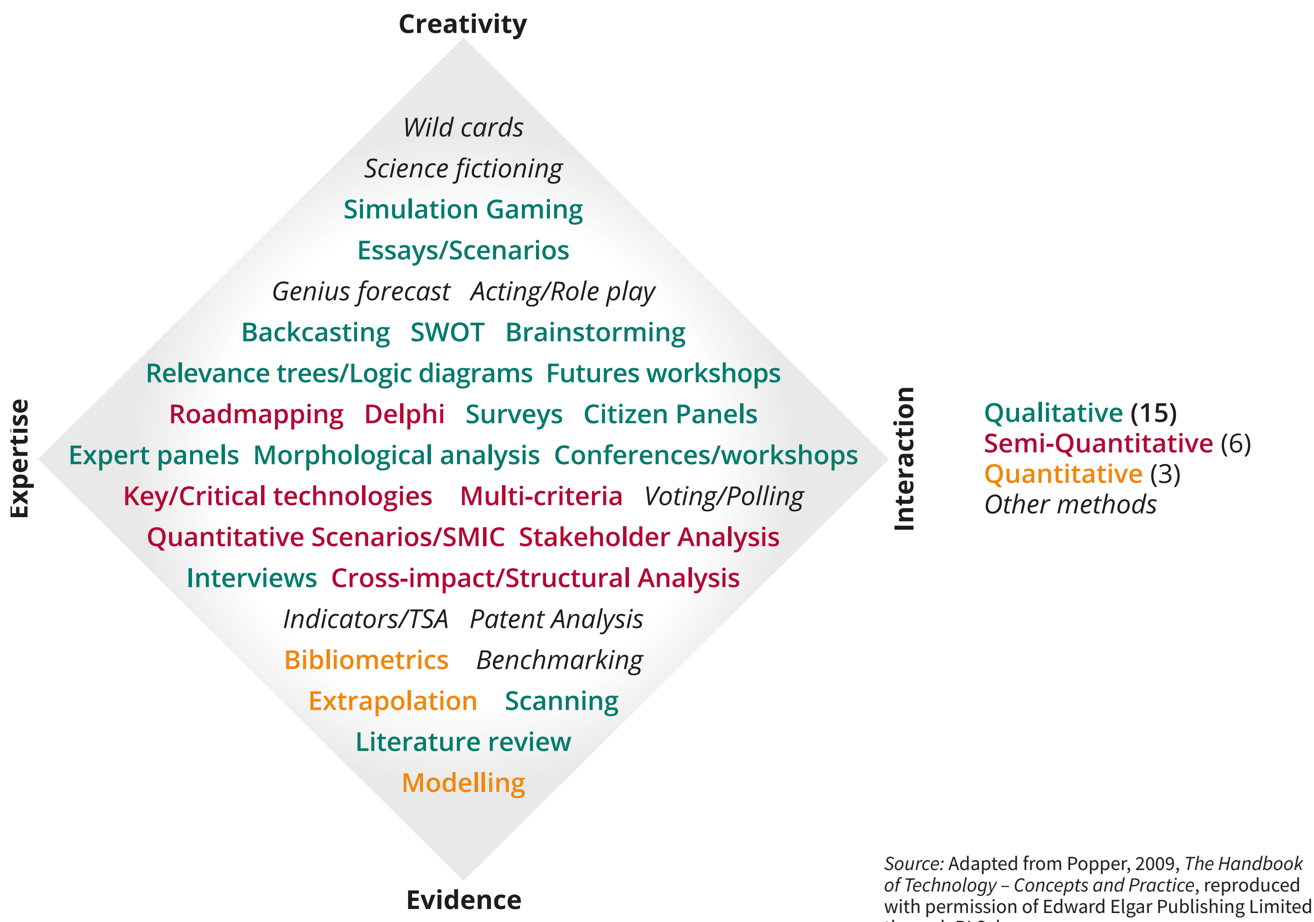
The fundamental thought-process behind the foresight concept involves acknowledging that the roots of multiple plausible future scenarios exist today in the form of weak and early signs that signal potential change. Monitoring these signs through systematic gathering of intelligence increases the likelihood of being prepared for emerging opportunities or challenges. Therefore, foresight recognizes that even though the future remains fundamentally unpredictable, it may be possible to actively influence and shape it, to some extent, to pre-empt undesirable scenarios.

Several factors both inside and outside the agrifood systems can either have a direct or indirect influence on the emergence of potential food safety hazards. Therefore, it is important to identify these issues at an early stage to mount timely intervention and perhaps even prevent their occurrence, i.e. marking a shift from reactionary to anticipatory approaches. Traditional monitoring and surveillance approaches, on the other hand, are only effective in identifying immediate hazards and risks in the food safety landscape; therefore, there is also a need to identify important medium- to long-term issues to facilitate preparedness for effective actions.

It is not only risks or challenges that need our attention from a foresight perspective. Keeping an eye on emerging trends and innovations that can have positive impacts on the food safety arena will ensure that there is ample time to weigh the pros and cons and therefore be better placed to take advantage of them as they materialize in the mainstream.

It is important to differentiate the role of foresight versus early warning systems in food safety. The latter are often geared toward responding rapidly to outbreaks, and sometimes even go as far as predicting when or where outbreaks may occur, based on climatic conditions, and known vector habitat distribution, among other conditions that tend to occur on a seasonal or annual basis (FAO, 2014). Foresight, on the other hand, allows us to ask *what* may be coming in the medium- to long-term time frame, *how* it might affect us and *what* can be done in advance to facilitate prioritization of resources and development of relevant strategies to bring about favourable outcomes in response to future threats or opportunities.

Figure 2. Various foresight methodologies



Source: Adapted from Popper, 2009, *The Handbook of Technology – Concepts and Practice*, reproduced with permission of Edward Elgar Publishing Limited through PLSclear.

What are the various foresight approaches?

Foresight is not a singular technique but a comprehensive set of different approaches that can cover a range of timespans and, depending on the nature of the issue at hand, can draw in participants from a wide range of relevant stakeholder groups, such as the scientific community, governmental and nongovernmental organizations, and private industry (FAO, 2014).

Foresight approaches generally focus on two major thematic outcomes: understanding trends and uncertainties, and guiding (inspiring, driving, informing) decision-making processes towards achievement of desired goals. The commonly used methodologies vary in terms of their qualitative, quantitative or semi-quantitative nature (**Figure 2**) (Popper, 2009):

- Qualitative methods can be used to interpret events and perceptions. Such interpretations tend to be based on subjectivity or creativity (e.g. interviews or brainstorming). These methods include horizon scanning, expert panels, conferences, workshops, surveys and so on.
- Quantitative methods measure variables and apply algorithms by using reliable statistical data (e.g. socioeconomic indicators) and generating quantitative

projections. These methods include benchmarking, modelling, trend extrapolation and so on.

- Semi-quantitative methods can be used to quantify subjectivity, rational judgements and viewpoints of experts and commentators (i.e. weighting opinions or probabilities) by applying mathematical principles. These methods include Delphi analysis, road mapping, stakeholder analysis and others.

Ultimately, the methods used in foresight exercises depend on the particular context and nature of the issue being examined, available resources for execution, as well as the desired outcome. Sometimes it is a combination of methods that is better suited to the particular purpose.

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How does the food safety foresight approach work?

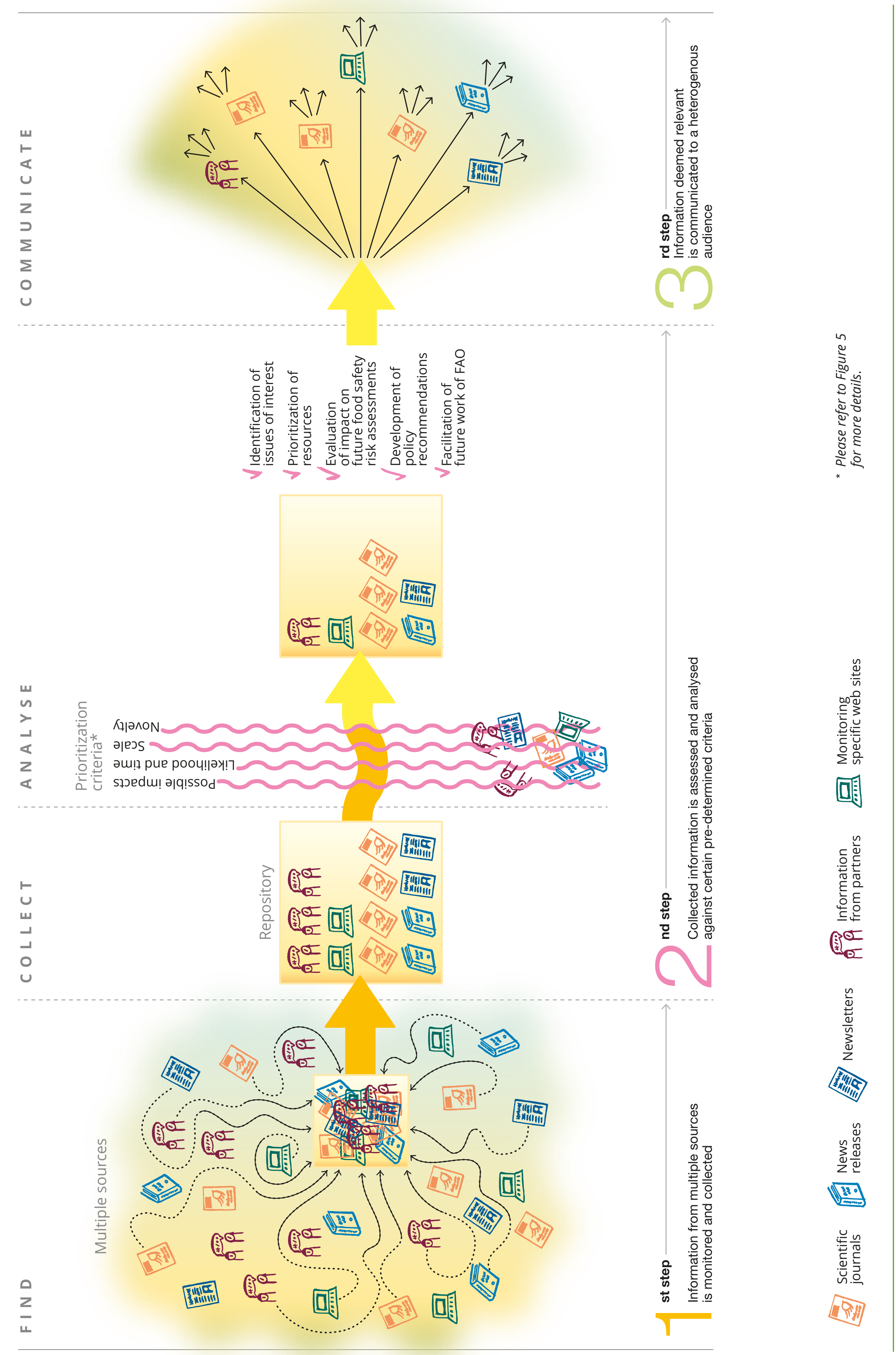
At the technical level of our food safety work, the foresight approach that best suited our purpose and limited resources was based on horizon scanning, defined as "…the systematic examination of potential hazards, opportunities and likely future developments which are at the margins of current thinking and planning" as well as being an approach that "may explore novel and unexpected issues, as well as persistent problems and trends" (DEFRA, 2002).

Our horizon scanning methodology consists of an exploratory approach where information is scanned and assembled from a wide variety of data sources, followed by prioritization, analyses and distribution of the scanned information. In short, our approach consists of *three* major steps (**Figure 3**).

The *first step* involves regular monitoring and identification of relevant issues, changes, trends and developments, from a variety of different sources, such as scientific articles, media reports, published documents from various organizations (both UN and non-UN) of interest, and social media. Horizon scanning allows us to focus on areas of interest that not only fall within the traditional food safety information bubble (emerging contaminants, changes to regulatory frameworks, among others) but also pertain to areas – population dynamics, changing consumer diets, and sustainability and circular economy – that are external to the field and may have varied degrees of influence on the conventional food safety topics, thus developing an "outside-in" way of thinking.

An important source of information is the diverse technical expertise within FAO that spans the spectrum of various areas representative of agrifood systems. In addition, FAO's unique position (**Figure 4**) allows for exclusive avenues to collect and analyse information through engagement with a variety of sources on all aspects of the agrifood systems. These sources include national and regional food safety authorities, private sector stakeholders, and academia. Another key source, and at the same time receiver of information, is the Codex system through its various technical committees as well as the Regional Coordinating Committees. The latter draw attention to the countries' needs and highlight emerging food safety issues arising from their respective regions, as part of their mandate.

Figure 3. Overview of the horizon scanning methodology followed



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An in-house repository served as a convenient collection point for the information gathered from the various sources.

The *second step* consists of assessing and interpreting the information collected using a range of criteria, such as novelty, likelihood and impact (**Figure 5**), through regular discussions within the food safety team. This prioritization of issues is based on several areas that have relevance to FAO's food safety work. The results of the "filtered" information are then further analysed to pinpoint areas of interest that will need to be monitored for future work of food safety in particular, and FAO in general. These discussions eventually led to the streamlining of the scanning process with subsequent emergence of certain trends and drivers, which are discussed below.

The *third step* of the process is about effectively communicating the results from the process so far to a heterogeneous audience that can benefit from the information. Properly disseminated, this information transfer can allow us to collectively adapt to changing environments through the development of well-informed, actionable policies, and even build further collaborations and partnerships. The applications of our foresight approach include:

- informing internal FAO network to plan and facilitate relevant work;
- providing opportunities for collaboration with external partners; and
- communicating to a larger audience through publications and reports.

Figure 4. FAO's intelligence network

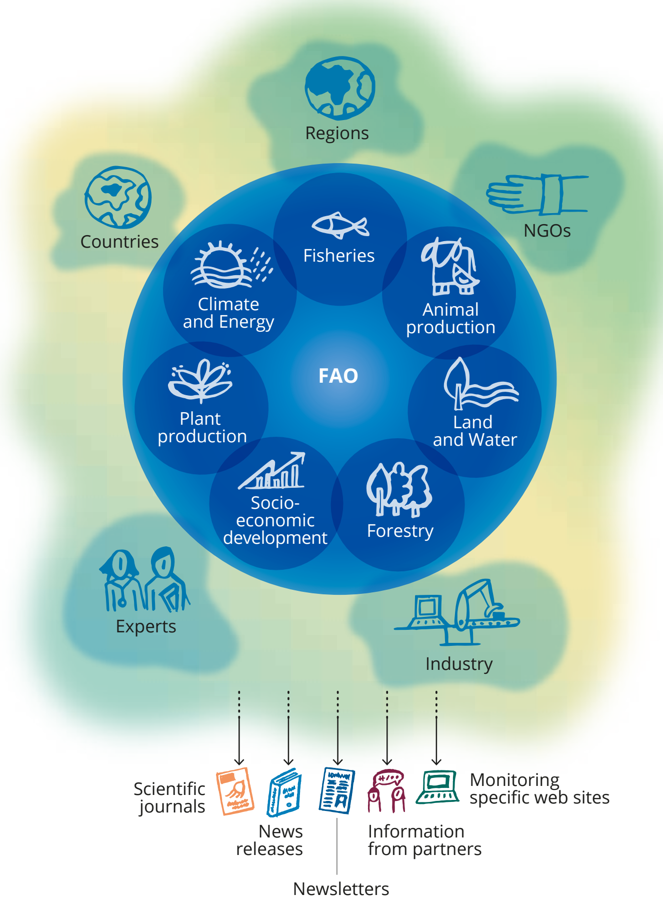


Figure 5. Prioritization of emerging issues

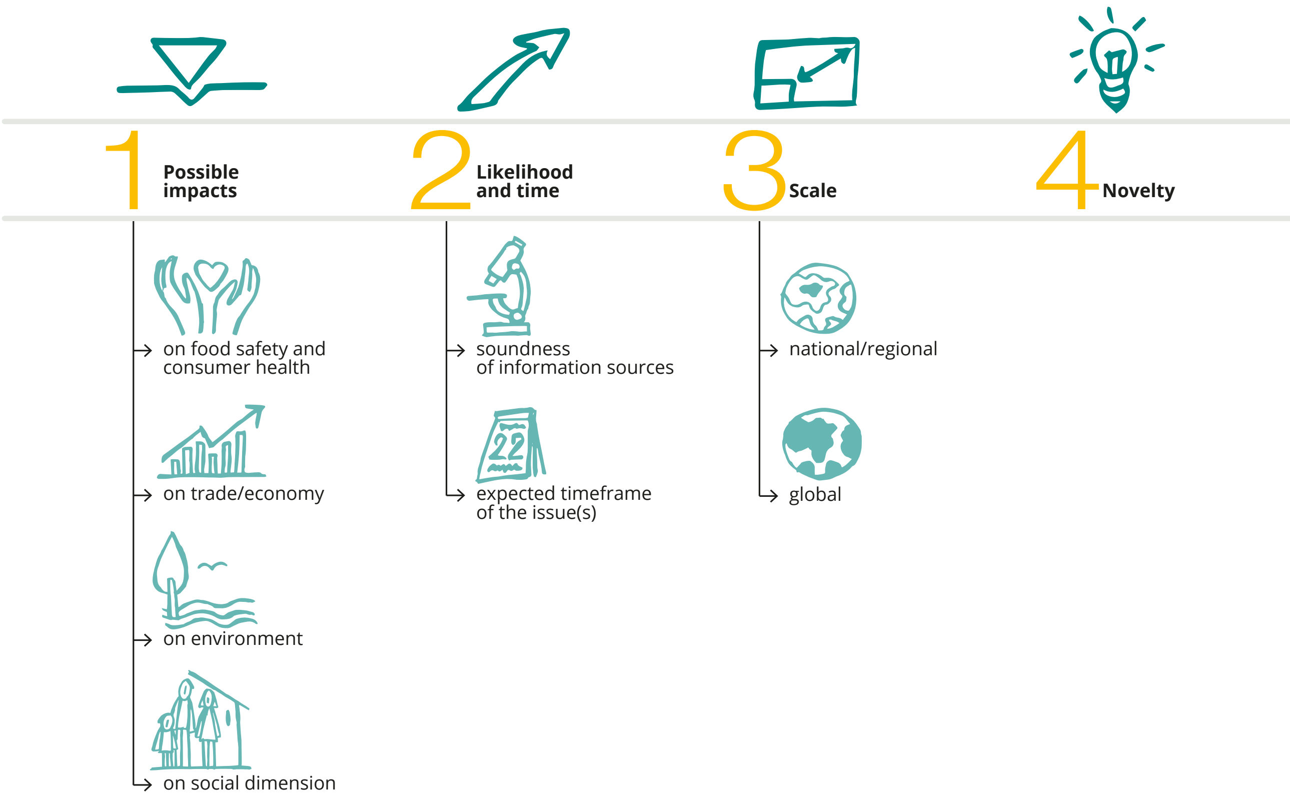


Table 2. The 18 key drivers identified by FAO's Corporate Strategic Foresight Exercise

A.	**Systemic (overarching) drivers**
1.	Population dynamics and urbanization, which are expected to increase and change food demand
2.	Economic growth, structural transformation and macro-economic outlook, which are not always delivering the expected results in terms of inclusive economic transformation of societies
3.	Cross-country interdependencies, which tie together agrifood systems globally
4.	Big data generation, control, use and ownership, which enable real-time innovative technologies and decision-making, also in agriculture
5.	Geopolitical instability and increasing conflicts, which include resource- and energy-based conflicts
6.	Uncertainties, which materialize in sudden occurrences of events in many occasions impossible to predict
B.	**Drivers directly affecting food access and livelihoods**
7.	Rural and urban poverty, with a high proportion of rural people living in poverty or extreme poverty
8.	Inequalities, characterized by high income inequality and inequalities in job opportunities, in gender, access to assets, basic services and inequitable fiscal burden
9.	Food prices, which are in real terms lower than in the 70s but higher than in the 80s and 90s despite the fact that they fail to capture the full social and environmental costs of food
C.	**Drivers directly affecting food and agricultural production and distribution processes**
10.	Innovation and science including more innovative technologies (including biotechnologies and digitalization) and systemic approaches (inter alia agroecology, and conservation and organic agriculture)
11.	Public investment in agrifood systems, which is often insufficient
12.	Capital/ information intensity of production, which is increasing due to mechanization and digitalization of production, including in food and agriculture
13.	Market concentration of food and agriculture input and output, which represents a challenge for the resilience and equitability of agrifood systems
14.	Consumption and nutrition patterns, resulting from behavioural change of consumers, which are increasingly being asked to make complex choices about the nutritional content and safety of what they eat and where shifting consumer demand in the direction of healthier patterns is key
D.	**Drivers regarding environmental systems**
15.	Scarcity and degradation of natural resources, including land, water, biodiversity, soil
16.	Epidemics and degradation of ecosystems, which may increase in the future due to rising trends in transboundary plant pests and diseases, agriculture encroaching in wild areas and forests, antimicrobial resistance, the increasing production and consumption of animal products
17.	Climate change, including weather extremes and variability of temperatures and rainfall patterns, which is already affecting agrifood systems and natural resources and is expected to accelerate hunger and poverty in rural areas
18.	The “Blue Economy”, where the development of economic activities related to the fisheries and aquaculture sector is increasing globally, and arising trade-offs require sound policymaking integrating technical, social and economic solutions, principles of ecosystem restoration of production systems, and cross-sectoral stakeholder involvement in the context of transformative agrifood systems

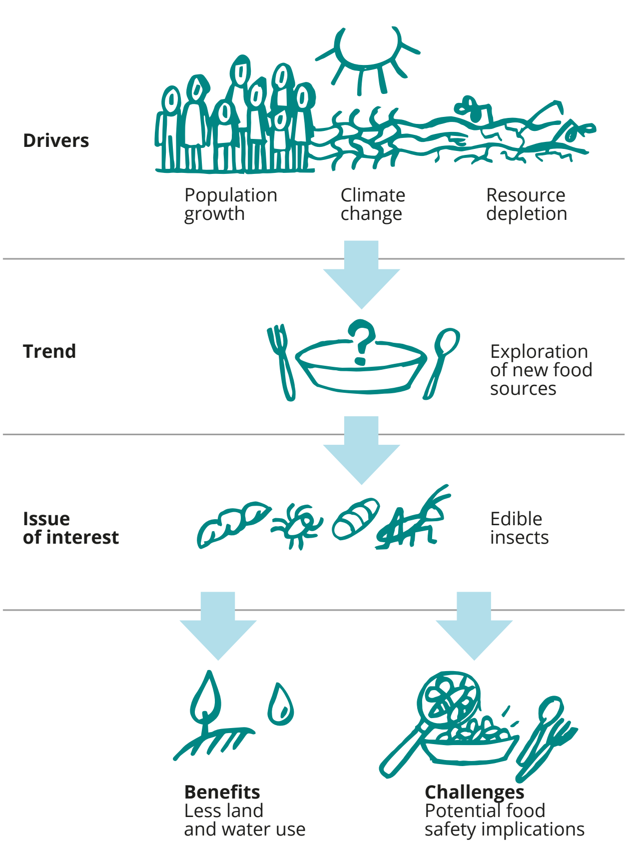
Source: FAO Strategic Framework 2022–31 (FAO, 2021).

Drivers of agrifood systems and related trends

Drivers are macro-level factors that derive from a broad spectrum of areas: societal, environmental, technological, political and economic. Drivers can be slow to form, but once in place cause changes with obvious wide-reaching impacts across a range of sectors, spanning different geographic areas and over varying time frames. The Corporate Strategic Foresight Exercise (CSFE) identified 18 major current and emerging interconnected socioeconomic and environmental drivers, which are shown in **Table 2**. The global agrifood systems both contribute to and are impacted by these drivers.

Identification and evaluation of drivers can be considered the foundational aspect of foresight analysis. In our effort to narrow down the multitude of drivers to those

Figure 6. Exploring the relationship between drivers and trends, as used in this publication, through the example of edible insects



considered most relevant to our area of interest, i.e. food safety, we focused on a few key drivers in this report. They include climate change, resource depletion and scarcity, population dynamics (migration, population growth, aging population), innovations and technological advances, globalization, and changes in consumer behaviour.

Trends are recognizable manifestations of drivers. A single driver can also be referred to as a trend and can be intended as the pattern followed by the driver in an observable past, and by extension in a projected future. Multiple drivers can concurrently cause or affect a trend (**Figure 6**). Similarly, multiple trends can be traced back to a single driver. Analysing trends over a period of time can yield important insights into the future transformations in a particular field. For instance, by evaluating the different benefits and challenges associated with edible insects (**Figure 6**), which is an emerging issue linked to a growing trend of new food sources, the global agrifood systems can be better positioned to sustainably integrate this new food source.[1]

The various opportunities and challenges associated with some of the drivers and related trends under consideration are discussed in the subsequent chapters

[1] Historically, insects have been part of the human diet, but this consumption has been restricted to certain specific regions globally. Currently, there is a growing interest to expand the consumer base for this food source, beyond the reaches of where they have been traditionally consumed. Therefore, for the purpose of this publication, insects have been categorized under "new" food sources to capture their rising popularity.

2. Climate change and food safety impacts


Climate change can lead to frequent flooding of fields and damaged crops, which have food safety implications.

"Change of climate (global temperatures, precipitations, wind patterns and other measures of climate) that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods"

United Nations Framework Convention on Climate Change (UNFCCC), 1992

T**hat human activities** have had a significant influence on climate change is undeniable. This has led to widespread changes in the atmosphere, ocean, biosphere and cryosphere. Some of these changes are not only occurring on an unprecedented scale but are also expected to be irreversible for centuries to millennia, especially in terms of the impacts on the ocean, global sea level rise and melting of the ice sheets (IPCC, 2021). It is suggested that global warming has impacted 80 percent of the world's land area where approximately 85 percent of the global population reside (Callaghan *et al*., 2021).

Based on recent national climate action plans (or nationally determined contributions) submitted by various countries, global warming is expected to exceed by more than 2.7 °C by the end of the century (IPCC, 2021; UNEP, 2021; UNFCCC, 2021). Limiting human-induced global warming requires strong reductions in GHG emissions with the IPCC Sixth Assessment Report (2021) suggesting that meeting the aspirational Paris Agreement goal of limiting global warming to 1.5 °C will be extremely difficult unless far reaching measures to decarbonize the global economy are taken (IPCC, 2021). One of the key developments at the recent Conferences of the Parties (COP26) summit was a historic commitment to curb emissions of methane,[2] the Global Methane Pledge, which was signed by 103 countries (UN Climate Change, 2021a).

At present, with global temperatures 1.2 °C warmer than pre-industrial temperatures, climate change is already exacerbating a series of extreme events – heatwaves, droughts, wildfires, hurricanes and floods – in different parts of the world, causing unparalleled losses to ecosystems, economies and lives.

What are the climate change impacts on food safety?

Extreme events attributed to climate change are becoming more frequent, severe and unpredictable. Such events not only impact food security by adversely affecting agricultural production and yield, and disrupting supply chains, but they also affect food safety. Elevated temperatures, alternation of severe drought periods and heavy rains, soil quality degradation, rising sea levels and ocean acidification, among others, have serious implications for various biological and chemical contaminants in food by altering their virulence, occurrence and distribution. This increases our risk of exposure to foodborne hazards. In addition, rapid globalization of the food supply chains facilitates amplification of foodborne hazards along the way providing opportunities for local foodborne incidents to become international outbreaks.

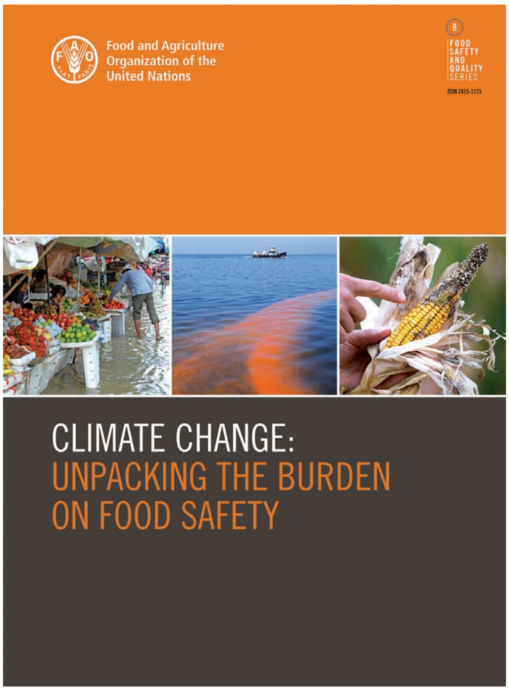
Unsafe food is unfit for consumption. With sufficient, affordable, nutritious and ***safe*** food considered the key components of food security, climate change impacts on food safety will hamper our efforts to achieve food security in the face of a rising global population and an increasing

[2] Methane is considered 80 times more powerful than carbon dioxide at trapping heat in the Earth's atmosphere (Nature, 2021).

demand for food. According to estimates, about 14 percent of food produced is lost during the production stage before it even reaches the retail level or the consumers. Part of this enormous loss is due to various food contamination issues (FAO, 2019) and climate change can exacerbate food loss by providing conditions conducive for the occurrence and dissemination of foodborne hazards.

In 2008, FAO published a pioneering report entitled *Climate change: Implications for food safety,* which provided a broad overview of the various effects of climate change on the food safety landscape. Subsequently, in recognition of the growing body of scientific evidence linking climate change to the various foodborne hazards that can enter the food chain FAO released a publication, *Climate change: Unpacking the burden on food safety* in 2020. By drawing on both publications, the climate impacts on a few select foodborne hazards – foodborne pathogens, algal blooms and mycotoxins – are briefly described below.

Changes in temperatures and precipitation are affecting the geographic distribution and persistence of foodborne pathogens. Higher incidences of infections by several pathogens like *Salmonella* spp. and *Campylobacter* spp. in different parts of the world can be linked to increasing temperatures (Kuhn *et al*., 2020; Lake, 2017). Frequent and severe hurricanes cause recurring flooding of croplands facilitating the distribution of pathogens in the food chain (**Box 2**).



Recent evidence points to a potential association between rising temperatures and increased rates of antimicrobial resistance in human pathogens (*Escherichia coli, Klebsiella pneumonia* and *Staphylococcus aureus*) (MacFadden *et al*., 2018; McGough *et al*., 2020). In a worrying trend, various food- and waterborne pathogens – *Vibrio cholerae*, *Campylobacter* spp., *Listeria monocytogenes*, *Salmonella* spp, *Escherichia coli*, and *Arcobacter* sp. – are increasingly showing resistance to clinically important antibiotics, underscoring the importance of monitoring this issue (Dengo-Baloi *et al.,* 2017; Elmali and Can, 2017; Henderson *et al*., 2017; Olaimat *et al*., 2018; Poirel *et al*., 2018; Van Puyvelde *et al*., 2019; Wang *et al*., 2014; Wang *et al.*, 2019).

The increase in the frequency and duration of harmful algal blooms along coastlines and in lakes globally can be attributed to a combination of eutrophication, intense precipitation, warmer temperatures, and ocean acidification, among other factors. While algae are a natural component of the aquatic ecosystem, algal blooms can block sunlight from other marine plants and animals. When the algae die, the decomposition process can cause "dead" or hypoxic zones that cannot support aquatic life. Certain algal species also produce toxins that can bioaccumulate in fish and shellfish and induce toxic syndromes in humans when consumed. Among others, ciguatera poisoning is caused by ciguatoxins, which are produced by dinoflagellates of the genera *Gambierdiscus* and *Fukuyoa*. Ciguatera poisoning is a major foodborne issue in the Pacific region, affecting the entire aquatic food chain (FAO and WHO, 2020).

Mycotoxins are toxic metabolites produced by various fungi that contaminate staple and cash crops (maize, rice, groundnuts, sorghum and so on). Factors – temperature, relative humidity and crop damage by pests – that influence both the susceptibility of plants to fungal infections as well as the production of mycotoxins, are affected by climate change. With cooler temperate zones becoming warmer and more conducive to agriculture, they are opening up new habitats for agricultural pests and toxic fungal species. For instance, aflatoxins, which were traditionally considered a problem mainly in tropical areas (such as in some parts of Africa), are now quite established in other geographical zones and regions (such as in the Mediterranean) (Chhaya, O'Brien and Cummins,

Box 2.
Shifting water availability impacts global food safety

Water is a crucial resource for all humanity. Alternation of the global water cycle is becoming more apparent as temperatures rise and extreme weather events become more frequent, unpredictable and severe due to climate change (UN Climate Change, 2021b). Certain places that were already wet are now prone to more heavy and uneven rainfall, with the IPCC Sixth Assessment Report predicting extreme rainfall to intensify by 7 percent for each additional 1 °C of global warming (IPCC, 2021). Some regions already water-stressed now experience unprecedented drought conditions, with research suggesting the populations facing acute water shortages may double by the late twenty-first century (Pokhrel *et al.*, 2021; UN Climate Change, 2021b). Moreover, there is a recognizable pattern of consecutive occurrence of extended droughts followed by extreme rainfall in the same area within a short time period, especially in the mid-latitude regions (He and Sheffield, 2020).

Recurrent droughts, excessive rainfall, sea level rise and other climate-change-induced situations that affect fresh water availability all have major impacts on agriculture and can jeopardize global food security as well as the achievement of several Sustainable Development Goals (SDGs) (FAO, IFAD, UNICEF, WFP and WHO, 2021). This challenge is expected to become more pressing as climate change conditions intensify together with rising global populations and concomitant growing demands for food.

In addition to food security, water availability also poses risks for food safety (FAO, 2020). Growing water scarcity is a major issue for the food industry as it creates competition with other sectors that are also water application-intensive. If not adequately prepared for, water scarcity may compromise hygienic conditions in food processing plants by affecting water usage patterns, such as for sanitizing equipment, and impact transmission of foodborne pathogens such as *Listeria monocytogenes* (Chersich *et al.*, 2018). As recycling of wastewater gains more attention amid water shortages, it is important to apply strict monitoring measures to ensure that the water meets the safety requirements for intended reuse applications. During extreme events, such as hurricanes, flooding can contaminate entire water supplies and reduce access to safe drinking water. It can also increase the risk of outbreaks of waterborne diseases like cholera (caused by *Vibrio cholerae*) by overwhelming public infrastructure for hygiene and sanitation. Inundation of agricultural fields may expose crops to pathogenic microorganisms and chemical contaminants such as heavy metals. In addition, toxin-producing mould may develop on crops as a result of exposure to water (FAO, 2020). Excessive rainfall can lead to runoffs which can pick up various chemical hazards and contaminate waterbodies by draining into them. For instance, fertilizers from agricultural fields can get washed into water systems promoting growth of toxic algal bloom

2021). Inadequate postharvest practices for drying, storage and transportation can exacerbate the risk of exposure to mycotoxins, such as aflatoxins and ochratoxin A.

For some of these foodborne hazards, such as mycotoxins and algal toxins, there are rising incidences in areas with no prior history of these foodborne illnesses. This puts the affected areas at a disadvantage as there may be insufficient surveillance systems and management measures put in place to detect and manage the outbreaks, thus putting public health at risk. Moreover, foodborne illnesses are usually underreported, which makes it challenging to estimate the true foodborne disease burden.

What is the way forward?

It is important to ensure that food supply chains and regulatory systems are better prepared to adapt to the growing climate change impacts on food safety. Widespread early warning systems and robust monitoring and surveillance measures are important elements for preventing and controlling foodborne outbreaks, especially in countries more climate-vulnerable than others. The success of these systems ultimately depends on effective information dissemination and transparency in data sharing with all relevant partners. However, the effectiveness of such systems is highly dependent on capacities for collecting and analysing information on climate impacts, and there is currently inadequate research on climate impacts from areas that stand to bear the greater brunt of climate impacts (Callaghan *et al.*, 2021). This “attribution gap” will need to be addressed by increasing the capacity and funding for research in the more climate-vulnerable countries.

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Integrating structured foresight systems would allow a more forward-looking approach to food safety that would complement monitoring and surveillance measures. Foresight approaches would help to identify and address emerging food safety concerns exacerbated by climate change. To bring the future of food to reality, a proactive approach rather than a reactive response to climate impacts will be needed. Along with preparedness, traceability along supply chains, as facilitated by digital innovations, will play an important role in keeping our food safe by tracking and removing contaminated food products before they become a public health issue.

Since climate change impacts on the global food safety is multidisciplinary by nature, this implies a unified response to the growing challenges, and an integrated and cross-sectoral approach is needed. Greater engagement among local, national and global efforts that harness expertise and resources across multiple sectors of environment, agriculture and health, in other words, a One Health approach to food safety issues, will need to be the norm in the face of climate change. Transformation of the agrifood systems will require greater emphasis on the connections across the various disciplines of the food system, which includes food safety, with an existential threat like climate change, as reiterated at the 2021 United Nations Food Systems Summit [3]

3 The United Nations Food Systems Summit took place on 23 September 2021. https://www.un.org/en/food-systems-summit.

3. Changing consumer preferences and food consumption patterns

Consumer preferences are changing and are dictated by a number of different factors.

C**onsumer preferences** are constantly evolving in response to a multitude of different factors. Today considerations such as lowering environmental impacts of food production, climate change, improving health especially amid the pandemic, awareness about food waste, concerns about animal welfare, rising incomes, urbanization, and others (Griffen, 2020; Nunes, Ordanini and Giambastiani, 2021) are driving changes in consumer behaviour and their food preferences.

There is also an increased emphasis for trustworthiness and authenticity from the food industry with consumers expecting greater transparency regarding the carbon footprint of their food products as well as a growing attention to responsible sourcing of food ingredients, simplifying food labelling and addressing concerns about the safety of food (Labelinsight, 2016; Macready *et al.*, 2020; Siegner, 2019; Shelke, 2020). Even though COVID-19 is not a food safety issue, it has significantly heightened the sensitivity of consumers to the concepts of hygiene and food safety (Borsellino, Kaliji and Schimmenti, 2020; Locas *et al.*, 2021), as many fundamental behaviours behind buying, preparing and consuming foods have changed (Clayton, Sims and Webster, 2021). Moreover, surveys report that the pandemic may have also influenced public trust towards the food sector (EIT Food, 2020; Edelman Trust Barometer, 2021).

How are changing consumer preferences impacting the food sector?

Food purchasing habits and consumption patterns of consumers are changing across the world in response to their shifting preferences and lifestyles. While this brief is not meant to provide an exhaustive review of all the trends, some of the more pertinent ones, from a food safety perspective, are discussed. Increased concerns about healthier diet choices and environmental sustainability are driving a growing interest in plant-based foods, a sector that is rapidly expanding to include plant-based alternatives for meat, dairy products, eggs and seafood (**Chapter 4.3**). Other alternative food sources are also gaining attention, such as seaweeds or macroalgae (**Chapter 4.4**), and edible insects (**Chapter 4.1**). Rapid urbanization together with demand for local and sustainable food production has also led to the development and expansion of urban agriculture (**Chapter 5**).

Along with consumer demands for healthy living, increased expectation for personalization as well as the rapid integration of technological innovations are contributing to the growth of the customized nutrition sector. An area in the spotlight is nutrigenomics,[4] with various companies attempting to leverage individual genomic data into developing tailor-made diet plans. Genetic information can help guide diet choices; for instance, people with *LCT* genetic mutation should avoid

[4] Genetic information about individual's health risk profiles is used to guide nutrition recommendations and vice versa.

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Meal kits are gaining popularity as a convenient way to cook food at home.

dairy as they have trouble digesting lactose. However, published research on personalized diets formulated solely based on genetic information, as made available through various direct-to-consumer programs, show that this approach may distract consumers from other considerations behind chronic health issues (obesity, cancer, diabetes), such as environmental risk factors and lifestyle (Camp and Trujillo, 2014; Dendup *et al.*, 2018; Gardner *et al.*, 2018; Lindsey, 2005; Magkos *et al.*, 2020).

Additionally, greater emphasis on healthier living and rising health care costs are contributing to the growth of functional foods or nutraceuticals sector (Hasler, 2002; Mohanty and Singhal, 2018; Uthpala *et al.*, 2020). While there is ambiguity regarding the definition of functional foods, it is generally agreed that they encompass foods or food components that, consumers believe, may impart additional health benefits, such as assisting in preventing diseases, which goes beyond "basic" nutrition that maintains overall health (Berhaupt-Glickstein and Hallman, 2015; Clydesdale, 2004; Hasler, 2002; Marcum, 2020). Examples of such foods include enriched or fortified foods, dietary supplements and even conventional foods with known bioactive compounds. While the perceived healthfulness and quality of such foods is driving market growth, the claims of the health benefits of functional foods can often be hard to substantiate due to insufficient rigorous scientific evaluations (Aggett, 2012; Scrinis, 2008). This complicates the development of strong regulatory oversight for this food sector, which is necessary as functional foods are often designed to be consumed by people of all ages, sometimes over extended periods of time.

What are the food safety implications to be considered?

With dietary patterns shifting to those that are rich in plant-based foods, caution should be taken to prevent inadvertent introduction of allergens into diets, for instance, by replacing cow's milk with almond milk. This can be particularly challenging for certain age groups, infants and children, who need to consume a variety of foods to achieve the intake of sufficient amounts of nutrients required for optimum growth and development (Protudjer and Mikkelsen, 2020).

Other common components of plant-based alternatives that can cause allergic reactions are legumes (soy, peanut, lupine, chickpea etc.), and cereals (wheat, rye, barley etc.). Individuals allergic to peas can also be sensitive to peanuts due to cross-reactivity among homologous proteins within the legume family, such as the vicilin homologues present in both pea and peanuts (Taylor *et al.*, 2021; Wensing *et al.*, 2003). While peanuts are known allergens, products containing peas can be found marketed as hypoallergenic, with pea protein concentrates and pea protein isolates often added to various foods as a plant-based high-protein source. This can be worrisome for those individuals who simultaneously suffer from significant peanut allergy and also from cross reactivity to pea allergens. The various potential food safety risks associated with plant-based alternatives are explored in detail in **Chapter 4.3**.

The popularity of Goji berries (*Lycium barbarum*) as functional food (both raw and dried forms) is on the rise in North American and European countries, propelled by various potential health-promoting benefits. Goji berries have been historically consumed in Asia (Ma *et al.*, 2019; Potterat, 2010; Ye and Jiang, 2020). Allergic reactions to Goji berries have been reported in literature, with lipid transfer protein (LTP), a panallergen, described as being responsible for cross reactivity as well as sensitization to Goji berries (Carnés *et al.*, 2013; Larramendi *et al.*, 2012; Salcedo *et al.*, 2004; Uasuf *et al.*, 2020).

With legalization of *Cannabis sativa* increasing in some regions of the world, there is greater commercial availability of food made from *C. sativa* or hemp (Bakowska-Barczak, de Larminat and Kolodziejczyk, 2020). There is evidence of contamination by toxigenic fungi (*Aspergillus* sp. and *Penicillium* sp.), pathogenic bacteria (*Salmonella* sp., *Escherichia coli*), as well as chemical hazards (heavy metals and pesticides) in *Cannabis* raising concerns about the safety of products meant for consumption (Montoya *et al.*, 2020).

Turmeric is a widely used spice, that is also increasingly being consumed as a supplement as it can be associated with anti-oxidant, anti-inflammatory, and even hepato- and nephro-protective properties (Shome *et al.*, 2016). However, highly bioavailable forms of curcumin, active compound in turmeric, have been linked to several cases of hepatotoxicity (Lombardi *et al.*, 2020; Luber *et al.*, 2019). Different methods can be used to increase the absorption of curcumin, such as by addition of piperine (black pepper) or using a nanoparticle-based delivery system (Donelli, Antonelli and Firenzuolo, 219; Lombardi *et al.*, 2020; Luber *et al.*, 2019; Shome *et al.*, 2016). In addition, adulterants added to turmeric can also result in exposure to heavy metals such as lead and chromium (Forsyth *et al.*, 2019a; Forsyth *et al.*, 2019b).

Demand for vitamin C (or ascorbic acid) supplements have risen dramatically, recently as a reaction to the pandemic (Grebow, 2021). This is due to claims that do not currently hold merit, such as associating prolonged, high vitamin C doses to detoxification of the body, charging of the immune system, cold and flu prevention, among others (Cerullo *et al.*, 2020). High intake of vitamin C, in excess of daily dietary reference values, has been associated with increased risk of developing kidney stones, mainly in men (Ferraro *et al.*, 2016; Thomas *et al.*, 2013).

More consumers are turning to purchasing their food through online portals that link them to restaurants, grocery stores or other retail establishments, with the pandemic cited as one of the major factors influencing this behaviour (Rodriques *et al.*, 2021). The high volume of online orders not only adds pressure on the e-order fulfilment infrastructure but also requires renewed adherence to food safety best practices. There is a rising popularity of mail-order food and meal-kits where different components of a dish – fresh produce, condiments, animal products, and cereals and grains – are packed in separate plastic packaging and shipped together in a box to the consumer who then prepares the meal according to instructions, which are also included in the box. A study that looked into the integrity of such home-delivered meal kits found a number of issues that raise food safety concerns, for instance insufficient cold-packaging, packages left outside for eight hours or more, crushed packages allowing cross-contamination issues between meat and ready-to-eat produce, among others. The authors also found insufficient and often inaccurate food safety information displayed on purveyors' websites suggesting that consumers may have difficulties having access to relevant food safety information (Hallman, Senger-Mersich and Godwin, 2015). The addition of third-party delivery-services may further complicate such home-delivery systems as traditional shipping companies may not have an adequate cold-chain system in place, which can exacerbate food safety risks in case of missed or late deliveries. Prioritizing temperature considerations for storage, staging and delivery, using tamper-proof packaging, maintaining safe handling practices and taking steps to reduce

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cross-contamination, providing proper cooking directions in the packaging as well as leveraging technology to implement good traceability systems are key to ensuring food safety in this era of ecommerce.

Another interesting issue connected to the online purchase of food relates to the responsibility of intermediate platforms and their role in the food chain. Countries have adopted different regulatory solutions that go from recognizing a special role and responsibilities to considering platforms as another actor in the food chain.

What is the way forward?

Various considerations from environmental sustainability to health concerns, socioeconomic factors, and others are influencing consumer behaviours. Shifting consumer preferences and consumption patterns can trigger changes in dietary risks, not just from a nutritional point of view, but also from potential contaminants and additives. Since food safety risk assessments quantify risks based on hazards and the amount of exposure, such evaluation processes will need to keep up with changes in consumption patterns to stay relevant and protect consumers.

The Internet has revolutionized how consumers can search for and share information, and form opinions about a variety of areas that influence their lives, thereby shaping consumers' perceptions and preferences. Consumers' food safety awareness is affected by the availability and accessibility to food safety information, through a number of different sources of information including social media and other online sources, television, radio and so on (Rutsaert *et al.*, 2013; Liu and Ma, 2016; Zhang *et al.*, 2019).

Online sources can be important tools to engage and educate consumers on food safety and good practices, for instance, to understand how to properly read labels, to find facts on food processing, and to reduce foodborne illness risks and so on. However, the online space can also expose consumers to a lot of inaccurate or "fake" information and facilitate confirmation bias. This coupled with rising inequalities and a waning trust in decision-making bodies can fuel panic and cause unnecessary food waste, loss of revenue for food businesses as well as further undermine consumer trust in food supply. A lack of correct information can also generate an information vacuum allowing misinformation to proliferate. With both correct and incorrect information merely a click away from each other, consumers may find it difficult to parse out what is authentic. However, monitoring and countering misinformation in the public sphere is not straightforward as susceptibility to misinformation varies widely (Baptista and Gradim, 2020; Pennycook and Rand, 2020). It requires broad resources, timely engagement and effective communication strategies – promoting media literacy early, providing evidence-based knowledge appropriately, guiding viewers towards trusted sources, among others – from relevant agencies, private technology companies and non-profit organizations on both traditional and social media platforms.

Technological innovations will continue to provide tremendous utility in keeping pace with changes in the food sector driven by shifts in consumer preferences and demands, for instance, by identifying emerging allergens and contaminants in new food sources, establishing appropriate standards and creating adequate risk management methods. This is especially true for emerging sectors like functional foods or neutraceuticals where there is lack of knowledge about their risks and benefits which hampers harmonizing regulatory frameworks to guide the safe application of such foods (Thakkar *et al.*, 2020)

4. New food sources and food production systems

Harvesting wheat.
Agriculture is increasingly putting pressure on our finite natural resources.

T

he global population is expected to reach 9.7 billion in 2050 with growth rates expected to vary across different regions (UN, 2019). To meet the increasing demand for food, the overall food production will need to be raised by about 70 percent above 2009 levels, by 2050 (FAO, 2009). However, gains made in food production so far have come at an enormous cost to the environment. Studies show that agriculture can contribute to climate change, and have considerable impact on the health of soils, forests and ecosystems (Poore and Nemecek, 2018; Ritchie and Roser, 2021). It is estimated that 34 percent (or 18 Gt CO_2 equivalent per year) of the total greenhouse gas (GHG) emissions in 2015 came from our food systems (Crippa *et al.*, 2021). Agriculture is also increasingly putting pressure on our finite natural resources with nearly half of all cultivated land on the planet and 70 percent of freshwater worldwide used by agriculture (FAO, 2017; FAO, 2020; Ritchie, 2019). On the other hand, climate change is already affecting our ability to maintain food production by reducing crop yields and nutritional content of major cereals (Beach *et al.*, 2019; MacDiarmid and Whybrow, 2019; Sultan, Defrance and Lizumi, 2019; Zhao *et al.,* 2017). Agnolucci *et al.* (2020) found that increasing temperatures will have more disproportionate impacts on countries that are already facing food insecurities.

Increasing awareness of these impacts is propelling efforts to find (or innovate) and bring to mainstream new food sources and food production systems that are more sustainable than those available conventionally.

Box 3. Discussions of new food sources and new production systems at the Codex level

The topic of new food sources and food production systems has garnered significant interest at the Codex level, with recent discussions at the Executive Committee of the Codex Alimentarius Commission (CCEXEC81) and the Codex Alimentarius Commission (CAC44).[1,2] Considering the cross-cutting nature of these issues, it was agreed to set up a sub-committee of CCEXEC to consider potential mechanisms that will begin to address this emerging topic

1 *Report of the Eighty-First Session of the Executive Committee of the Codex Alimentarius Commission*. Joint FAO/WHO Food Standards Programme, Codex Alimentarius Commission, Forty-fourth session.

2 *New food sources and production systems: Need for Codex attention and guidance?*, Joint FAO/WHO Food Standards Programme, Codex Alimentarius Programme, Forty-fourth session.

Dietary shifts to those that incorporate sustainable choices while reducing consumption of animal-based foods have been promoted as potential means of mitigating environmental and animal welfare concerns as well as alleviating some public health issues. New food sources imply those that have not been widely consumed, either because their consumption have been historically restricted to certain regions in the world or they have recently emerged in the global retail space thanks to technological innovations. They are also considered new within the framework of existing Codex standards (**Box 3**). New food production systems reflect novel innovations or advancements in preexisting food technologies that are involved in producing some of the new foods that are finding their way into the mainstream.

Some of the new food sources highlighted in the subsequent sections are edible insects, jellyfish, plant-based alternatives, and seaweeds (or macroalgae). Cell-based food production as a new food production system is also discussed

4.1. Edible insects

Insects have been part of the human diet, in different regions of the world, for centuries (Meyer-Rochow, 1975), as insect-eating habits are not only connected to nutrition, but also stem from various socio-cultural practices and religious beliefs (FAO, 2013). Edible insects are classified under "new food sources" in this publication. This is because while they have been consumed in specific regions globally, there is currently a rising interest in incorporating insect-based products into the wider consumer base, including the Western countries where insect consumption is not popular.

Nutritionally, edible insects can be a good source of protein, dietary fibre, beneficial fatty acids, and micronutrients like iron, zinc, manganese and magnesium. However, the nutritional profiles of insects tend to be species dependent (Oibiokpa *et al.*, 2018; Rumpold and Schlüter, 2013). Selling edible insects that are either farmed or collected from the wild can offer economic opportunities to rural communities through livelihood diversification (Doberman, Swift and Field, 2017; FAO, 2013; Imathiu, 2020). While most edible insects are harvested from the wild (Jongema, 2017), large-scale insect farming, for both human food and animal feed, is on the rise due to the ease of cultivation of insects and growing concerns about the environmental impacts of livestock production. While life cycle assessments are available for limited few insect species, insect farming is generally associated with less land and water use, and lower levels of greenhouse gas emissions as opposed to conventional livestock farming, making it attractive from an environmental sustainability standpoint (Doberman, Swift and Field, 2017; Miglietta *et al.*, 2015; Oonincx and de Boer, 2012; Oonincx *et al.*, 2010; van Huis and Oonincx, 2017). Some of the insect species of commercial importance include black soldier flies, yellow mealworms, lesser mealworms, crickets, grasshoppers and house flies.

What are the food safety implications to be considered?

The benefits this developing sector may bring must be weighed against potential challenges, one of which is determining possible food safety aspects that may impact the health of consumers. As with other foods, edible insects can be associated with certain food safety hazards, and a thorough assessment of food safety hazards will help to establish appropriate standards for the sector. Some of the key food safety implications for the production and consumption of edible insects have been covered in detail in a recent FAO publication entitled *Looking at edible insects from a food safety perspective. Challenges and opportunities for the sector* (2021).

In general, food safety risks associated with edible insects depend on the insect species, substrates (or feed) for insects used, how they are raised, harvested, processed, stored and transported (EFSA Scientific Committee, 2015; EFSA NDA Panel, 2021). Insects gathered from the wild and consumed raw may carry higher food safety risks than those that are raised and processed under controlled hygienic conditions (Garofalo *et al.*, 2019; Grabowski and Klein, 2017; Stoops *et al.*, 2016). The microbiota of insects

can harbour foodborne pathogens, for instance spore-forming bacteria like *Bacillus cereus* sensu stricto (s.s.) and others like *Salmonella* sp. and *Campylobacter* sp. (Belluco *et al.*, 2013; Osimani *et al.*, 2017; Vandeweyer, Lievens and van Campenhout, 2020; Wales *et al.*, 2010). More studies on the microbial species that typically make up the microbiota of commercially important insects are needed as insects are often consumed in their entirety. Improper handling and unhygienic storage of edible insects can also lead to contamination issues after processing methods (e.g. blanching, drying or frying) have been used to eliminate foodborne pathogens.

Certain alternatives to conventional substrates are being explored, for instance, food waste, agricultural by-products and even manure from livestock farms, to not only promote a circular economy but also to reduce economic costs associated with insect farming. However, the quality and safety of substrates need to be carefully monitored for any contaminants (biological and chemical) that they may contain as the nutrient content and safety of the produced insects depend on the substrates used for rearing (EFSA Scientific Committee, 2015). Pesticides used on agricultural products and antimicrobial residues in manure may also be found in insects if they are raised on such substrates (Houbraken *et al.*, 2016). The accumulation of heavy metals (cadmium, lead, arsenic, etc.) in edible insects depend on various factors such as environmental contamination, insect species, metal type, as well as the substrates used (Charlton *et al.*, 2015; EFSA Scientific Committee, 2015; Greenfield, Akala and van Der Bank, 2014; van der Fels-Klerx *et al.*, 2016; Vijver *et al.*, 2003; Zhang *et al.*, 2009). Some of the other potential chemical hazards that can be found associated with various edible insects are flame retardants, dioxins, heterocyclic aromatic amines, among others. More details on such contaminants can be found in the FAO (2021) publication.

Determination of allergenic potential of edible insects and the effect of processing on the allergenicity need further research. Individuals allergic to crustaceans (shrimp, prawn etc.) may be more vulnerable to allergic reactions to insects and insect-based foods (Broekman *et al.*, 2017a; Reese, Ayuso and Lehrer, 1999; Srinroch *et al.*, 2015). Cross-reactive allergies can be caused by certain pan-allergens, like arginine kinase and tropomyosin, that are common in arthropods[5] (Belluco *et al.*, 2013; Leni *et al.*, 2020; Phiriyangkul *et al.*, 2015; Ribeiro *et al.*, 2018; Srinroch *et al.*, 2015). In addition, *de novo* sensitization to yet unknown allergens from insects may occur and therefore require further research (Broekman *et al.*, 2017b; Westerhout *et al.*, 2019).

What is the way forward?

Interest in alternative sources of food (and feed) is rising in response to growing awareness of the environmental impacts of food production, which will need to be ramped up in the face of increasing global population. This is propelling development of the edible insects sector, with mass production of various insect species underway in different regions.

Edible insects may have the potential to provide a number of benefits, namely nutritional, environmental and socioeconomic. However, to successfully integrate edible insects into our food systems, the food safety perspective of this food source will need careful considerations, some of which have been described in the FAO (2021) publication. Characterization of the food safety hazards will enable creating insect species-specific hygienic practices for rearing, processing, and distribution. It will also pave the way for developing international standards and regulatory frameworks , which is also one of the major barriers in the way of establishing markets for insects and insect-based products (FAO, 2021)

5 Insects and crustaceans belong to the arthropod family.

4.2. Jellyfish

Jellyfish are marine invertebrates that are abundant in both cold and warm ocean waters, along coastlines and in deeper waters. They belong to the phylum Cnidaria and are different from the cephalopods (squids, octopuses, cuttlefish), but closely related to corals and sea anemones (Boero, 2013).

Jellyfish aggregations are a natural feature of a healthy marine ecosystem (Griffin *et al*., 2019; Hays, Doyle and Houghton, 2018) with periodic fluctuations in their occurrence and abundance (Condon *et al.,* 2013). While there is lack of data to show if the global jellyfish population is rising (Condon *et al.*, 2013; Mills, 2001; Sanz-Martín *et al.*, 2016), there is a general agreement that over the last few decades certain regions have observed a significant increase in the number and duration of jellyfish blooms[6] (Boero, 2013; Brotz *et al.*, 2012; Dong, Liu and Keesing, 2010). Around the world some of these blooms have been appearing beyond their traditional habitats.

Conditions brought by climate change – warming seas, ocean acidification – as well others such as increase in plankton numbers and oxygen depletion from eutrophication events can be conducive to these population increases and geographic expansions (Boero, 2013; Mills, 2001; Purcell, Uye and Lo, 2007). Overfishing removes top predators (red tuna, swordfish, sea turtles) and competitors allowing certain jellyfish populations to thrive (Boero, 2013; Purcell, Uye and Lo, 2007). Other factors that can potentially be linked to jellyfish blooms include introduction of non-native species of jellyfish by ships or ocean currents, and proliferation of man-made coastal structures (sea walls, oil rigs, docks, offshore windfarms and so on) which act as shaded habitats for jellyfish polyps[7] (Boero, 2013; Purcell, Uye and Lo, 2007; Vodopivec, Peliz and Malej, 2017).

All over the world jellyfish blooms have been disastrous for the fishing and aquaculture industries by clogging nets and destroying fish farms (Bosch-Belmar *et al.*, 2021; Dickie, 2018; Siggins, 2013; Tucker, 2010). They have forced temporary closures of power plants in Sweden and Israel (Kiger, 2013; Rinat, 2019) and a desalination plant in Oman (Vaidya, 2003) by blocking pipes that bring in seawater. Jellyfish blooms have also impacted coastal economies and public health by swarming popular tourist destinations (Tucker, 2010).

What is driving the recent interest in jellyfish consumption?

Flourishing jellyfish blooms create a vicious cycle where the jellyfish prey on fish eggs and larvae as well as compete for the same food source as the fish stock that are already affected by overfishing (Boero, 2013). Attempts to capture and remove jellyfish blooms, together with moving towards diversifying sustainable fishing to feed a growing global population may necessitate creating commercial markets for jellyfish across various global regions (EC, 2019; Petter, 2017; UN Nutrition; 2021; Youssef, Keller and Spence, 2019).

While eating jellyfish may strike many as unconventional, jellyfish have in fact been consumed in some places of Asia as part of the traditional cuisine for generations and are

6 A jellyfish "bloom" results from a substantial population increase within a short time frame.

7 Sessile life stage of jellyfish.

valued for their health benefits (Brotz, 2016). The edible species tend to be low in carbohydrates and lipids, high in protein (mainly represented by collagen) content and several minerals (De Domenico *et al*., 2019; Khong *et al*., 2016; Leone *et al*., 2015).

While some jellyfish species can be toxic to humans, there are others that are safe to consume (Brotz, 2016). Jellyfish fisheries can be found in a number of Asian countries such as Japan, Malaysia, Republic of Korea, and Thailand, with export industries also found in Australia, Argentina, Namibia, Bahrain, Nicaragua, Mexico and the United States of America, among others (Brotz, 2016; Brotz *et al*., 2017). Though the total marine capture of *Rhopilema* spp. and *Stomolophus meleagris* (cannonball jellyfish) was estimated at approximately 300 000 tons in 2018 (FAO, 2020), there is no reliable data on comprehensive catch statistics for jellyfish.

What are the food safety implications to be considered?

Like other foods, jellyfish are also associated with some food safety hazards which must be taken into consideration to drive further development in this sector.

Microbiological hazards

Fresh jellyfish tend to spoil readily at ambient temperatures and therefore they tend to be processed relatively quickly after capture. This reduces risks associated with microbiological contamination. According to studies, no foodborne pathogens have been found to be associated with jellyfish (Bonaccorsi *et al*., 2020; Raposo *et al*., 2018). However, research on the diversity of bacterial community associated with jellyfish show the presence of potentially pathogenic bacterial genera – *Vibrio*, *Mycoplasma*, *Burkholderia* and *Acinetobacter*, among others (Kramar *et al.,* 2019; Peng *et al*., 2021). This denotes that jellyfish can serve as vectors of pathogenic bacteria implicated in affecting human health as well as the health of marine animals (Basso *et al*., 2019). In addition, Bleve *et al*. (2019) reported low level of *Staphylococci* in jellyfish and attributed that to the microbial content found in the specific marine environment where the jellyfish were collected.

Chemical hazards

Heavy metals: Bioaccumulation of pollutants from the marine environment is an issue of food safety concern in jellyfish. Epstein, Templeman and Kingsford (2016) studied the rate of uptake and retention of trace metals in *Cassiopea maremetens* and found that metal accumulation in jellyfish began within 24 hours of exposure to treated water. High concentrations of copper were observed, reaching more than 18 percent above ambient concentrations (Epstein, Templeman and Kingsford, 2016). Another study conducted by Muñoz-Vera, Castejón and García (2016) assessed the possibility of bioaccumulation of various trace and heavy metals (aluminium, titanium, chromium, manganese, iron, nickel, copper, zinc, arsenic, cadmium and lead) by *Rhizostoma pulmo*, in the Mediterranean coastal lagoon from southeast Spain. The bioconcentration of these elements in the jellyfish, in relation to seawater metal concentration, was high, especially arsenic (Muñoz-Vera, Castejón and García, 2016). This risk underscores the importance of carrying out constant monitoring of the water where jellyfish are captured or bred.

Algal toxins: A solitary case of suspected ciguatera poisoning after ingestion of imported jellyfish has been reported in published literature (Zlotnick *et al*., 1995). Further investigations (Cuypers *et al*., 2006; Cuypers *et al*., 2007) will be needed to explore this potential risk. No other reports of intoxication, from marine toxins, upon consumption of edible jellyfish was found in literature.

Allergenic potential: Research shows that people with history of allergic reactions to crustaceans, cephalopods and/or fish can safely eat jellyfish without any adverse reactions (Amaral *et al*., 2018; Raposo *et al*., 2018). Most allergic reactions to jellyfish consumption have been recorded in people who have been previously stung by the invertebrate (Imamura *et al.,* 2013; Li *et al*., 2017). However, there are a few instances of anaphylaxis post jellyfish-ingestion recorded in individuals with no history of being stung by jellyfish (Okubo *et al*., 2015). The allergens in jellyfish that cause these allergic reactions upon consumption are yet to be identified.

Other chemical hazards from the post-harvest stage: A traditional way of processing jellyfish employs a brining solution containing alum.[8] This process dehydrates the jellyfish and decreases the pH, and can extend the shelf-life if the jellyfish is kept at a suitable temperature post processing (Hsieh, Leong and Rudloe, 2001; Lin *et al*., 2016). There are concerns regarding the amount of aluminium retained in

[8] Alum refers to salts of aluminium, such as aluminium potassium sulphate.


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A jellyfish bloom.

jellyfish products as a result of using alum (FAO and WHO, 2012; Lin *et al*., 2016). A study looking at dietary exposure to aluminium in China, Hong Kong SAR observed high levels of aluminium in ready-to-eat jellyfish and jellyfish-based products (Wong *et al.,* 2010). Although maximum levels (MLs) have not been established at the level of the Codex Alimentarius, some Asian countries have set MLs for aluminium (100 mg/kg in dry weight), specifically for jellyfish. In addition, the Joint FAO/WHO Committee on Food Additives (JECFA) have determined a provisional tolerable weekly intake (PTWI) of 2 mg/kg body weight for aluminium, with estimates of dietary exposure to aluminium (not including jellyfish, in most countries) known to potentially exceed the PTWI (FAO and WHO, 2011).

High levels of dietary aluminium have been suggested to play a role in developmental problems in infants and young children as well as liver damage, reproductive toxicity, inflammatory bowel disease (IBD), and potential risk for developing Alzheimer's disease in adults (de Chambrun *et al.,* 2014; FAO and WHO, 2006; FAO and WHO, 2011; Lin *et al*., 2016; Tomljenovic, 2011; Yokel, 2020).

Physical hazards

Jellyfish, like other marine organisms, have been reported to ingest plastics (macro, micro and nano) from their environment, facilitating their transfer up the trophic level and potentially posing as physical hazards (Costa *et al*., 2020; Iliff *et al*., 2020, Macali and Bergami, 2020; Macali *et al*., 2018; Sun *et al.,* 2017). While the implications of microplastics on human health is still not well understood (**Chapter 6**), any potential risk of human exposure to microplastics through jellyfish consumption will need to be explored through further studies.

What is the way forward?

Consumption of edible jellyfish is not prevalent in Western countries due to the lack of market demand for jellyfish products as well as the absence of adequate processing methods and lack of national safety and quality standards. Research on alternative processing techniques to eliminate alum, for instance, by using high-temperature treatment, can open up potential markets (Leone *et al*., 2019). In addition, thorough assessment of food safety hazards associated with jellyfish harvesting, processing and consumption will help to establish appropriate hygiene and manufacturing practices as well as develop relevant regulatory frameworks for the sector.

While it may be tempting to exploit this marine resource as food, it is important to note that jellyfish populations can be extremely variable in their abundance from year to year, which can make investments in infrastructure to create new fisheries quite challenging. Few jellyfish species are edible, and therefore not all blooms can be managed by fishing them. In addition, only a small subset of jellyfish species form blooms. Focusing on a few species may not be environmentally sustainable as it increases the chances of overfishing them unless proper management strategies are put in place. For instance, commercially important *Rhopilema esculentum* is subjected to stock enhancement in China where juvenile jellyfish are reared and released in Liaodong Bay of Bohai Sea (Dong *et al*., 2009; Dong *et al*., 2014). This is in response to natural fluctuations in their population as well as overfishing. Furthermore, it is essential to promote jellyfish research (Gibbons and Richardson, 2013) by an ecosystem-based approach to advance knowledge and predictive modelling of jellyfish blooms as well as to implement strategic monitoring and management plans to develop this resource as a sustainable food source

4.3. Plant-based alternatives

Currently, there is an uptick in adoption of plant-based diets, as correlated by the rising trends of vegetarianism, veganism and flexitarianism.[9] A variety of reasons – health, environmental concerns, animal welfare issues and religious beliefs – are mentioned in connection with the adoption and practice of plant-based diets (Cramer *et al*., 2017; Sabaté and Soret, 2014; Willett *et al.,* 2019).

A plant-based diet, generally, focuses on the primary consumption of foods derived from plants (fruits, vegetables, nuts, seeds, legumes and whole grains). But it can also include small amounts of foods of animal origin – dairy, eggs, meat and fish. Therefore, the term "plant-based diet" is quite broad in its connotation.

The growing trend in adopting plant-based diets is propelling advancements (**Box 4**) in the plant-based alternatives industry (McClements and Grossmann, 2021). While consumers are reducing their consumption of animal-based products due to various reasons, many still desire the specific flavour, texture, mouthfeel and feeling of satiety associated with various animal-derived products. This has led to the development of various plant-based alternatives that mimic the taste and consuming experience of animal-based products (McDermott, 2021). Plant-based dairy alternatives, referred to in this report as beverages,[10] and meat alternatives are quite popular and widespread in various regions globally, with plant-based alternatives for eggs and seafood trailing only somewhat behind in development and market penetration. The global retail sales for plant-based foods (primarily those of plant-based meat alternatives and beverages) are expected to reach USD 162 billion by 2030, up from USD 29.4 billion in 2020 (Elkin, 2021).

Among the various factors that are driving the growth of the plant-based alternatives sector, environmental and nutritional aspects are two of the major reasons behind the trend. Some of the opportunities and challenges associated with the two factors are discussed below.

- Environmental aspects: Livestock production is often critiqued for various negative environmental impacts – greenhouse gas emissions, landscape degradation, overuse of water supplies, eutrophication potential, among others (Eshel *et al*., 2014). The environmental impacts of plant-based alternatives are perceived as potentially less resource intensive (Eshel *et al*., 2019) than livestock production. A 2018 study by Poore and Nemecek suggested that producing a glass of dairy milk requires almost nine times more land and produces three

9 Flexitarians eat plant-based foods while reducing, but not eliminating, meat and other animal products.

10 Several plant-based "dairy" options are available in this space, derived from oats, almonds, hazelnut, rice, hemp, pea plants, cashews, potatoes, coconuts and more.

times more greenhouse gases than growing any of the plants needed for dairy alternatives. Many popular plant-based alternatives are derived from legumes, which in addition to being nutritious also enrich soil fertility through nitrogen fixation.

However, the comparison of environmental impacts between livestock and plant-based alternatives may not always be as straightforward as are often portrayed. For instance, life cycle analysis suggests that plant-based meat alternatives can have a lower environmental footprint when compared to feedlot-finished beef, but higher than beef raised in well-managed pastures (van Vliet, Kronberg and Provenza, 2020).

- Nutritional aspects: According to published literature, plant-based diets tend to be associated with higher dietary quality and reduced risk for chronic metabolic diseases that are commonly linked to consumption of animal-based foods (Key *et al*., 2014; Kim *et al*., 2019; Satija *et al*., 2016; Tuso *et al*., 2013).

However, from a public health perspective there has been limited research on the nutritional aspects of plant-based alternatives. van Vliet *et al*. (2021) suggests caution while categorizing plant-based alternatives as equivalent to the corresponding animal-based products. From a metabolomics study, they concluded that the animal-based product (beef) and the plant-based alternative for meat are more likely to be complementary, rather than interchangeable, in terms of provided nutrients.

Certain plant-based beverages do not make suitable substitutes for animal-derived dairy due to limited nutrient diversity (Drewnowski, 2021; Ranga and Raghavan, 2018; Rizzo *et al*., 2016). This incongruity must be taken into account for vulnerable populations, for instance, the emerging trend of plant-based formula and nutrition products for infants and toddlers. In addition, essential minerals like iron, zinc, magnesium and calcium may be less bioavailable in some of the plant-based ingredients found in the alternatives (Antoine *et al*., 2021; Gibson, Heath and Szymlek-Gay, 2014). Food processing may also lead to the loss of certain nutrients and phytochemicals found in plant-based foods. These factors necessitate more research into the nutritional aspects of such food products.

Certain plant-based meat alternatives contain more salt than the meat products that they are formulated to replace (Curtain and Grafenauer, 2019; Sha and Xiong, 2020). High sodium content is considered to be nutritionally undesirable and may predispose individuals, over time, to greater risk for cardiovascular issues (WHO, 2020a).

Box 4. Exploring circular economy through food upcycling

An estimated 931 million tonnes of food, or 17 percent of total food available for consumption in 2019, was wasted at the retail, food service and household levels (UNEP, 2021). With a staggering 3 billion people unable to afford a healthy diet (FAO, IFAD, UNICEF, WFP and WHO, 2020), it is important to tackle the issue of food waste. Some companies, especially within the plant-food sector, are trying to reduce food waste by "upcycling" low-valued foods or food-processing by-products, that would otherwise not be used for human consumption, to new food products.

Foods that are considered for upcycling tend to be those that are surplus, both at an institutional level or at a household consumption level, do not meet the standards of grocery stores in terms of appearance and are by-products formed during production of other foods, among others. Some of these food items are usually destined for either the compost pile or used as animal feed (Zaraska, 2021). Instead, depending on the type of food waste collected for upcycling, they can get converted into different end-products – protein powders, vitamins, jams and jellies, bakery products and beverages (Holcomb and Bellmer, 2021; Kateman, 2021). Certain economically viable upcycled food products are already on the market – whey protein, from cheese production, is used in protein powders and health bars, and wheat middlings that are left over from milling are added to breakfast cereals to bulk up fiber and other nutritional content, among others.

Upcycling is an emerging area in the food industry. In order to develop appropriate guidelines and standards for this sector, it is important to understand the food safety implications that come with it

Plant-based alternatives for dairy.

What are the typical constituents of plant-based alternatives?

The protein sources typically used in plant-based alternatives range from legumes to nuts, seeds, cereals and tubers (Sha and Xiong, 2020). Another growing segment within the plant-based protein industry is mycoproteins, which are derived from filamentous fungi like *Fusarium venenatum* (Hashempour-Baltork *et al*., 2020; Ritala *et al*., 2017). The dietary fats in plant-based alternative products are usually derived from a variety of plant products (such as canola oils, cocoa butter, coconut oil and sunflower oil) often used in mixtures to achieve desired physico-chemical and nutritional parameters. In plant-based meat alternatives, the plant proteins are bound together by methylcellulose (used as thickener and emulsifier is many foods) (Sha and Xiong, 2020).

One of the major advantages of plant-based alternatives is the opportunity to use a larger variety of ingredients to adjust the composition of the product to meet the technological, nutritional, functional needs and consumer preferences alike. Therefore, in addition to bulk ingredients and additives used to impart colour, form and texture, a number of these products also tend to be fortified with vitamins and minerals to enhance nutritional content and in some cases to account for nutritional differences between the plant-based ingredients and the animal-derived products they are intended to replace.

What are the food safety implications to be considered?

Food safety implications for food derived from plants depend on the soil, the agricultural inputs used where the source plants are grown, how the plants are harvested, stored, transported, and processed to obtain the protein isolates, handling of products post-processing and at the retail level as well as implementation of appropriate food safety management practices.

Certain plant-based food products tend to have a higher diversity of ingredients in them than animal-based products, potentially providing a variety of sources from where hazards may arise. Therefore, food safety can be a varied challenge for plant-based alternatives with multiple entry points for different contaminants – biological and chemical. Some key food safety implications for plant-based alternatives are discussed below.

Microbiological hazards

Contamination of plant-based food products with pathogens can occur through contact with sources like animal manure or contaminated water (Rubio, Xiang and Kaplan, 2020). These factors are however not unique to plant-based food products. The high-moisture content and neutral pH of plant-based meat alternatives can provide a suitable environment for the growth of foodborne pathogens (Wild *et al*., 2014). A study by Geeraerts, De Vuyst and Leroy (2020) found high bacterial counts of spoilage microorganisms, such as *Lactobacillus sakei* and *Enterococcus faecium*, in plant-based meat alternative products (but lower than what was found on uncooked animal-based meat products) bought commercially in Belgium. The addition of non-sterile food ingredients post extrusion (McHugh, 2019),[11] unsanitary handling and cross contamination may introduce microbial contamination necessitating further treatments. In terms of storage, to prevent proliferation of microbial activity Wild *et al*. (2014) had suggested that the system for storage and handling of plant-based meat alternatives should be similar to that of raw meat. Research is needed to determine if heat-resistant, endospore-forming bacteria like *Bacillus* spp. and *Clostridium* spp. survive the extrusion process or any other methods used in processing plant-based alternatives.

Plant-based ingredients have different components and concentrations of macronutrients (carbohydrates, fats, proteins) than animal-based products, which leads to variation in the types and resulting levels of microbial contamination that can occur (Floris, 2021). Various proteins found in plant-based beverages show differences in solubility and reaction to heat (Floris, 2021; Nasrabadi, Doost and Mezzenga, 2021; Sethi, Tyagi and Anurag, 2016), creating additional hurdles with regards to options available to maintain adequate food safety standards. At temperatures traditionally used to destroy harmful pathogens and reduce microorganisms associated with spoilage in animal-based products, many plant proteins denature, which affects the taste, texture and nutritional value of plantbased alternatives. This necessitates an exploration of different processing techniques to achieve food safety, while keeping the taste and texture of plant-based products intact (Floris, 2021).

[11] Carried out at high temperature and pressure to create meat and seafood-like textures for plant-based alternatives.

Chemical hazards

Mycotoxins: There are many known mycotoxins that can be present in food derived from plants (Bennett and Kilch, 2003). Mycotoxins present in the raw ingredients – cereals (oat, rice), nuts (almond, walnut), legumes (soy) – may get carried over to end products, like plant-based beverages. Miró-Abella *et al*. (2017) analysed several plant-based beverages (soy, oat and rice) for the presence of certain mycotoxins (deoxynivalenol, aflatoxin B1, aflatoxin B2, aflatoxin G1, aflatoxin G2, ochratoxin A, T-2 toxins and zearalenone). They found that all the plant-based beverages were susceptible to the mycotoxins considered, albeit at varying levels (quantification ranged between 0.1 µg L^{-1} to 19 µg L^{-1}). In another study, Hamed *et al*. (2017) explored the presence of *Fusarium* toxins (fumonisin B1 and B2, HT-2 and T-2 toxins, zearalenone, deoxynivalenol and fusarenon-X) in oat, rice and soy used for plant-based beverages and found that oat-based beverages were most susceptible to contamination with deoxynivalenol (191 – 270 µg L^{-1}). Oat-based beverages have also been found to be susceptible to contamination with enniatins and beauvericin by Arroyo-Manzanares *et al*. (2019) who studied the presence of certain emerging mycotoxins in some plant-based beverages (soy, rice and oat).

Antinutrients: Certain compounds naturally present in legumes – phytic acid, protease inhibitors, lectins, saponins, among others – may reduce bioavailability of key nutrients and interfere in mineral absorption when present in diet at moderate to high quantities (Joshi and Kumar, 2015; Petroski and Minich, 2020; Rousseau *et al.,* 2019). Phytoestrogens,[12] like isoflavones, lignans and coumestan found in various plant-based foods may affect the endocrine system (Thompson *et al*., 2006), potentially leading to adverse health implications. The most studied phytoestrogens are isoflavones (daidzein, genistein, glycitein) found mainly in soy (Divi, Chang and Doerge, 1997; Patisaul, 2017). There are several processing techniques that can be used to inactivate or reduce the levels of these antinutrient factors (Rousseau *et al*., 2019; Samtiya, Aluko and Dhewa, 2020).

[12] Phytoestrogens are plant-derived compounds that are found in a variety of foods. These compounds have a structural similarity to estrogen, the primary female sex hormone, allowing the phytoestrogens to bind to estrogen receptors in the body and affecting hormone metabolism.

Allergenic potential: One of the major protein components of plant-based alternatives is soy. While soy-based alternatives to dairy products may be preferred by those who are allergic to cow's milk, research shows that soy proteins may trigger allergic reactions in cow's milk allergic individuals (Sicherer, 2005). A study by Rozenfeld *et al*. (2002) suggested that this was due to cross-reactivity between caseins from cow's milk and the B3 polypeptide from the 11S globulin of soy. Other components of plant-based alternatives that can cause severe allergic reactions are tree nuts, legumes (peanuts) and gluten-containing cereals.

Some other allergens are also gaining attention, such as buckwheat and sesame. While the former has become increasingly more common outside of Asia, where it is widely consumed, the latter is gaining international attention and is set to be the ninth major allergen that is required to be labelled on food packaging (Beach, 2021; FAO and WHO, 2021; Heffler *et al*., 2014). Though sesame is not considered as a significant protein source, efforts are underway to produce a high-protein content variety of the seed (Ferrer, 2021) making it important to monitor this emerging space. Celiac disease is a disorder that is characterized by an intolerance to gluten, a major protein found in some cereals (e.g. wheat, barley, rye) (Joshi and Kumar, 2015).

A major source of plant-based protein is legumes (green peas, soy, peanut, lupin, green beans and pulses such as chickpeas, lentils, kidney beans and other dried beans) and the allergenic potential of several legumes has been identified and characterized so far (Cabanillas, Jappe and Novak, 2017; Verma *et al*., 2013; Villa, Costa and Mafra, 2020). There is a high rate of cross-reactivity among different legumes with individuals allergic to one showing sensitivity to others, but not necessarily to all (Kakleas *et al*., 2020). The recent trend of adding plant-based sources, such as pea protein concentrates and pea protein isolates, into a variety of foods to add bulk and increase protein levels may induce allergic reactions in some upon consumption (Abrams and Gerstner, 2015; Fearn, 2021). Individuals who are allergic to peanuts may also be vulnerable to peas and vice versa (Morrison, 2020; Wensing *et al*., 2003). The Codex Alimentarius Commission includes a priority allergen list as part of its General Standards for the Labelling of Prepackaged foods that is based on predetermined criteria, including global prevalence (FAO and WHO, 2018; FAO and WHO, 2021). Countries are encouraged to consider the inclusion of other food allergens on regional priority lists based on individual (or country-specific) consumption patterns and data.

While limited literature is available on allergenic potential of mycoproteins, Jacobson and DePorter (2018) analysed self-reported allergic reactions to mycoproteins and found that some reactions occurred on an individual's first exposure to a mycoprotein-based food product. Research by Hoff *et al*. (2003) suggests that individuals sensitized to mould aeroallergens (*Fusarium culmorum* allergen Fus c 1) through respiration can experience allergic reactions upon consumption of mycoprotein-based food products due to cross-reactivity with allergen protein P2 from *Fusarium venenatum*.

Chemical hazards arising from processing: Based on how compounds like heterocyclic aromatic amines, nitrosamines and polycyclic aromatic hydrocarbons are formed in meat products, He *et al*. (2020) proposed that during the manufacturing and processing of plant-based meat alternatives these compounds may also emerge. However, production of toxic compounds due to the high-temperature processing of plant-based meat alternatives have yet to be investigated; for instance, the potential for the occurrence of glycidyl fatty acid esters, 2-monochloropropanediol (2-MCPD) and 3-monochloropropanediol (3-MCPD), which are heat-induced contaminants in food (FAO and WHO, 2017; GAO *et al*., 2019). Possible occurrence of trans-fatty acids, that are formed during partial hydrogenation of vegetable oil, in certain plant-based alternatives will also need to be determined. Several countries already have legislation in place to ban industrially produced trans-fatty acids from their food products (WHO, 2020b).

Other chemical hazards: Agriculturally important plants can absorb and accumulate heavy metals from soil (Galai *et al.*, 2021; Zhao and Wang, 2019), which can lead to contamination of the end products with such chemical hazards. In addition, concentrations of potentially toxic rare earth elements, like thallium and tellurium, are increasing in our environment due to their applications in agriculture and various industries. These elements have also been detected in several plant-based foods (legumes, cereals, vegetables, among others) necessitating the need for hazard evaluation and risk assessment (National Food Institute – Technical University of Denmark, Doulgeridou *et al.,* 2020). Research is also needed to evaluate other chemical hazards, such as residues of pesticides and antimicrobial agents, that can be associated with plant-based ingredients (Lopez *et al*., 2020).

Food safety concerns from the addition of soy leghemoglobin to plant-based meat alternatives, which is added to enhance the product's "meat"-like flavour (Sha and Xiong, 2020) are currently being explored. Correlations are being made between high intake of heme iron, which can be sourced from both plant and animal-based products, and an increase in body iron stores with a greater risk for type 2 diabetes mellitus (Bao *et al*., 2012).

What is the way forward?

While understanding that the ecological impacts of human diets as well as the broader socioeconomic implications are not as simplistic as most discussions around plant versus animal would seem to indicate, a brief on plant-based alternatives is presented to showcase the potential benefits and challenges, focusing on the various food safety issues.

The food safety considerations for plant-based alternatives to animal-derived products can be quite different from the ones necessary to produce animal-based products, and hence any transition will require a careful retooling for food safety management processes. Some companies are trying to incorporate predictive modelling approaches in early product design stages (Floris, 2021). This process involves carrying out initial microbial risk assessments *in silico* based on processing conditions, intrinsic properties of the product, and intended storage and consumption conditions (Floris, 2021). The presence of mycotoxins and other chemical hazards necessitates putting in place proper controls to reduce exposure to chemical contaminants through this new food source. As plant-based diets expand, more awareness about introducing allergens from foods not commonly consumed before is needed prior to entering our diets. While most plant-based alternatives contain ingredients that have been previously approved for human consumption, ambiguities around the nomenclature of plant-based alternatives can create obstacles in developing guidelines relevant for the labelling of plant-based foods (Sha and Xiong, 2020).

Apart from food safety, price-point and cultural appeal of plant-based alternatives are other challenges to consider. The cost of plant-based alternatives is expected to reduce as consumer demand increases (Specht, 2019). Currently, plant-based meat alternatives are tailored for a more Western-type diet (burgers, nuggets, sausages), with insufficient foray into more traditional foods in different regions, thereby limiting consumer base and acceptance.

There are some potential trends on the horizon in the plant-based alternatives space, for instance, hybrid milk (combination of animal dairy and plant-based beverages), mixture of animal-based products and plant-based ingredients (such as animal-based meat combined with mushrooms).

While all or some of these plant-based alternatives could potentially represent a significant opportunity to reduce environmental impact of food production, they can also represent a disruption in agrifood systems, which could have important public health, environmental, and regulatory implications. Progress in this area will therefore depend on taking an integrated multidisciplinary approach to consider and overcome the various challenges

4.4. Seaweeds

Seaweeds are macroscopic, photosynthetic plant-like organisms that fall under three broad groups based on their pigmentation: brown (Phaeophyta), red (Rhodophyta) and green (Chlorophyta) algae. While the majority of brown and red seaweeds are strictly marine, the green seaweeds are mainly found in freshwater environments (FAO, 2021).

Seaweeds have long been important providers of socioeconomic benefits and contributors to food security (**Box 5**) around the world through diverse food and non-food applications (FAO, 2021). Though traditionally used as food in various countries (for instance, China, Japan and the Republic of Korea), seaweeds in Western diets have been largely limited to artisanal practices and coastal communities, but has gained wider consumer interest in recent years, driven in part by the health-food industry (Cherry *et al*., 2019).

Box 5. Livelihood diversification of fishing communities

The fishing community all over the world has started to feel the effects of overfishing as well as the collapse of wild stocks of various commercial fish species like cod (Meng, Oremus and Gaines, 2016). In addition, climate change related issues – migration of fish species towards the poles (Pinsky *et al.*, 2018), oyster cages being destroyed due to frequent hurricanes, ocean acidification destroying oyster seeds, lobsters moving away from coastal areas due to warming seas (Greenhalgh, 2016) and many others – are also affecting the livelihoods of the fishing community. These factors are driving more interest in diversifying livelihoods, including cultivation of seaweeds which does not require extensive resources to set up

Why is seaweed utilization gaining interest?

Two key factors are driving the growing interest in seaweed utilization: heightened attention to sources of food that are nutritious as well as sustainable; and versatility in terms of applications of seaweeds in several industries, such as pharmaceuticals and cosmetics in addition to food and animal feed. Some of these benefits are described below.

Nutritional characteristics

- Human food and potential health aspects: Nutritionally seaweeds consist of minerals (iron, calcium, iodine, potassium, selenium) and vitamins, particularly A, C and B-12. Seaweeds are also one of the only non-fish sources of natural omega-3 long-chain fatty acids. They also tend to be high in soluble dietary fibres, and some can be good sources of protein (FAO, 2018, Gupta and Abu-Ghannam, 2011; Wells *et al.*, 2017).
- Certain bioactive components from various seaweed species have been suggested to confer properties – anti-inflammatory, prebiotic, antioxidant, among others – that are beneficial to health (Joung *et al.*, 2017; Yun *et al.*, 2021). They have also been used as traditional medicines in Asia; for example, some have been used as vermifuge,[13] and to treat iodine deficiency (Ganesan, Tiwari and Rajauria, 2019; Liu *et al.*, 2012; Moo-Puc, Robledo and Freile-Pelegrin, 2008).
- Animal Feed: Research has shown that the addition of seaweed like *Asparagopsis taxiformis* to diets of cattle can reduce enteric methane emissions drastically (close to 80 percent) (Kinley *et al.*, 2020; Roque *et al.*, 2019; Roque *et al.,* 2021). Seaweeds can be a sustainable and suitable alternative ingredient in both livestock and aquaculture feeds considering their nutrient profiles, which show species-specific variability (Costa *et al.,* 2021; Kamunde, Sappal and Melegy, 2019; Makkar *et al.*, 2016; Morais *et al.,* 2020; Wan *et al.*, 2019).

Sustainability characteristics

Various varieties of seaweeds not only grow fast, but their cultivation also does not require fertilizers, land degradation or deforestation. In addition, seaweeds provide a number of environmental benefits, some of which are described below.

- Combat ocean acidification – Macroalgae are great carbon dioxide sinks (Duarte *et al.*, 2017). It is estimated that globally seaweeds sequester approximately 200 million tonnes of CO_2 each year, and when they die, much of the trapped carbon gets transported deep into the ocean (Krause-Jensen and Duarte, 2016). This helps to buffer against ocean acidification, which is a consequence of rising atmospheric CO_2 levels. While this property presents an opportunity for climate change mitigation, the current scale of seaweed growth, both from farming and naturally occurring species, is insufficient to support a global role in this endeavour (Duarte *et al.*, 2017).
- Habitat for fish – The seaweeds can provide refuge for various fish species and help to maintain the diversity of marine life. Co-culturing (**Box 6**) seaweed and shellfish can capitalize on the potential of seaweeds to buffer against acidification, thereby promoting shell calcification of farmed shellfish (Fernández, Leal and Henríque, 2019).
- Prevent eutrophication – In large quantities, nutrients, such as nitrogen and phosphorus, from stormwater runoffs and point-sources cause toxin-producing algal blooms, which have harmful effects on both humans and animals (Anderson, Gilbert and Burkholder, 2002; Heisler *et al.*, 2008). Seaweeds can lower the concentrations of nitrogen and phosphorus in aquatic systems (FAO, 2003) and therefore have potential for wastewater treatment.
- Reduction of pollutants in the area – Macroalgae can accumulate heavy metals from the environment and therefore, could act as bio-monitors to measure the extent of contamination along coastlines (Morrison, Baumann and Stengel, 2008). They can also be cultivated to reduce the levels of heavy metals and other pollutants, thereby improving the health of coastal ecosystems. The seaweeds grown for such purposes should not be used for human or animal consumption.

Other noteworthy applications of seaweed include:

- Food additives and non-food applications (agar, carrageenan, and alginates):
  - Thickening/emulsifying agents used in numerous industries including textile, food and beverage, chemical and pharmaceutical, healthcare, and paper.
  - Alternatives for single use plastics: seaweed extracts are being used to make biocompostable packaging for food as well as other articles of single use

[13] An agent with anti-parasitic activity.

Box 6.
Integrating seaweed harvesting with other applications

The idea of offshore or ocean aquaculture, as opposed to marine, bay or estuarine aquaculture, has gained significant traction with striped bass and cobia grown successfully in farms off the shores of Panama and Mexico, respectively (Gunther, 2018). However, there are a number of concerns about open-sea aquaculture, like excess nutrients from leftover feed and resulting fish faeces causing algal blooms (including toxic species).

One of the ways to address these issues is by growing seaweeds to complement aquaculture. For instance, adding seaweed production to Integrated Multi-Trophic Aquaculture (IMTA) which combines fed aquaculture (finfish and shrimp) with extractive aquaculture that includes suspension feeding species (mussels and oysters), macroalgae, and deposit feeding species (sea-cucumbers and sea-urchins) (Buck *et al*., 2017).

Apart from waste mitigation, seaweeds also provide safe nursery grounds for a number of young fish and crustaceans that can be harvested for consumption. Moreover, the presence of seaweeds also prevents deep sea trawling which protects the sea floor.

Man-made structures in the open ocean like decommissioned oil-rigs and off-shore wind farms also offer opportunities to set up seaweed production areas, with or without IMTA. Wind turbine pylons and foundations of oil rigs can serve as anchors for the production infrastructure as well as provide protection against the rough elements out in the open seas. One of the first trials to farm seaweed offshore, for the purposes of animal and fish feed along with biofuels, within a wind farm, was carried out in 2012, with several countries exploring similar options (Buck *et al*., 2017)


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Seaweeds are a major source of livelihoods and food security in various regions.

plastic ware. Few companies around the world are already exploring the possibilities of marketing their technologies on a larger scale.

- Agriculture: There is a growing interest in using seaweeds and their extracts as foliar fertilizers to increase resistance to fungi and insects as well as to serve as sources of nutrition and moisture in the soil (Chojnacka, 2012; Vijayaraghavan and Joshi, 2015). There is also research on capturing the nitrogen run off and returning it back to the farmers to use as fertilizers (Seghetta et al., 2016).

Production estimates of seaweed

The current market value of the global seaweed crop is around USD 5.6 billion, of which sale for human consumption make up the greatest share (FAO, 2020). The main market for seaweed is in Asia and the Pacific, but there growing demand in Europe and North America (FAO, 2020).

Table 3. Major farmed seaweed producers in the world (thousand tonnes, live weight)

Country	*2005*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*% of total, 2016*
China	9 446	10 995	11 477	12 752	13 479	13 241	13 835	14 387	47.9
Indonesia	911	3 915	5 170	6 515	9 299	10 077	11 269	11 631	38.7
Philippines	1 339	1 801	1 841	1 751	1 558	1 150	1 566	1 405	4.7
Republic of Korea	621	902	992	1 022	1 131	1 087	1 197	1 351	4.5
Democratic People's Republic of Korea	444	444	444	444	444	489	489	489	1.6
Japan	508	433	350	441	418	374	400	391	1.3
Malaysia	40	208	240	332	269	245	261	206	0.7
United Republic of Tanzania	77	132	137	157	117	140	179	119	0.4
Madagascar	1	4	2	1	4	7	15	17	0.1
Chile	16	12	15	4	13	13	12	15	0
Solomon Islands	3	7	7	7	12	12	12	11	0
Viet Nam	15	18	14	19	14	14	12	10	0
Papua New Guinea	0	0	0	1	3	3	4	4	0
Kiribati	5	5	4	8	2	4	4	4	0
India	1	4	5	5	5	3	3	3	0
Others	25	14	15	16	13	12	16	8	0
Total	**13 450**	**18 895**	**20 712**	**23 475**	**26 780**	**27 270**	**29 275**	**30 050**	

Source: The global status of seaweed production, trade and utilization (FAO, 2018).

Globally fresh seaweed supply comes from two sources: wild stocks and aquaculture (FAO, 2018). Between the two, aquaculture supplies the greater share (**Table 3**). In 2018, farmed seaweeds represented 97.1 percent by volume of the total of 32.4 million tonnes of wild-collected and cultivated aquatic algae combined (FAO, 2020).

Cultivation of *micro*algae, which are unicellular algal species, is also carried out in various parts of the world for a number of different applications: dietary supplements (**Box 7**), extraction of bioactive compounds, natural food colourants, and animal feed, among others (FAO, 2021). Production of microalgae can be located in areas that cannot be employed for agriculture, thereby making use of nonarable land (Winckelmann *et al.,* 2015). Microalgae cultivation can also be potentially used for wastewater treatment (Molazadeh *et al.,* 2019; Winckelmann *et al*., 2015). However, many of these applications are not yet fully commercialized. While further discussion of microalgae is beyond the scope of this brief, as it focuses on macroalgae or seaweeds, the recent FAO publication (2021) has covered the topic of microalgae in greater detail.

Box 7. Cyanotoxins in algal supplements

Phycotoxins are an important food safety consideration when *micro*algae are used in food. Food supplements that contain algae (blue-green algae) are derived from blooms by non-toxic algal species (primarily *Spirulina* and *Aphanizomenon flos-aquae*). However, these species can coexist with other harmful strains of cyanobacteria (*Microcystis* sp.), thereby creating potential contamination issues for the supplements if the species are all collected from the same natural environment (ANSES Opinion, 2017; Roy-Lachapelle *et al*., 2017; Testai *et al*., 2016). In addition, it has been found that *A. flos-aquae* can produce neurotoxins (Cox *et al*., 2005)

What are the food safety implications to be considered?

Given that production of seaweeds is expected to increase globally (Duarte *et al*., 2017) to meet the rising demand as an alternative source of nutrients, this warrants close attention to the various food safety issues that may arise. Some of the key food safety hazards that should be considered are discussed below.

Microbiological hazards

Microbial contamination can occur during growth, cultivation, harvest, processing and handling, and storage of seaweed. While studies have highlighted that coastal seaweeds can act as reservoirs for *Vibrio parahaemolyticus* and *Vibrio vulnificus* populations, the bacterial species are relatively sensitive to heating and drying processes and therefore may not survive the food processing systems (Mahmud *et al*., 2006; 2007; 2008). However, because seaweed can be consumed raw, microbial risks from such marine foodborne pathogens remain pertinent. Potential risks arising from spore-forming pathogens (*Clostridium* spp. and *Bacillus* spp.) are yet to be fully explored.

Outbreaks of foodborne diseases from seaweed can occur if aquaculture farms lack appropriate measures to maintain hygiene and sanitation, such as inadequate facilities for bathroom and handwashing for employees. Location of farms is also important, for instance, if farms are in the vicinity of wildlife refuge (Nichols *et al*., 2017). Norovirus outbreaks have been linked to seaweed consumption in several countries (EFSA, 2017; Kusumi *et al*., 2017; Park *et al*., 2015; Whitworth, 2019).

Chemical hazards

Heavy metals: Seaweeds can bioaccumulate high levels of heavy metals like arsenic, lead, cadmium and mercury from the aquatic environment (Almela *et al.*, 2006; Chen *et al.*, 2018; Karthick *et al.*, 2012; Sartal *et al.*, 2014). These heavy metals can come from both anthropogenic activities (mining, petrochemical processing, electronics waste, municipal waste) and natural causes (volcanic activities). Consumers may be exposed to heavy metals present in seaweed either through direct consumption or indirectly through the food chain, for instance, consuming fish that bioaccumulates the metals by feeding on seaweed. There are a couple of factors that contribute to the process of bioaccumulation: geographical location, especially one with close proximity to a contaminated area; time of harvest, as younger leaves may not contain as much heavy metals as the older leaves; and the intrinsic uptake capacity of the seaweed species concerned (Duncan *et al.*, 2014; Larrea-Marin *et al.*, 2010).

In seaweeds, arsenic can exist in inorganic forms (As^{III} and As^{V}) and in its organic forms (monomethylarsonic acid, dimethylarsinic acid, arsenobetaine and arsenocholine) (Francesconi *et al.*, 2004; Rose *et al.*, 2007), with the former considered to be more toxic (McSheehy *et al.*, 2003). While the typical concentration range of As in the oceans range between 1–3 µg l^{-1}, the total As content (As_T) in seaweeds can be 1 000–50 000 times higher than the surrounding water. Members of Phaeophyta tend to accumulate more arsenic followed by Rhodophyta and Cholorophyta (Ma *et al*., 2018). There is some evidence to suggest that application of seaweed-based fertilizer to soil may gradually increase the amount of organic and inorganic arsenic concentrations in the treated soil, triggering food safety concerns (Castlehouse *et al.*, 2003).

A range of concentrations has been reported for cadmium in seaweeds intended for human consumption, from below the detection limit (0.001 µg/mL) to 9.8 mg/mL dw (Banach, Hoek-van den Hil and van der Fels-Klerx, 2020). While cadmium has been found to occur at higher levels in red than in brown seaweeds, the case for mercury is the opposite (Chen *et al*., 2018; Banach, Hoek-van den Hil and van der Fels-Klerx, 2020). Accumulation of lead in brown and green seaweeds was reported by Squadrone *et al*. (2018) from a location with high anthropogenic activity. According to Almela *et al*. (2006), the reported lead levels in seaweed range from <0.05 mg/kg to 2.44 mg/kg dry weight. The human exposure to lead from seaweed consumption can be considered minimal (FSAI, 2020).

Iodine content: Iodine is an essential mineral for mammals and is required for biosynthesis of thyroid hormones. While iodine content of seaweeds varies considerably by species, many seaweeds can have significant bioaccumulation capacity for iodine (Nitschke and Stengel, 2015; Roleda *et al*., 2018). This can result in high mineral content, sometimes up to 100 times higher than terrestrial vegetables (Circuncisão *et al*., 2018). They are therefore considered iodine-rich foods and depending on volumes consumed could cause excessive intake of the mineral, posing potential health risks (EC SCF, 2002). Post-processing methods can also influence iodine concentrations and

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Women harvesting seaweed.

therefore human exposure (Dominguez-González *et al*., 2017; Nitschke and Stengel, 2016).

Persistent organic pollutants (POPs): Since seaweeds are very low in lipid content, concentrations of lipid-soluble pollutants like dioxins and polychlorinated biphenyls (PCBs) tend to be low (Duinker *et al*., 2016). However, such chemicals can concentrate in seaweeds if they are grown in areas with high chemical contamination. Dioxins such as polychlorinated dibenzo-p-dioxins (PCDDs) that occur due to industrial contamination (municipal incinerator, power plants, amongst others) have been found in commonly consumed seaweeds such as *Undaria* and *Ecklonia* (Banach, Hoek-van den Hil and van der Fels-Klerx, 2020). Also, PCBs have been reported to be absorbed by and concentrated in some seaweeds such as *Ulva* (Cheney *et al.,* 2014).

Phycotoxins: There are food safety concerns stemming from the potential accumulation of marine toxins (or phycotoxins) by seaweeds. Phycotoxins are produced by harmful microalgal species that can be inadvertently present in areas where seaweeds are harvested from. The growth of filamentous cyanobacteria on edible seaweeds and production of toxins from opportunistic dinoflagellates that can be isolated from seaweed have been flagged as emerging issues of concern (EFSA, 2017; Monti *et al*., 2007). Risks from algal blooms are of greater concern under climate change-induced conditions (**Box 8**), such as rising sea temperatures, and ocean acidification.

Some marine toxins such as palytoxin (PTX), domoic acid (DA) and analogs, ciguatoxins, and cyclic imines (CIs) can be found associated with seaweeds (Banach, Hoek-van den Hil and van der Fels-Klerx, 2020). Similarly, ciguatoxin-producing *Gambierdiscus toxicus* can live in epiphytic association with brown, red and green seaweeds (Cruz-Rivera & Villareal, 2006; FAO, 2004). Various marine sources, including seaweeds, have been reported to cause amnesic shellfish poisoning, which is caused by DA, a potent neurotoxin (FAO, 2004).

Box 8. Climate change – a major threat to the seaweed farming industry

Seaweed production has provided food security and opportunities for livelihood diversification to many coastal communities across the world. However, climate change poses a major threat to the global seaweed sector. For instance, elevated temperatures in the Indian Ocean in combination with algal blooms in the shallow waters, drastically reduced (by 94 percent) the production of commercially important *Eucheuma cottonii* in the region in 2015 (Ott, 2018).

Risk of exposure to certain food safety hazards from seaweeds can be exacerbated by climate change

Xu *et al*. (2019) found that seaweeds grown in conditions which mimicked future ocean acidification conditions accumulated more iodine. Elevated sea surface temperatures were not as important a factor in causing iodine accumulation. This poses food safety as well as nutritional concerns as the global seas undergo acidification due to climate change.

With climate change exacerbating conditions that lead to harmful algal blooms, further research to determine how it affects the presence of phycotoxins in seaweeds is needed. This is especially true for seaweeds grown in areas that are already experiencing an increase in algal blooms.

There is some evidence to suggest that the uptake of arsenic by certain species of seaweed (*Fucus spiralis* and *Ascophyllum nodosum*) is accelerating under elevated sea surface temperatures (Fereshteh *et al.*, 2007; Klumpp, 1980). Considering the gradual warming of seas due to climate change, this area will need close monitoring

Allergenicity: Allergic reactions upon consumption of red seaweeds (*Chondrus crispus*, *Palmaria palmata*) were identified by Thomas *et al*. (2018). However, there is limited information about the allergenic potential of proteins present in seaweeds. *In silico* proteomic analysis has revealed the allergenic potential of certain algal proteins (aldolase A, thioredoxin h, troponin C, among others) found in *Ulva* sp. (Polikovsky *et al*., 2019). Dried nori (*Porphyra* sp.) has an immunoreactive component (molecular weight 37 kDa) which is identical to the mass of tropomyosin, a known allergen, commonly found in crustaceans (Bito, Teng and Watanabe, 2017). In addition, seaweed is cultivated on long-lines which may be exposed to fouling organisms, including crustaceans, and shellfish allergens are considered a potential hazard in seaweed in the United States of America (Concepcion, DeRosia-Banik and Balcom, 2020).

Other chemical hazards: Agrochemicals such as pesticides and herbicides can enter the marine environment through runoffs from agricultural fields. Monitoring measures will help to establish if these chemicals can enter the food chain through coastal seaweed aquaculture farms. Radionuclides may be a potential hazard from seaweeds harvested from an area that has experienced nuclear incidents, for instance, the 2011 Fukushima incident in Japan (Banach, Hoek-van den Hil and van der FelsKlerx, 2020). According to guideline levels for radionuclides in food set by the Codex Alimentarius, the limits can range from 10 Bq/kg to 10 000 Bq/kg, based on specific radionuclides (FAO and WHO, 2011). The ability of seaweeds to accumulate low levels of radionuclides from the marine environment make them suitable in biomonitoring programmes for radionuclide discharges (Goddard and Jupp, 2001). Seaweeds used for such purposes should not be later used for human or animal consumption.

Pharmaceuticals used both for humans and animals can be found in the marine environment, through sources such as waste disposal, sewage effluent, aquaculture, animal husbandry, among others. Information on the presence of pharmaceutically active compounds in seaweeds is limited. In a study presented by Álvarez-Muñoz *et al*. (2015), seaweeds *Saccharina latissima* and *Laminaria digitata* collected near salmon farm cages showed the presence of four pharmaceutically active compounds, azithromycin (antibiotic), metroprolol (β-blocker), propranolol (β-blocker), and diazepam (psychiatric drug), in levels above the detection limit (Álvarez-Muñoz *et al*., 2015). Experimental evidence shows that chloramphenicol, furaltadone, and sulfathiazole can be taken up by *U. lactuca*, with chloramphenicol exerting a potential growth promoter effect on the seaweed (Leston *et al*., 2011; 2013; 2014).

Seaweeds can utilize nitrogen and nitrogen-derivatives (nitrates) for their biological cycles. While this makes them suitable for capturing and concentrating nitrogen run-offs from agricultural fields, consumption of certain seaweeds may expose consumers to high levels of nitrates (Martin-León *et al.,* 2021). The current acceptable daily intake for nitrate as determined by the Joint FAO/WHO Expert Committee on Food Additives (JECFA) is 3.7 mg/kg body weight per day (FAO and WHO, 2002). Nitrates, from various food sources, can get converted to nitrites in our bodies. Both nitrates and nitrites may contribute to the formation of a group of compounds known as nitrosamines, some of which are carcinogenic (Grosse *et al*., 2006; Hord, Tang and Bryan, 2009). There is currently no legislation regulating the content of nitrates in seaweeds.

Physical hazards

Physical hazards such as small pebbles and pieces of shells might be present with harvested seaweeds. Processing and packaging of seaweed may introduce other hazards like metal pieces or glass (Concepcion *et al.,* 2020). Micro- and nanoplastics can attach to seaweeds in the aquatic environment, which can then pose potential physical contamination issues down the food chain (Gutow *et al*., 2016; Li *et al*., 2020). However, this area has limited information with many knowledge gaps on the occurrence of micro- and nanoplastics in both wild-harvested and cultured seaweeds as well as subsequent health impacts on consumers.

What is the way forward?

Without thorough assessment of food safety risks of seaweeds, developing laws and regulations will be difficult, especially in regions where the sector is just starting to emerge, thereby, impeding progress. While there is global trade of seaweeds, there are no Codex standards or guidelines that specifically address food safety concerns in this food source. Some of the significant gaps in regulations for food safety hazards in seaweeds along with a more detailed overview of the various food safety concerns in seaweeds are captured in an upcoming FAO publication (FAO and WHO, forthcoming).

Upscaling of seaweed production to meet market demand is a challenge for the sector. Long-term data on the environmental impacts of seaweed cultivation at an industrial scale is still lacking. Balancing potential benefits of seaweed production with environmental risks to ensure that the carrying capacities of the receiving environments are not exceeded will be needed. In addition, utmost care must be taken not to introduce non-native species in an area as that might impact the local biodiversity. Implementing a One Health approach to seaweed cultivation will support further development of the sector while ensuring sustainable production and mitigating potential drawbacks (Bizzaro, Vatland and Pampanin, 2022)

4.5. Cell-based food production

W**hile the world** begins to understand the importance of transforming the current agrifood systems to be more sustainable and environmentally conscious, there is also an increasing consumer demand for animal-based food products worldwide (FAO, 2018). The intensification of animal production may contrast with sustainability objectives, resulting in trade-offs in various environmental aspects, food security and animal welfare (FAO, 2020; Henchion *et al*., 2021; OECD and FAO, 2021). New technology presents a potential alternative: the production of land and aquatic animals without requiring large-scale farming and slaughtering.

In 1932, Winston Churchill stated: "We shall escape the absurdity of growing a whole chicken in order to eat the breast or wing, by growing these parts separately under a suitable medium" (Churchill, 1932). After decades of research and development, the technology has now matured, and his idea has become a reality. The production can be done via *in vitro* cultivation of animal cells and then processed into products whose composition can be equivalent to conventional animal products without needing the whole animal (Kadim *et al*., 2015; Post, 2014).

Since the initial studies in the early 2000s, cell-based food production methodologies have been well characterized, meaning they are now ready to move from laboratories to production facilities. In 2013, the first beef burger produced through this technology was presented to the world (Jha, 2013). In December 2020, the first cell-based chicken nuggets were approved by a competent authority in Singapore. As of November 2021, there are at least 76 companies developing similar products around the world (Byrne, 2021). Many types of products and commodities such as various types of meat, poultry, fish, aquatic products, dairy and eggs are in the pipeline for future commercialization.

Terminology and definitions

Various terms are currently in use (**Box 9**), as yet there is no internationally harmonized terminology to indicate this type of food product or the production process (Ong, Choudhury and Naing, 2020). For example, some people call meat analogues "cultured", "cell-based" or "cultivated" meat. Product marketers may call it "animal-free", "clean" or "slaughter-free" meat. For the purpose of the present brief, and without setting a precedence, the term "cell-based" is used. Some may identify the whole technology as "cellular agriculture" or "cell-culturing". The lack of clear definitions for these terms creates the potential for confusion. National authorities will be most effective if the terminology they use is 1) transparently representative of the products; 2) informative for food labelling, clearly communicating to consumers that the products produced through the new technology are different from the conventional products with which they may already be familiar, but also contain the same potential allergens; and 3) neither disparaging nor generating consumer reactions (Hallman and Hallman, 2020).

Box 9.
Some modifiers or adjectives used as terminology for cell-based food products

- animal-free
- artificial
- cell-based
- cell-cultured
- cellular
- clean
- cruelty-free
- cultivated
- cultured
- in vitro
- lab-grown
- slaughter-free
- synthetic
- test tube
- vat-grown

Box 10.
A generic production overview of cell-based food products

1. Cell selection from the source animal
2. Production: The cells selected in step 1 are allowed to multiply in bioreactors; cells may be anchored to microcarriers or a scaffold to organize tissues in a 3D structure.
   a. Cell preparation
   b. Cell proliferation
   c. Cell differentiation
3. Harvesting of the product
4. Food processing: The harvested products may be processed further to shape it in desired forms and/or be combined with other ingredients for commercialization

Table 4. A generic map of potential hazards/concerns in cell-based food production processes

	Transmission of zoonotic infectious diseases	*Residues and by-products*	*Novel* inputs*	*Microbiological contamination*
Cell selection	x	x		x
Production	x	x	x	x
Harvesting		x		x
Food processing		x	x	x

* *A novel input means an added step, material, technology or technique that has not commonly been used in conventional food production (i.e. scaffolds or modified cell properties).*

What are the food safety implications to be considered?

Production overview and hazard/concern mapping

Food safety is one of the foremost concerns when new technology is applied to food production processes. Within the risk analysis paradigm, the first step of safety assessment is hazard identification, which can be conducted following the production steps. For cell-based food production, the methodologies and production steps can greatly vary depending on the company, the desired final product, manufacturing facilities and equipment. To illustrate the indicative food safety hazard identification process, a generic overview of production steps is presented in **Box 10**, followed by a generic map of potential hazards/concerns (**Table 4**).

Potential food safety hazards/concerns

Source cell lines: The desired starting cell lines are often sourced from a live or slaughtered animal of choice followed by cell isolation. A common alternative is to use induced pluripotent stem cells (iPSCs), reprogrammed adult cells that can differentiate into any type of cells (Takahashi and Yamanaka, 2006). Although iPSCs have been well studied in mice since their discovery, the differentiation protocols for various livestock animal cells such as chicken remain elusive (Post *et al*., 2020).

The chance of infectious zoonotic and foodborne disease occurrence is considerably reduced when compared to conventional livestock production (Treich, 2021), but major considerations must be given to the use of animal serum in the culture media, which may introduce pathogens including virus, bacteria, parasites as well as prions (Hadi and Brightwell, 2021; Ong *et al*. 2021). However, early detection of cell infections via careful monitoring can greatly limit such hazards. Also, as it is for any food production processes, following good hygiene practices (GHP) throughout the whole production process is critical.

The entirety of cell-based food production can be done in a well-controlled environment without the risk of contamination from faeces or external sources (Chriki and Hocquette, 2020). However, the application of antibiotics during some of the production steps may still be conducted. Consequently, residues may remain in the final product as antimicrobial residue (Agmas and Adugna, 2018).

Components of the growth medium: Animal-serum based culture media, especially those with fetal bovine serum (FBS), are currently the most common option (Hadi and Brightwell, 2021; Post, 2012; Post *et al*., 2020); and they may present a higher risk of microbiological contamination (Chriki and Hocquette, 2020). Such hazards can be managed and controlled by monitoring for key pathogens appropriately (Specht *et al*., 2018). Moreover, there has been a substantial effort in developing animal serum-free media to overcome concerns surrounding FBS, and there are currently at least 100 different media formulations available (Andreassen *et al*., 2020).

Adherent surfaces: For cells to increase in size and to generate muscle fibres, they are attached to 3D scaffolds, which physically exercise the cells. Scaffolds can be either synthetic or made up of edible materials, the latter may be preferable as they do not have to be removed from the final product (Allan, Ellis and De Bank, 2021; Campuzano, Mogilever and Pelling, 2020; MacQueen *et al*., 2019). Most biomaterials used as scaffolds in cell-based food production are not known to cause allergic reactions upon consumption. Careful attention needs to be paid to ensure materials derived from known sources of allergenicity are not inadvertently introduced. For instance, chitin or chitosan may trigger allergic responses in individuals who are also allergic to crustaceans.

Changes in physico-chemical properties: To obtain exponential cell growth and optimum cell density, the initial cell lines are constantly sub-cultured (Masters and Stacey, 2007). As in all cell lines that are allowed to propagate over many generations, there can be a risk that genetic or epigenetic drift may occur and this needs to be suitably monitored. (Ong *et al*., 2021).

Cryoprotectants: Cryoprotectants such as inulin and sorbitol can be used for cell storage (Elliot *et al*., 2017). Care must be taken that no carry-over into the final product occurs at concentrations that may cause a risk for consumers (MacDonald and Lanier, 1997; Savini *et al*., 2010).

Microbiological contamination throughout the process: As with all food processing and fermentation techniques, cleanliness of operations, ongoing monitoring and strict adherence to GHP and GMP are critical to avoid microbiological contamination, which may occur at any step of the production process. Application of the hazard analysis (and) critical control point (HACCP) system is also considered to be effective.

End-product food safety assessment

FAO, together with the World Health Organization (WHO), provides scientific advice to the Codex Alimentarius, the international food standard setting body, according to established principles and guidelines for the risk assessment of individual substances such as chemical additives, residues and contaminants (FAO, 2021a), microbiological risk assessment (FAO, 2021b), and whole food safety assessment (FAO and WHO, 2011). Molecular characterization, biochemical/physical analysis, assessment on toxicity and allergenicity, and nutritional composition analysis are the main elements of the generic whole food safety assessment (FAO and WHO, 2008). Experts suggest such standardized principles and

Table 5. Comparison of estimated environmental impacts of producing 1 kilogram of meat (conventional and cell-based) products in the United States of America

Impact category	*Beef*	*Pork*	*Poultry*	*Cell-based*
Land use (m^2/year)	92–113	15.8–18.3	9.5	5.5 (2–8)
Energy (MJ)	78.6–92.6	16.0–19.6	26.6	106 (50–359)
Greenhouse-gas emissions (kg CO_2-eq)	30.5–33.3	4.1–5.0	2.3	7 (4–25)

Source: Adapted from Mattick, 2018.

methodologies are applicable to conduct end-product food safety assessment of cell-based food. As of today, all risk assessments of whole food items are performed on a case-by-case basis, and no consensus has yet emerged as to when cell-based food products require a separate risk assessment.

Novelty and food safety considerations

Ong *et al.* (2021) has listed the key areas of research to enhance the food safety assurance of cell-based food products and stated that it is important to focus on the products' novelty. Despite the potential knowledge gaps and uncertainties that may be present, most identified hazards and concerns are unlikely to be new, thus prioritizing any novelty and differences in the process and the products is key (Ong *et al*., 2021).

What are the drivers and other key considerations?

Is it meat?

"Cell-culturing" technology can use both plant and animal cells as a source, and it can also lead to the production of acellular products such as milk, proteins or fats (Rischer, Szilvay and Oksman-Caldentey, 2020). While plant-based meat alternatives would not be categorized as meat, it is not yet clear whether this is also true for animal cell-based food products. Furthermore, if cell-based meat is categorized as meat and/or includes "meat" in its name, it may have various implications for relevant existing regulations for safety and quality assurance and labelling.

Who should be in charge?

The glossary of the World Organisation for Animal Health (OIE) states that meat "means all edible parts of an animal" (OIE, 2021), but an animal does not necessarily have to be involved in cell-based food production. The chosen nomenclature may therefore define who will oversee the management of cell-based food products at the regulatory level. Depending on the existing national regulatory frameworks and the categorization choice, cell-based food products can fall under the regulations of 1) meat/livestock (or other commodity-related sector), 2) alternative proteins, 3) novel foods, 4) food safety or 5) any combinations of the above.

Sustainability and environment

While less land use is expected for cell-based food production when compared to conventional livestock farming, this comparison is not straightforward as livestock farming also plays important environmental roles such as maintaining soil carbon content and soil fertility (Chriki and Hocquette, 2020). According to Mattick (2018), cell-based food production may also have a reduced potential for eutrophication, similar to conventional poultry production, but lower than beef or pork (**Table 5**).

The potential advantage of cell-based meat over livestock in terms of greenhouse gas emissions is not clear. Methane (CH_4) emissions are the primary concern with ruminants, in addition to carbon dioxide (CO_2) and nitrous oxide (N_2O). On the contrary, CO_2 is the main greenhouse gas associated with cell-based food production due to high fossil energy use. Lynch and Pierrehumbert (2019) concluded through their modelling studies that cattle farming may be a better option than cell-based meat production due to the high fossil-fuel energy use of the latter while assuming that current consumption patterns of meat are maintained. Mattick *et al*. (2018) suggested that

Inside a cell-based food production facility.

cell-based meat could involve some trade-offs, with high energy use leading to cell-based meat having potentially greater global warming impacts than pork or poultry, but lower than beef, while retaining possible gains in land use. Smetana *et al*. (2015) noted that among cell-based meat, the various protein alternatives (plant-based, mycoprotein-based, dairy-based) and chicken, cell-based meat had the highest environmental impact due to its high energy requirements but had lower land use and eutrophication potential than others. This may lead national authorities to consider, in addition to the definite need for food safety assurance, the need for overall environmental impact assessment and monitoring.

Food and nutrition security

Cell-based food must be produced indoors without being disrupted by extreme climate conditions; therefore, some developers claim that this may contribute to food security. Also, animal-derived products (meat, poultry, dairy, eggs, fish and aquatic food products) are a significant source of protein. Seeking more efficient ways to produce such proteins may help ensure nutrition security. Cell-based food production is presented by some as an option for those who want to act responsibly without altering their diets and cultural norms (Chikri and Hocquette, 2020; Shapiro, 2018). In addition, it is suggested that some countries may find the technology attractive for rendering their food supply more self-sufficient through cell-based production, without having to expand and intensify their current livestock and/or aquaculture production.

Animal welfare

Some developers substantiate the importance of this technology with the claim that it will drastically improve animal welfare (Bhat, Kumar and Fayaz, 2015) as the overall number of livestock raised and slaughtered are expected to be significantly reduced (Schaefer and Savulescu, 2014). However, as the first step is generally to conduct biopsies on animals to collect the cells, some may still have concerns over animal welfare issues since some animals would still need to be raised (Alvaro, 2019) and potentially slaughtered.

Food loss

From a food loss perspective, carcass utilization has been a challenging issue in conventional livestock farming. There are companies such as gelatine, pet food and fish feed manufacturers, that do utilize byproducts from livestock and therefore help to reduce food loss. Cell-based food production can provide the means of producing meat that greatly contributes to resolving issues related to carcass utilization (Stephens *et al*., 2018). However, the environmental impacts that may occur if other products of livestock farming, such as leather and wool, are produced separately and the economic impacts on such industries have not been explored (Mattick, Landis and Allenby, 2015).

Aquatic cell-based food products

While aquatic cell-based food production may open the door for aquatic resource-poor countries, this specific sector has an additional terminology-related consideration. Aquaculture products are usually referred to as "farmed" or "cultured" fish/seafood in order to be distinguished from wild-catches. Therefore, the terms used for cell-based food production of aquatic products may need different words to clearly differentiate aquaculture products from cell-based aquatic products (Hallman and Hallman, 2020).

Ethics, religion, lifestyle and philosophy

As the technology requires significantly fewer animals than conventional livestock farming, cell-based food products may be attractive to those who follow a vegetarian or vegan lifestyle. Any ethical issues raised with regards to cell-based food production will need due consideration. In addition, questions may be asked about whether such products can be considered Kosher, Halal and so forth keeping with the respective religions, values and/or traditions (Hamdan *et al*., 2018; Krautwirth, 2018).

Consumer perceptions

Not every consumer is necessarily knowledgeable of the science behind cell-based food production, and the terminology will eventually affect the meaning and connotations attributed to cell-based food products (Bryant and Barnett, 2019; Byrant *et al.*, 2019). Learning from past technology-driven food production, it is extremely important for the competent authorities to understand consumer perceptions in the local context and to start inclusive and transparent dialogue with them at the earliest stage possible (Nucci and Hallman, 2015).

Production costs and product prices

The first cell-based beef hamburger was created at a cost of USD 375 000 in 2013 (Kupferschmidt, 2013) and the first cell-based chicken nugget for USD 50 in 2019 (Corbyn, 2020). The production costs for cell-based meat have fallen but remain expensive for large-scale retail purposes. The growth media currently make up a bulk of the total production costs for cell-based meat (Choudhury, Tseng and Swartz, 2020; Swartz, 2021). In addition, substituting fossil fuel-based energy with renewable energy sources, maintaining adequate oxygen supply, wastewater treatment, transportation across the globe as well as labour expenses may also drive up the cost of the final product (Mattick, 2018; Risner *et al*., 2020). However, cell-based food products have the potential to be sold at USD 5.66 per kg by 2030, which is cheaper than some of the conventional meat currently on the market (Swartz, 2021).

Regulations for commercialization

If cell-based food products fall in a category that requires food safety assessments according to the existing regulatory frameworks, it is a responsibility of the food safety competent authorities to set up the procedures for such assessments. Also, if consumers demand special labelling, it is the relevant authorities' responsibility to establish a clear policy. Labelling is usually not a straightforward issue to manage, as it almost always requires the quantification of the ingredients/products. Thus, in this case, the policy will need to set a threshold of how much of the food has been produced through cell-based techniques for the purpose of labelling.

International trade

It is always important to consider the case of asynchronistic regulatory approvals. Some countries might not even require regulatory approvals, and some might struggle in establishing the approval process with limited technical capacities. However, the reality is that once a cell-based food product has been approved in one country, it is only a matter of time for that product to travel to another country where regulatory frameworks may be

Box 11.
FAO initiatives for cell-based food production

To provide timely and sound scientific advice on food safety aspects of cell-based food production, the following activities are ongoing.

- Three preliminary technical papers on:
  - nomenclature;
  - existing regulatory frameworks; and
  - existing production processes for food safety hazard identification.
- Consultations with the relevant international agencies and bodies (i.e. WHO, OIE, OECD, Codex), national food safety competent authorities, academia, research institutes and the private sector
- Case studies from two countries
- Global expert consultation (to be organized in late 2022 or 2023)

different. For this reason, it is important to have inclusive global dialogues at an early stage so that the sharing of information and experiences can benefit many low- and middle-income countries (LMICs). FAO has begun several initiatives to provide scientific advice on the food safety considerations of cell-based food products (**Box 11**).

What is the way forward?

As described in the food safety consideration section, the majority of the potential hazards in this technology is not new. Thus, it is important to learn from various past experiences and consider effective application of the risk analysis paradigm (Ong *et al*., 2021). In adopting several established safety assessment/evaluation methodologies in a range of disciplinary fields such as pharmaceuticals and food biotechnologies including both conventional and modern technologies, various hazards can be systematically identified, and relevant safety assessments can be appropriately conducted. There are also many risk-mitigating tools available in the area of food safety, such as good practices (GHP, GMP, GCCP and HACCP) and general principles and methodologies for the end-product whole food safety assessment (FAO and WHO, 2009). While there are many existing tools that can be useful for the safety assessment, additional steps for the safety assessment might be required for some particularly novel processes or products. Therefore, with cell-based food products, it is important to focus on the significant differences from existing foods so that effective methodologies to assess the safety of all elements can be established.

Many countries have not yet experienced an urgent need to conduct food safety assessments of cell-based food products. However, preparedness is key; and it is important for the competent authorities to start dialogues with various stakeholders including consumers, private sector, civil society, partner agencies and policy makers. Experts have emphasized the importance of securing inclusiveness and transparency, while preparing for necessary regulatory actions (FAO and WHO, 2016). For LMICs, it is also important to initiate the assessment of technical capacity for safety assurance of cell-based food products as they may benefit from having dialogues with other countries and international organizations to learn from their experiences and to obtain technical assistance. Engaging in the relevant global discussions is recommended for all countries, as shared information and data can only contribute to the global good, without duplication of efforts.

Food safety is a joint responsibility. Active and transparent communications through public and private collaboration are crucial not only to better prepare the industries and governments, but to maximize the effectiveness of their safety assurance programmes. Competent authorities' clear food safety guidelines for the private sector would enable and promote the "safety by design" approach to jointly aim at assuring food safety of cell-based food production

5.
Food safety considerations for agriculture within urban spaces

Vegetables grown
in a vertical farm.

At present, over half of the world's population live in cities, and by 2050, two-thirds of the global population are expected to live in urban areas, with 90 percent of this increase taking place in Asia and Africa (FAO, 2019a). Rapid urbanization and the expansion of cities across the globe (Malakoff *et al*., 2016) is placing urban food systems in a unique position to help shape the transformation of the overall agrifood systems. While up to 70 percent of all food produced globally is destined for consumption in urban areas (FAO, 2020), urban agriculture is also on the rise in response to growing population in cities. As urban food systems develop, factors like changing demographics, ensuring food security, evolving food preferences, health concerns and climate change will compel greater engagement in issues related to urban agriculture (Knorr, Khoo and Augustin, 2018).

Urban agriculture can be defined as "the growing of plants and raising of animals for food and other uses within and around cities and towns..." (FAO, 2007). Therefore, it encompasses agriculture from both urban and peri-urban contexts. For the purpose of this brief, we focus on agriculture and food production that takes place only within an urban space, i.e. agriculture from an intra-urban perspective.

Urban agriculture or farming can repurpose unused land and space, provide year-round access to fresh food and encourage healthier diets, create employment and livelihood opportunities, and promote affordable food prices (Carbould, 2013; Poulsen *et al*., 2014). The most important crops of urban farmers tend to be perishable food products and have the locational advantage of being close to the consumers (FAO, 1996). By making it possible to grow food closer to population centres, food miles can be reduced (FAO, 2014; Weber and Matthews, 2008). While the contribution of reduced food miles to the total greenhouse gas (GHG) emissions arising from urban agriculture is still under debate (Weber and Matthews, 2008), the vast majority of GHG emissions are suggested to be mainly attributed to the production and storage phases of food (Mok *et al*., 2014; Santo, Palmer and Kim, 2016).

Urban farming operations can be of different types and tend to vary by scale. They can be geared towards individual or community consumption, or they can be used for commercial profit (owned by small, medium or large-scale private companies, small-scale family urban farms, community cooperatives, and so on) (Andino, Forero and Quezada, 2021). Urban farms can be found in gardens formed in backyards, rooftops (greenhouses or open-air) and balconies, roadside gardens, community gardens set up in vacant lots and parks, edible walls and indoor farms (Santo, Palmer and Kim, 2016). Open air urban farms can help cool down cities in the summertime, provide valuable habitats for bees and other pollinators, and retain precipitation thereby providing flood-risk mitigation (Dekissa *et al*., 2021; Rosenzweig *et al*., 2015; Santo, Palmer and Kim, 2016). Urban agriculture can also include production of non-food plants as well as animal husbandry, beekeeping, aquaculture, and even insect farming for food and feed.

Innovations in indoor farming techniques, where crops can be layered in tiers, are challenging the viewpoint of looking at arable land as one of the metrics for food security (Galeana-Pizaña, Couturier and Monsivais-Huertero, 2018; Park, 2021). Vertical farming and micro-farming (Beyer, 2019), either with soil or soilless using the hydroponic, aeroponic or aquaponic systems, have become popular approaches in mainly indoor forms of urban agriculture.[14,15,16,17] Such farms are pushing the limits of innovation, using technology to digitally monitor and tightly control environments (temperature, light intensity, humidity and nutrient conditions) that allow them to grow food all year-round, while avoiding challenges like erratic weather patterns and pests (Al-Kodmany; 2018; Despommier, 2011). These systems also tend to use less water compared to outdoor farms. For instance, water used in hydroponic farms can be captured and reused rather than being allowed to drain and run-off into the environment. This is especially important in areas where water is already scarce and drought conditions are exacerbated by climate change (Al-Kodmany, 2018).


A community garden.

Urban farms, when designed right, can contribute to improving food security issues in cities (Corbould, 2013). However, there are constraints on the quantity, and depending on the agricultural approach, on the diversity of food that can be grown within urban areas (Clancy, 2016; Costello *et al*., 2021). A study showed that by dedicating every potentially suitable vacant lot to farming, it would only satisfy the needs of 160 000 people (erstwhile population: 8.1 million) living in New York City, United States of America (Ackerman, Dahlgren and Xu, 2013).

Unlike open farming, some indoor farming setups may need pollination to be carried out manually, which can be labour intensive and costly. In addition, encroachment of expanding cities into the surrounding productive farmlands or areas with wildlife will need to be factored in to weigh the environmental impacts of sustaining urban food production.

Urban agriculture approaches like vertical farming can be energy-intensive, which not only has environmental ramifications but can also bring economic uncertainties (Love, Uhl and Genello, 2015; The Economist, 2010). Martin and Molin (2019) found that electricity demands, growing medium, transportation and packaging materials all have significant impacts on the environmental sustainability of a vertical hydroponic system. Based on their findings by replacing coir as the growing medium, using paper pots instead of plastic ones, choosing better energy sources such as LED lights powered by solar energy can lead to reductions in the environmental impacts of vertical hydroponic systems. While investing in renewable energy sources would help to lower the carbon footprint of such systems, there may be other trade-offs to consider, for instance, the price of solar energy, and energy backups that may be reliant on fossil fuel, among others. In addition, extreme weather events, exacerbated by climate change, can cause power supply outages, which can be very detrimental to such agricultural systems.

14 Unlike traditional farming which takes place horizontally, vertical farming produces food in vertically stacked layers. The setup is commonly integrated inside buildings like skyscrapers, or repurposed warehouses and shipping containers, with the latter having the potential to be moved around as needed.

15 In a hydroponic system, plants are grown in water and chemical fertilizers or nutrient solutions without the presence of soil.

16 In an aeroponic system plants are grown with their roots exposed to a nutrient-laden mist environment. https://modernfarmer.com/2018/07/how-does-aeroponics-work/

17 In an aquaponic system fish are raised with the fish wastewater serving as the water and nutrient source for plants. This type of farming can be established in both indoor and outdoor environments.

What are the food safety implications to be considered?

As **in all food production systems**, food safety aspects in an urban food system will need to be considered throughout the farm to fork continuum extending from how the food is produced, stored, packed, sold and consumed. Urban farming is associated with both benefits and challenges when it comes to food safety. Some of these advantages include enhancing traceability, and fewer food miles that can prevent food spoilage and therefore, also reduce food loss (Despommier, 2011). According to published literature, consumers may perceive locally produced food as safer than produce grown elsewhere (Khouryieh *et al*., 2019).

Indoor urban farms can prevent risks of foodborne illnesses arising from wildlife (deer, birds, feral pigs) having access to produce as it can happen in open fields (Jay-Russell, 2011) and reduce uncertainties of weather, which is becoming more unpredictable due to climate change. A few food safety challenges with urban farming that need to be considered are discussed below.

Concerns arising from soils used in urban agriculture: The location where an urban farm can be set up is a very important food safety consideration as land use in urban areas can leave a legacy of contaminated soil. Therefore, it is important to have knowledge of the history of use of the land where produce will be grown. Multiple contaminants may be found in urban soils at varying levels.

Areas or properties which may have real or perceived contamination issues that pose a serious threat to the safety of food grown there fall under brownfields. These include abandoned gas stations, scrap yards, former factory sites or where older structures have not been demolished correctly, places near dry cleaners, illegal dumping sites, landfills, among others. Sites of former commercial or industrial buildings can be contaminated with asbestos, petroleum products, lead-based paint chips, dust and debris. Older cities tend to have higher levels of heavy metals because of historic use of certain products that contained such chemical hazards. The soil around older homes and under roof drip lines can have higher concentrations of lead from paint and other building materials used on the structures. Air pollution, paint, litter and trash, treatments on wood, coal ash, sewage, and pesticides leave behind various contaminants like heavy metals (such as lead and arsenic), and polycyclic aromatic hydrocarbons (PAHs) as well as antimicrobial resistant microbes that can enter the food chain through urban farming (Defoe *et al*., 2014; Kaiser *et al*., 2015; Marquez-Bravo *et al*., 2016; Nabulo *et al*., 2012; Säumel *et al*., 2012; Wortman and Lovell, 2013; Yan *et al*., 2019; Zhao *et al*., 2019).

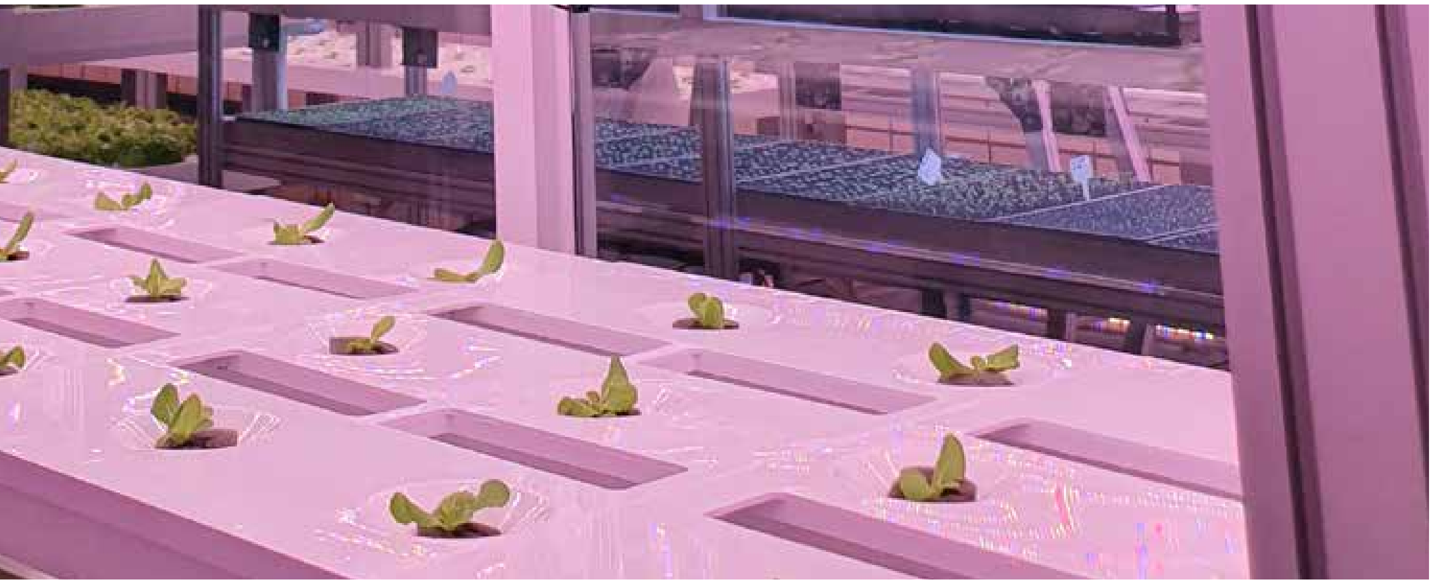
Norton *et al.* (2013) found that produce grown in open-air farms close to historic mining areas can get contaminated with heavy metals from direct contact with soil. Studies have found that the concentration of heavy metals in urban soils and plants can vary with distance from contamination "hot-spots" such as heavily trafficked roads (Antisari *et al*., 2015; Werkenthin, Kluge and Wessolek, 2014). While it is difficult to establish a definite quantitative relationship between heavy metal content in soil and in produce, it has been shown that plants can uptake and accumulate heavy metals like lead, cadmium, barium and arsenic from the soil (Augustsson *et al*., 2015; Izquierdo *et al*., 2015; McBride *et al*., 2014). For instance, rice is known to accumulate heavy metals like cadmium and arsenic, both in the plant as well as the grain, which increases risk of exposure to these chemical hazards (Muehe *et al*., 2019; Suriyagoda, Dittert and Lambers, 2018; Zhao and Wang, 2020). A study by Brown, Chaney and Hettiarachchi (2016) found that lead tends to concentrate mainly in the roots implying that root vegetables like carrots, beets and potatoes may have a higher concentration of lead than produce that is above ground.

Regardless of former use, soils used for urban farming may require testing and if necessary, remediation to lower the concentrations of contaminants to an acceptable level. However, testing for an array of contaminants is not always feasible for urban gardeners. In addition, remediating the soil can be a huge challenge as well. Therefore, some urban farmers tend to remove the old soil, add compost or other regulated soil amendments like biosolids to "dilute" out any heavy metals in the soil, or they sometimes apply phosphate-based fertilizers to reduce bioavailability (Wortman and Lovell, 2013). Sometimes an impermeable barrier is placed on the ground and new soil is added on top. In addition, erecting suitable barriers between urban farms and busy roadways are also advised as a means to keep produce safe from contamination issues.

Other chemical hazards: The warmer microclimates usually found in urban areas (or urban heat island effect) can provide ideal habitats for certain pests (Meineke *et al*., 2013) prompting growers in open-air urban farms to use higher doses of pesticides to protect their farms. There is currently a lack of studies on the identification and quantification of pesticide residues found in fresh produce grown in urban farms. Overuse of pesticides in the urban environment (from urban farms and general use in residential areas – lawn, turf and home gardens) not only impacts human health through the food chain but also affects the biodiversity in the area and the aquatic ecosystem when the chemicals find their way into the surrounding waterbodies (Meftaul *et al*., 2020). Many municipalities around the world have regulations to control pesticide applications in urban areas with close proximity

to residential locations. Additionally, indiscriminate use of fertilizer or compost application may pollute surface water or storm run-off with excessive quantities of nitrogen and phosphorus, which can potentially exacerbate conditions leading toxic algal blooms in the waterbodies in or near the cities (Wielemaker *et al*., 2019). However, it must be pointed out that the potential for eutrophication and algal blooms is not unique to urban agriculture. Due to high anthropogenic activity, microplastics can be pervasive in urban environments, soil and atmosphere as well as waterbodies (Evangeliou *et al*., 2020; Qiu *et al*., 2020). However, the impact of this pollutant on urban farming and subsequently on human health is still unclear (Fakour *et al.,* 2021; Lim, 2021).

Certain green leafy vegetables like lettuce can be a source of high levels of dietary inorganic nitrates and can pose possible health risks (EFSA, 2008; FAO and WHO, 2002; Quijano *et al*., 2017). Application of excessive nitrogen-based fertilizers is one of the major ways nitrates can accumulate in produce (Fewtrell, 2004). However, Jokinen *et al*. (2022) found that soilless cultivation methods like hydroponic systems have a potential to serve as functional mechanisms to control nitrate content in green leafy vegetables through application of glycinebetaine to the roots of the plants.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Water source: While urban centers are increasing globally, sanitation coverage (collection and treatment) has not kept pace with this growth everywhere (Larsen *et al*., 2016). Contamination of urban produce (during growth or post-harvest) with pathogenic organisms or chemical hazards from usage of urban wastewater (for irrigation or postharvest cleaning) that is untreated or improperly treated is an important food safety issue (Strawn *et al*., 2013). A number of foodborne disease outbreaks have been attributed to consumption of fresh produce that was irrigated with wastewater. Apart from foodborne pathogens – different strains of *Salmonella*, enterohemorrhagic *Escherichia* coli, *Listeria monocytogenes*, and viruses such as norovirus – found in wastewater, the issue of antimicrobial resistance can also be exacerbated by the use of wastewater in agriculture (Adegoke *et al*., 2018; Strawn *et al*., 2013). Improperly treated wastewater can also be a source of contaminants like pharmaceuticals, as well as act as a reservoir of antimicrobial resistance by being an ideal environment for pathogens to persist. Treatment of wastewater often have limited impact on antimicrobial resistance genes, which do not degrade easily and can be transferred between microbial communities in the environment (horizontal gene transfer) conferring and spreading resistance (Alexander, Hembach and Schwartz, 2020; Mukherjee *et al*., 2021; Paltiel *et al*., 2016; Pruden *et al*., 2006; Zammit *et al*., 2020).

The quality of water used and its safe reuse in vertical farming systems is a major consideration for ascertaining food safety risks. In an aquaponic system, fish feces can be a potential source of Shiga toxin-producing *E. coli*. According to Wang, Deering and Kim (2020), Shiga toxin-producing *E. coli* was found in the water and in the root system of plants, but not detected in the edible portion of the plants. However, if the water tests positive for this microbiological contaminant, it is possible that accidental splashes (during growth or harvest) can lead to contamination of the edible parts of the plant. This is of food safety concern especially if the produce is consumed uncooked. No presence of *Listeria* spp. or *Salmonella* spp. were found in the aquaponic or hydroponic systems under study (Wang, Deering and Kim, 2020). In aquaponic systems, sources of microbiological contamination can also be introduced through contaminated fish stocks, through visitors, improper handling measures and through the damaged root systems of plants.

While the safest option in food production is the use of potable or drinking water quality, it is not always a feasible or responsible solution considering increasing water scarcity in many areas. Other types of water can be made fit-for-purpose provided that they do not affect the safety of the final product (FAO and WHO, 2019). Raising awareness among farmers about wastewater use in urban agriculture and the various health risks associated with it will be important for improving food safety in the urban produce food chain (Antwi-Agyei *et al*., 2015; Ashraf *et al*., 2013). A publication by FAO lays out some low-cost and low-tech practices that farmers can utilize for wastewater treatment

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as well as safe irrigation practices that can be adopted to grow food safely (FAO, 2019b).

Air pollution: Air pollution (ozone, carbon monoxide, sulfur oxides, nitrogen oxides, ammonia, methane, particulate matter, dioxins, heavy metals, polycyclic aromatic hydrocarbons) is increasing in urban areas and can be difficult to control. Urban air quality is affected by a number of anthropogenic factors,[18] such as fossil fuel combustion and greenhouse gas emissions from transportation, agriculture activities, energy supply, industries, among others (Domingo *et al*., 2021). Climate change also alters the concentration and distribution of air-borne pollutants. While traffic-related air contaminants can disperse quite widely, buildings can act as barriers to focus these hazards in a given area.

Studies have shown that air pollution can reduce the yield and nutritional quality of certain crops grown in urban areas (Agrawal *et al*., 2003; Thomaier *et al*., 2014; Wei *et al*., 2014; Wortman and Lovell, 2013). However, the impact of ambient air quality on open-air urban farming and subsequently on the safety of the food produced is still not fully explored. Certain contaminants like dioxins, heavy metals and polycyclic aromatic hydrocarbons can accumulate in plants and can pose a risk when consumed (Ortolo, 2017). Particulate matters can accumulate on leafy vegetables and act as vectors for other contaminants, such as heavy metals. However, this risk was reduced when plants were thoroughly washed with potable water before consumption (Noh, Thi and Jeong, 2019).

Animal husbandry: Raising animals within urban limits may have food safety implications that are discussed below. However, this activity is more suited for peri-urban areas (Taguchi and Makkar, 2015).

An increasing demand for meat and dairy products, especially in low to middle income countries, combined with lack of sufficient cold-chains can be attributed to the rise of urban livestock farms. Animals such as goats, sheep, cows, pigs, poultry (chickens, ducks) and buffaloes can be found in urban farms across some regions of the world (FAO, 2001). Animal husbandry in cities (on land or offshore) represent an additional source of income through sale of various animal-based food products as well as

18 The **Urban Air Action Platform** is a UN-coordinated platform which brings together data collected on air quality by governments, NGOs, companies, local community groups and individuals. https://www.unep.org/explore-topics/air/what-we-do/monitoring-air-quality/urban-air-action-platform?_ga=2.107580418.1663653424.1629668659-41112530.1629668659

manure that can be sold for improving urban soil fertility.[19] There are a number of potential hazards to human health that can be associated with urban livestock systems arising from poor hygiene, cramped conditions for keeping animals, flies and parasites that can breed on animal waste, as well as the risk of zoonoses. Backyard poultry can carry foodborne pathogens like *Salmonella* sp. that can spread to humans if proper hygienic practices are not implemented (News Desk, 2021; Tobin *et al*., 2015). While most people recover from such illnesses without antibiotics, certain *Salmonella* strains are increasingly showing resistance to commonly used antibiotics, complicating public health concerns (CDC, 2021; Wang *et al*., 2019).

Exposure to chemical hazards like dioxins can occur by feeding livestock plant material gathered from the roadside that is heavily trafficked. These chemical hazards tend to accumulate in the fatty tissues of animals and therefore enter the food chain. Inadequate infrastructure in place for animal slaughter, disposal of carcasses, and waste management (removal of manure and urine) can also pose a number of food safety risks to people living in the vicinity as well as to consumers (Alarcon *et al*., 2017). Proper access to veterinary care and regulations limiting flock or herd numbers in urban spaces are also important considerations.

Vertical fish farming is an emerging approach in aquaculture where fish are reared in a vertical, multi-trophic, mostly closed-loop systems. These structures can be built in urban areas where land is scarce or even offshore (Tatum, 2021). How such systems use and re-use water, treat and dispose effluents from fish and use antimicrobial agents will not only determine the safety of the produced fish but may also influence other public health issues such as potential for eutrophication in nearby waterbodies.

Urban foraging: While this brief focuses on obtaining food by intentionally growing it in an urban space, it will be remiss if gathering or foraging for food in urban areas is not mentioned.[20] A clearer understanding of potential safety concerns and nutritional value associated with urban foraging (Stark *et al*., 2019) is needed as there is a growing recognition that foraged foods are an often-neglected component of urban food systems. More research is needed to determine the extent of exposure to various biological hazards (pathogens and parasites) and chemical contaminants (heavy metals, pesticides and so on) found in urban environments through plants that are collected from both private and public spaces in the urban landscape.

Urban waterways can become polluted from runoff from streets, industrial sites, and gardens. In addition to various waterborne pathogens and parasites, knowledge of which aquatic plants can absorb chemical contaminants like heavy metals from water (Li, Xu and Luan, 2015) is imperative when harvesting them for consumption.

While Gallagher *et al*. (2020) found lead in urban foraged apples from Boston, United States of America, the level of lead was lower than what the United States Environmental Protection Agency considers safe in a day's supply of drinking water from the tap. However, systematic evaluation of potential contaminants commonly found in urban landscapes will be needed to adequately address public health concerns.

What is the way forward?

Growing urbanization is driving profound changes in agrifood systems with urban agriculture undergoing rapid development. However, there is inadequate research on potential human health risks arising from consuming food specifically produced within urban spaces. Improved availability of fit-for-purpose land/space and water, access to markets, greater capital and operating funds, opportunities for technical training to improve the knowledge base of urban producers and their agricultural skills, and development of appropriate regulatory frameworks and strategies are some of the areas that also determine the success of urban agriculture. Greater attention also needs to be paid to infrastructure for hygienic intra- and interurban processing, storage and transportation, as well as integration of urban food production into urban planning to ensure land allotments are at a safe distance away from main roads and other contamination sources to facilitate safe food production in urban areas.

Further development of urban agriculture entails increasing access to land which may propel efforts to remediate and rejuvenate brownfields. However, turning brownfield sites into areas that are safe and suitable for food production is often not straightforward and requires

[19] In 2018, the world's first floating or offshore dairy farm was set up in the Port of Rotterdam, the Netherlands (Fry, 2018).

[20] Urban foraging involves collecting food, primarily fruits, mushrooms, leafy greens and nuts, from plants in cityscapes not deliberately grown for human consumption.

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greater engagement with municipal authorities and landowners, regular monitoring for contaminants in these spaces, and knowledge dissemination among the public (Miner and Raftery, 2012).

The concept of creating a "circular city" is gaining attention whereby various organic disposals from different processes are repurposed as resources to promote agricultural productivity in urban areas (Ellen MacArthur Foundation, 2019; Skar *et al*., 2020). However, care must be taken to ensure that the inputs into such a closed-loop bioeconomy are safe to use and that sources of contamination are not introduced as this can facilitate concentration of contaminants if adequate monitoring and treatment procedures are not put in place.

Advancements in digital technologies may allow urban farmers to "farm from afar" whereby multiple urban farms can be accessed remotely, for instance to tweak conditions – soil pH value, nutrient level, light intensity, among others – as needed or even to sound alarms if manual interventions are required. Digital innovations may also facilitate periodic testing for foodborne pathogens at various points in vertical farms as well as enhance traceability mechanisms to enable identification and removal of contaminated produce before it becomes a public health issue.

In order for cities to foster inclusive, nutritious, safe and sustainable urban food systems and to effectively address challenges, good governance (mechanisms, capacities, policies, financial support) specific to urban food systems will be needed. This is a transdisciplinary area that needs multisectoral engagement from local governments, civil society, the private sector as well as municipal, provincial and national governments (Knorr, Khoo and Augustin, 2018; Ramaswami *et al.*, 2016; Tefft *et al.*, 2020). However, lack of suitable regulatory frameworks to govern urban agriculture has been identified as a barrier for market expansion in different studies (FAO, 2012; Sarker, Bornman and Marinova, 2019). Regulation of urban agriculture would require considerable resources, and currently many LMICs lack the infrastructure and institutional framework to monitor it (Merino *et al.*, 2021)

6. Exploring circular economy through plastic recycling

Fruits chopped and packaged in plastic for sale.

W**e are living in the Plasticene era** or the age of plastics where they are an integral part of everyday life (Haram *et al*., 2020). Plastics are made up of an array of synthetic or semi-synthetic polymers, with varying chemical compositions, derived primarily from fossil fuels (Wiesinger, Wang and Hellweg, 2021). It is estimated that over 8.3 billion metric tonnes of plastic have been produced since the 1950s (Geyer, Jambeck and Law, 2017), which marks the beginning of the time frame of compilation of global manufacturing data on plastics. Plastics continue to be one of the fastest growing sectors. Due to properties that make them versatile, lightweight, durable and cheap to produce, they can be found in a number of applications – building and construction, electrical and electronics, automotive industry as well as agriculture and healthcare sectors (Yates *et al*., 2021).

However, plastics are among the most ubiquitous and persistent pollutants on Earth (Dris, Agarwal and Laforsch, 2020). Some of the very properties that make them useful for certain applications also make them resistant to degradation when they reach the end of their intended purpose allowing them to accumulate in our environment for decades or longer. Plastics that are littered or dumped in landfills can be found in soils (FAO, 2021a) or find their way into rivers by rain or wind, and eventually end up in the ocean (Drummond *et al.,* 2022). An estimated 8 million metric tonnes of plastic waste enter the ocean each year (National Academies of Sciences, Engineering, and Medicine, 2021). However, the endurance of plastics is dependent on their environment, with various environmental conditions contributing to the breakdown or fragmentation of plastics into macro-, micro- and nano-sized particles (**Box 12**). Apart from being pervasive, plastic pollution is also a cross-boundary issue (Borrelle *et al*., 2017),[21] with extreme weather events, such as hurricanes and flooding, linked to climate change potentially exacerbating the distribution of plastic pollution in the terrestrial and aquatic ecosystems. Moreover, manufacturing and refining of plastics in addition to extraction and transport of fossil fuels for plastic production make it one of the more greenhouse gas intensive industries, contributing to climate change (CIEL, 2019).

According to United Nations Environment Programme, the natural capital cost of plastic use in the consumer goods sector, from environmental degradation, greenhouse gas emissions, and health impacts, was estimated to be USD 75 billion annually, but the figure is likely to be a significant underestimate (UNEP, 2014). Over 30 percent of the figure is estimated from greenhouse gas emissions from raw material extraction and processing, with marine pollution amounting to the most significant downstream cost.

21 Plastic in a bottle, 2021: https://pame.is/projects/arctic-marine-pollution/plastic-in-a-bottle-live-map, Wageningen University and Research.

Box 12. The issue of microplastics

Microplastics (>5 mm), a term coined in 2004 (Thompson *et al*., 2004), are created when plastics, from a variety of sources, get weathered and broken down into smaller pieces (1µm to 5 mm) in the environment through processes such as photodegradation, physical abrasion, hydrolysis and biodegradation (Evangeliou *et al*., 2020). They can also be produced industrially and find application in various products, such as cosmetics and abrasive cleaners (SAPEA, 2019).

Microplastics are so ubiquitous in our environment that Brahney *et al*. (2021) suggested that they now circulate around the Earth, almost like global biogeological cycles, with distinct "resident" times in the atmosphere, oceans, cryosphere and terrestrial systems (Evangeliou et al., 2020; Hou *et al*., 2021). While methods to detect and track their distribution in the environment are improving (Evans and Ruf, 2021), there is no reliable data on the quantitative global estimates of their presence in our environment. Inhalation and ingestion from various sources are the two major known routes that humans are exposed to microplastics (Rahman *et al*., 2021), with aquatic products being one of the more well-studied sources of dietary exposure (Garrido Gamarro *et al*., 2020). New sources of microplastics – fishmeal, infant feeding bottles, organic fertilizers and table salt – that can find their way into our diets are also being routinely identified (Lee *et al*., 2019; Li *et al*., 2020; Thiele *et al*., 2021; Weithmann *et al.,* 2018).

Microplastics represent a diverse class of contaminants as they are of different orders of magnitude in size, come in diverse shapes (e.g. fragments, fibres) and are composed of various polymeric materials and chemical mixtures. This diversity imparts distinct transport and fate characteristics as well as determines how they impact both biota and humans. However, the mechanisms of action by which microplastics pose a risk to human health is still not well understood (Lim, 2021; Rahman *et al*., 2021), and one of the major challenges in risk assessment and exposure characterization is the lack of standardization of analytical methods for effective sampling, identification and quantification of microplastics, which leads to data incomparability.

Various microorganisms, including opportunistic human pathogens, are known to colonize microplastics and form biofilms (Amaral-Zettler, Zettler and Mincer, 2020). Microplastics can also facilitate distribution of potentially harmful pathogens, such as *Vibrio* spp., pathogenic serotypes of *Escherichia coli*, invasive algal species, and pathogenic fungi, into new areas, as well as facilitate the spread of antimicrobial resistance (Amaral-Zettler, Zettler and Mincer, 2020; Gkoutselis *et al.*, 2021; Pham, Clark and Li, 2021).

Various chemicals, either originating from the polymeric raw materials of the plastics themselves or through adsorption from the environment, have been identified in microplastics that may potentially pose a health risk to humans (Diepens and Koelmans, 2018; Arp *et al.*, 2021). These include persistent organic pollutants, endocrine disruptors, heavy metals, flame retardants, and pthalates that can leach into the environment and therefore the food chain (Campanale *et al*., 2020; Chen *et al*., 2019; Lim, 2021; Rahman *et al*., 2021). Whether ingesting microplastics directly significantly raises our exposure to these chemicals is a question that still needs to be determined (FAO, 2017; FAO, 2019; Lim, 2021). Nanoparticles (<1 µm) that are small enough to penetrate and accumulate in tissues and cells can be a cause for concern (Fournier *et al.*, 2020) and more studies are needed to understand the scope of this impact

Plastics in agrifood systems and circular economy

Modern agricultural practices include the use of plastics in a wide variety of applications, such as mulch films, bags/sacks, silage films, driplines, plant protectors among others. A new report by FAO provides an overview of the extent of plastic use in agriculture, the benefits and trade-offs, followed by recommendations on how to reduce their potential for harm to human health and the environment (FAO, 2021a).

Plastic packaging of food acts as barriers for contamination thereby prolonging the shelf-life, preserving the quality and maintaining the safety of food products. Since food supply chains often involve moving food products across long distances, packaging also plays an important role in facilitating the transit of food (Han *et al*., 2018). While it is estimated that approximately 42 percent of plastics produced globally since the 1950s have been used for packaging, it is difficult to obtain data on the exact amount of plastic packaging used exclusively for food (Geyer, Jambeck and Law, 2017; Schweitzer *et al*., 2018).

Most plastic packaging are engineered for function and tend to be used only once with generally no appropriate end-of-life management processes in place. Prevention and management of food waste often provided as the justification for single-use plastics. However, according to Schweitzer *et al.* (2018) per capita food waste and plastic waste rates in Europe remain one of the highest globally, demonstrating that food packaging that is not fit-for-purpose to the food needs may not sufficiently contribute to preventing food loss and waste (Verghese *et al*., 2015).

On the other hand, recycling of plastic packaging remains a challenge as plastics tend to be made of different types of polymers, mixed with various processing additives (flame-retardants, colourants, plasticizers, UV-stabilizers and so on). In addition, packaging in general can be comprised of multi-materials – plastics, glass, metal and so on – which makes it difficult to separate before recycling (Hopewell, Dvorak and Kosior, 2009). It is estimated that as of 2015 only 9 percent of the approximately 6 300 metric tons of plastic waste generated globally has been recycled (Geyer, Jambeck and Law, 2017). Plastics that do get recycled cannot often be turned into products of the same quality and can get relegated to lower value applications that may not be recyclable again after use (Ellen MacArthur Report, 2016).

To help overcome some shortcomings commonly associated with mechanical recycling (Schnys and Shaver, 2020), various biorecycling and chemical recycling methods are under development – the former uses microbes or insects to break down plastics (Espinosa *et al*., 2020; Yang *et al.,* 2015), while the latter can recover the petrochemical components of the polymers which can then be used to remanufacture plastics (Lantham, 2021; Meys *et al*., 2020; Zhao and You, 2021). Most of these recycling methods are still in their infancy and come with their own technical challenges (Rollinson and Oladejo, 2020).

Scientific advancements in recycling approaches, development and introduction of new materials, improvements in sorting and reprocessing technologies, are offering opportunities to move from a linear to a circular economy when it comes to plastic packaging. In addition, as awareness of plastic pollution grows together with efforts to reduce demand for fossil fuels and recognition of the short term impacts of clean-up activities, many are advocating for a change in how we manufacture and use plastics in agrifood systems (Yates *et al*., 2021). Circular economy is a model which aims to close material loops by keeping resources in use for as long as possible to extract the maximum value out of them while minimizing the negative impacts associated with disposing them (Stahel, 2016). This concept has been gaining a lot of attention globally as a way to overcome our linear way of consumption of resources (Ghisellini, Cialani and Ulgiati, 2016). Redesign-reduce-reuse-recycle are the main options under circular economy approach with respect to plastic food packaging, whereby the usage of single-use (and virgin) plastics is reduced while encouraging the effective reuse and recycle of plastics already in circulation through better coordinated strategies, and redesigning our current systems to be more sustainable by integrating greater environmental and social responsibility throughout the supply chain (FAO, 2021b).

In addition to reusing and recycling of plastics, biobased plastics are gaining attention as environmentally friendly alternatives with similar functionality to conventional petroleum-based non-biodegradable plastics (van der Oever *et al*., 2017). Although still ill-defined at this point, the term “bioplastics” tend to be used interchangeably with either biobased plastics or biodegradable plastic, or both. Biobased plastics are made from renewable natural resources (such as corn, sugar cane, potatoes, seaweeds, and others) and can be engineered to be either biodegradable or non-

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Plastics littered near a waterbody.

biodegradable. Plastics made from materials that can degrade naturally by microorganisms are biodegradable plastics. Compostable plastics are a subset under this category (Davis and Song, 2006; FAO, 2021a; Lambert and Wagner, 2017).

While such alternative plastics are available, they do not yet represent viable substitutes for the conventional plastics, for most applications. Plastics containing variable amounts of both petrochemical and biobased components can also be found labelled as "bioplastics", but they are not easily biodegradable (FAO, 2017). In addition, a number of plastics marketed as "biodegradable" do not degrade, as quickly or effectively, in the natural, open environment if they are littered or found in landfills (Napper and Thompson, 2019; Nazareth *et al*., 2019), leading to concerns about introducing additional sources of microplastics (and nanoplastics) (**Box 12**) in the environment (FAO, 2017; Weinstein *et al*., 2020). Bioplastics may require industrial composting conditions to break down properly and therefore, such plastic waste will have to be properly managed and routed to specialized recycling facilities, which may not be compatible with the existing waste management options (Ferreira-Filipe *et al*., 2021; Silva, 2021). In addition, with a number of bioplastics derived from carbohydrate-rich plants (corn, sugarcane, etc.), there are a number of concerns raised, for instance, potential for exacerbating deforestation, pesticide usage, and societal impacts linked to competition from food production.

What are the the food safety implications to be considered?

While the concept of circular economy for food packaging seems feasible in theory, recycling and reuse of food packaging require careful considerations. Apart from requiring post-consumer collection and sorting of packages of mixed materials, as well as giving consideration to the extent of contamination originating from their initial use, economic viability of the recycling process, and constraints

from lack of appropriate legislative frameworks, there are also food safety concerns that arise from the plastic recycling processes that need to be acknowledged for food-contact applications.

Using recycled or virgin plastics or a mixture of both, if not adequately assessed and controlled, have the potential for introducing chemical hazards into foods and beverages. Food contact materials are not inert and contain many different chemicals from known components that can migrate from packaging into food (Groh *et al*., 2019).[22] Some of these chemicals are not added intentionally (also called the Non-Intentionally Added Substances or NIAS) – known or unknown impurities, reaction products and breakdown products of the ingredients used to make the food contact materials or can be derived from possible contaminants from the manufacturing processes, or through indirect sources such as printing inks, coatings, adhesives and secondary packaging. Substances of concern may also arise if non-food grade polymers enter the recycling process for food-grade materials, for instance, the presence of brominated flame retardants originating from electric and electronic equipment in black food contact articles (Samsonek and Puype, 2012).

Chemicals that can migrate from food contact materials (from both recycled and virgin plastics) and are of particular food safety concern include poly-fluoroalkyl substances (PFAS), phthalates, 4-nonlyphenol, mineral oils, among others (Edwards *et al*., 2021; Kitamura *et al*., 2003; Lyche *et al*., 2009; Rubin, 2011; Yuan *et al*., 2013). These chemical hazards can pose various health risks like carcinogenicity, mutagenicity, reproductive toxicity, and others through various modes of action, such as persistence and bioaccumulation, endocrine disruption, among many. Therefore, risk assessments are required to take into account the extent of actual exposure to such chemicals. But not all regions have validated methods to measure the migration of chemicals and therefore, assess the potential health impacts. This migration or leaching depends on a number of factors, including temperature and time of contact between food and packaging; food matrix properties and composition; presence of functional barriers; and physicochemical properties of packaged food or beverage, such as pH. (Fang and Vitrac, 2017).

As awareness about these chemical hazards grow, functional alternatives for them are being sought out, sometimes with potential adverse health consequences either not fully characterized or no different than the original option. For instance, because of potential health concerns arising from migration of bisphenol A (EFSA, 2015; FAO and WHO, 2010; Ma *et al*., 2019; Vilarinho *et al*., 2019), it was replaced by other bisphenols (bisphenol S and bisphenol F). However, the alternatives were also found to have migration issues of their own, with potential human health impacts that are not yet fully understood (Kovačič *et al*., 2020; Rochester and Bolden, 2015).

Nanomaterials – nanoclay (Montmorillonite clay), nano metal oxides (silver, zinc, copper, titanium, among others), nanocellulose and so on – can be added to polymers to produce nanocomposites in order to confer certain properties, such as increased mechanical strength, provide better barriers against water, antimicrobial properties, among others (Bumbudsanpharoke and Ko, 2015; Garcia, Shin and Kim, 2018). Adverse health impacts from the ingestion of some nanoparticles, as described in literature, include potential to interfere with the normal functioning

[22] Migration can be defined as the "mass transfer from an external source into food, in physical contact with it, by sub-microscopic processes" (Katan, 1996).

of the gastrointestinal tract and cause dysbiosis of the gut microbiota, impacts on the immune system, genotoxicity and carcinogenicity, depend on the different compositions, structures and properties of nanoparticles (McClements and Xiao, 2017). However, the release, migration and measurement of nanoparticles from food contact materials is still not well understood, which complicates the assessment of nanomaterial safety (Bandyopadhyaya and Sinha Ray, 2018; Froggett *et al*., 2014; Störmer, Bott and Franz, 2017; Szakal *et al*., 2014).

Plastic alternatives like bioplastics, including those that have food contact applications, contain a broad set of chemicals, similar to conventional petroleum-based plastics, that can potentially migrate and induce toxicity (Yu *et al*., 2016; Zimmerman *et al*., 2020). Biobased food contact materials that are produced from a diverse biomass derived from agricultural products raise additional food safety issues, such as presence of heavy metals, persistent organic contaminants, residues (e.g. pesticides), mycotoxins, among others. These hazards also have the potential to migrate upon contact with food (FERA, 2019).

Apart from food packaging, the food we consume also comes in contact with various other materials – utensils, cutting boards, cups and so on – which may be potential sources of food safety risks, especially as new materials are being explored from a circular economy perspective (Bilo *et al*., 2018). For instance, stalks left over after wheat grains are harvested are traditionally treated as waste, but they can instead be turned into wheat-based straws as a substitute for single-use plastic straws. A number of different mycotoxins produced by the *Fusarium* spp. are known to be associated with wheat under poor storage conditions. In addition, depending on their composition allergenicity may be another issue with wheat-based straws (FERA, 2019). However, only limited information about such food safety risks and their potential for migration in biobased food contact materials is available in the published literature. It is also not known if processing and manufacturing processes involved in the production of such biobased food contact materials breaks down or modifies any of the chemical hazards mentioned earlier.

What is the way forward?

The circular economy can decouple plastics from fossil fuel feedstocks and find ways to sustainably produce plastics, repurpose plastic waste as well as manage plastic pollution. Such policies are likely to have consequences across multiple sectors, including the food sector, with overlapping implications for health and food safety, the environment, food security and economic outcomes. While there are many innovations and improvement efforts to implement a circular economy approach for plastics that show potential, they are still too fragmented to make any lasting impact at larger scales and remain largely disconnected from the development and deployment of appropriate after-use systems. The implementation of circular economy is also characterized by various barriers – financial, logistical, lack of technical knowledge and skills, and technological gap.

It can be difficult to recycle certain types of plastics without perpetuating the harmful chemicals they contain unless adequate regulatory frameworks are put in place to control it and risk assessments underpinning these frameworks are carried out with wide support. How some of these chemical hazards, arising from recycled plastics as food contact materials, pose a risk to human health remains to be fully determined. Risk assessments currently focus on monomers and plastic additives used in the manufacture of food contact products, but it does not cover plastic polymers and complex chemical mixtures formed during the production processes. There is a need for improved international harmonization of the methods used to assess the fates and physiological effects of chemicals arising from plastic packaging in contact with food. The lack of crucial data on exposure, also in terms of migration of chemical mixtures, presents a knowledge gap that needs to be addressed moving forward (Groh *et al*., 2021; Muncke *et al*., 2017). Advances in analytical or quality control measures may provide a feasible way to assure that the supply of recycled plastics is safe for the intended end-use (Geueke, Groh & Muncke, 2018; Muncke *et al*., 2017; Muncke *et al*., 2020). In addition, as the debate for plastic alternatives continue (van der A & Sijm, 2021), migration of substances and their potential for chemical toxicity will need to be an area that is given due consideration. Solutions for improving the safety of food contact materials, especially within the context of circular economy, will need to include all relevant experts and stakeholders of the supply chain (Muncke e*t al*., 2020)

7.
Microbiomes, a food safety perspective

Soil being prepared for rice planting. Microbiomes across soils, plants, animals and humans are interconnected.

Microbiomes are a complex and dynamic network of microorganisms (bacteria, viruses, fungi, archaea) that adapt and live in a functional relationship with their specific habitats (e.g. human, soil, plant, water, animals, production sites along the food chain) (Berg *et al.*, 2020). Neighbouring microbiome ecosystems exert mutual influences, even when physically separated (e.g. animal and soil) (Flandroy *et al.*, 2018). In addition, microbiomes are very sensitive to environmental conditions and exposure to substances of different nature. In humans, various factors (e.g. genetics, diet, drugs, lifestyle, oxygen, pH) contribute to shaping the microbiomes' subpopulations along the various sections of the gastrointestinal tract (Shetty *et al.*, 2017).

Why is the gut microbiome gaining interest?

There is an increasing amount of scientific information associating – or to a lesser extent demonstrating – that the gut microbiome has the potential to influence human health. For example, the microbiome influences the development of the immune system, has a protective role (first line of defence in the gut), and synthesizes metabolites essential for maintaining human homeostasis (vitamin D and shortchain fatty acids). In addition, microbiome imbalances have also been associated with some non-communicable disorders (NCD), including inflammatory and metabolic diseases (obesity, diabetes, inflammatory bowel disease) (Lynch and Pedersen, 2016).

Non-human microbiomes have also been associated with the health status of other ecosystems, e.g. soil and plant (Flandroy *et al.*, 2018). Such microbial populations present in the different environments along the food chain are also contributors to food quality and food safety (Weimer *et al.*, 2016).

Since the microbiome may play a role in human homeostasis, it can be used as a target for different dietary interventions to maintain and promote health (e.g. optimizing fibre intake, administration of pre- and probiotics) (Wilson *et al.*, 2020). On the other hand, microbiome disruptors (e.g. imbalanced diet) are also attracting attention as they may lead to dysbiosis,[23] which can eventually result in adverse effects on human health (Das and Nair, 2019). Much of the current interest gathers around the capacity of food additives, chemical residues (pesticides and veterinary drugs), antibiotics or other environmental pollutants to lead to biologically relevant microbiome perturbations (Cao *et al.*, 2020; Chiu *et al.*, 2020).

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[23] Dysbiosis: changes in the microbial composition and function that are associated with a negative health outcome (Das and Nair, 2019).

Technological advancements enhancing our understanding of microbiomes

Until recently, traditional microbiology has focused on the individual identification of microorganisms and related functions in, for instance, food production (e.g. fermentation), promoting health status (e.g. probiotic gut bacteria) or as contributors to disease (e.g. pathogens). New technological advances in the omics and bioinformatic fields have enabled the holistic study of microbial community structures (microbiomes) and their functional activity within a given environment (Galloway-Pena and Hanson, 2020). Metagenomics tools sequence the DNA material and provide information on the taxonomical composition of the microbiome and gene diversity, which provides an indication of the potential microbial functions. Other omics technologies target the microbiome activity. They indicate active metabolic pathways through the analysis of gene expression by RNA sequencing (transcriptomics and metatranscriptomics), the protein resulting from such expression (proteomics) or final end-products or metabolites (metabolomics). The science supporting the microbiome study is relatively new and still evolving. It is still lacking standardization and generates immense amounts of data that cannot yet be interpreted. Therefore, our understanding of microbiomes and interactions with their ecosystems is still limited.

What are the food safety implications to be considered?

The study of the microbiome from farm to fork has the potential to improve our understanding of hazards and health risks. Within the context of food safety, different microbiomes can be exploited for different purposes.

The microbiome is not a food safety risk *per se*. Until recently, the microbiome has been an unexplored contributor to food safety and quality. The holistic understanding of the microbiome-environment-host interactions, and their influence on human exposure to different types of biotic or abiotic factors, open a new avenue to better understand hazards and health risks, and therefore microbiological and chemical assessments.

Microbiomes in food production chains as indicator for hazards

Now that microbial populations can be evaluated in a holistic manner by using omics technologies (e.g. complete DNA or RNA analysis by culture-independent deep shotgun metagenomics or metatranscriptomics, respectively, proteomics or metabolomics), it will be possible to monitor for the full potential or the presence of microbial hazards (e.g. pathogens, pathogenic factors and antimicrobial resistance) up and downstream in food production, not only in food and food ingredients, but also in the environment of production sites (Beck *et al.*, 2021; De Filippis *et al.*, 2021). It will also improve our understanding of factors (processing steps, microbiomes in the environment, storage) influencing the pathogenic potential at a given location and the acquisition and flow of antimicrobial resistance along the production chain. Therefore, the study of the microbiomes will bring a new perspective to the characterization of microbial hazards. Moreover, it will provide the basis for the development of suitable and effective preventive measures. There are numerous scenarios where the microbiome and microbial compounds can be used as hazard indicators of food safety and quality (Weimer *et al.*, 2016). The following are some examples: selection of safe starter cultures and their monitoring during product manufacturing, evaluation of air microbiome in age-drying chambers to minimize the potential transfer of pathogens from the environment to the product, and the influence of storage conditions in the composition and production of compounds affecting the food safety and quality.

The interaction between the gut microbiome and exogenous compounds and implications in human health

In addition to macro and micronutrients, the gut microbiome can enter in contact with other compounds through food and water consumption. These can be intentionally introduced in the product formulation (i.e. food additives) or result from upstream activities in the food chain (e.g. residues of veterinary drugs and pesticides) or be present inadvertently in the diet (e.g. environmental or industrial contaminants). The gut microbiome can metabolize and transform compounds, alter their bioavailability and modify their toxic potential (Claus,

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A yoghurt production plant.

Guillou and Ellero-Simatos, 2016). Therefore, microbial activities can modify human exposure to such substances. Moreover, exogenous compounds also have the potential to induce changes in the composition and activity of the microbiome and lead to dysbiosis (Abdelsalam *et al.*, 2020). Such microbial imbalance could eventually have implications for human health.

Exogenous compounds such as food additives, residues of veterinary drugs and pesticides or microplastics are very heterogeneous groups of chemical compounds. Out of this broad chemical spectrum, research has only been conducted on a limited number of compounds and show their potential to disturb the gut microbiota. Most studies, which differ in design and methodologies, are generally conducted at levels that exceed those found in a normal diet (Roca-Saavedra *et al.*, 2018). Therefore, this information is of limited use from the perspective of food safety risk assessment as it does not reflect a realistic (low-level) dietary exposure. However, the limited number of studies specifically designed to evaluate exogenous compounds at low residue levels provides an indication that effects of exogenous compounds on the microbiome follow a dose-dependent relationship (Piñeiro and Cerniglia, 2021). Although some associations are made between microbiota alterations and adverse health effects observed in laboratory animals, the causal role of microbial disturbances specifically induced by these exogenous compounds on host alterations remains unclear (Walter *et al.*, 2020). Microbiome science is a quickly developing field of research. Food safety risk assessment bodies are closely watching the emerging research regarding its significance for food safety risk assessment (Merten *et al.*, 2020; National Academies of Sciences and Medicine, 2018; Piñeiro and Cerniglia, 2021). However, the science available to date does not provide enough consensus, mechanistic understanding and has not established sufficient repeatability (Sutherland *et al.*, 2020), so that no clear conclusions can be drawn at the moment.

The role of the gut microbiome against foodborne pathogens

The gut microbiome contributes to the resistance against the colonization by foodborne pathogens and the proliferation of commensal opportunistic pathogens (Pilmis, Le Monnier and Zahar, 2020). Pathogen colonization does not only depend on the infective dose and the host's immune system but also on the health status of the gut microbiota. Alterations on the structure and function of the gut microbiome, which may be caused by dietary imbalances or exposures to certain substances, can offer a window of opportunity for pathogens to break the gut barrier. Colonization resistance is one of the endpoints used to determine the microbiological Acceptable Daily Intake (mADI) in the assessment of veterinary drug residues (VICH, 2019).

Antimicrobial resistance (AMR)

In 2015, within the context of One Health approach, the World Health Organization (WHO) developed a Global Action Plan (GAP) on AMR (WHO, 2015). It acknowledges the role of the food and agriculture sectors in the global fight against AMR (Cahill *et al.*, 2017). The food chain offers favourable conditions for AMR transmission, which link the animals, humans, food and environmental microbiome ecosystems (Cahill *et al.*, 2017). The gut microbiota has been described as a reservoir of antimicrobial resistance (Hu and Zhu, 2016) and the high microbial density in the gut, especially in the large intestine, makes it highly susceptible to the transfer of genetic material (Smillie *et al.*, 2011). In fact, the gastrointestinal tract is constantly

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exposed to new bacteria coming from the environment, including food, which may carry and potentially transfer antimicrobial resistance genes to members of the gut microbiome (Economou and Gousia, 2015; Penders *et al.*, 2013). Metagenomics has enabled monitoring the resulting resistome (Hendriksen *et al.*, 2019; Kim and Cha, 2021).[24] This holistic approach allows to study of the prevalence, distribution and trends of antibiotic resistance genes in a population, the co-resistance to antibiotic and non-antibiotic compounds, and the potential for horizontal transfer (Feng *et al.*, 2018; Hendriksen *et al.*, 2019).

What are the regulatory implications of microbiome research?

Chemical risk assessments aim at evaluating the safety of food additives, chemical residues in food and environmental pollutants and contaminants, and serve as the basis to establish health-based guidance values (e.g. Acceptable Daily Intake ADI, Acute Reference Dose ARfD). With the further step of exposure assessment, a risk can be characterized, and this serves as a basis to set up regulatory levels such as, for example, Maximum Residue Limits (MRLs) for veterinary drugs and pesticides, Maximum Levels (MLs) for contaminants, and Maximum Use Level (MUL) for food additives. Although the Joint FAO/WHO Expert Committee on Food Additives (JECFA) and the Joint Meeting on Pesticide Residues (JMPR) have advanced their procedures to complement toxicological chemical assessments with a microbiological component (FAO and WHO, 2009), there are many ongoing discussions among risk assessors about further integrating the microbiome in chemical risk assessment (Merten *et al.*, 2020; National Academies of Sciences and Medicine, 2018; Piñeiro and Cerniglia, 2021).

Regulatory decisions require careful consideration, given their impact on the food system. For this reason, the science supporting risk assessment needs to be robust, reproducible and based on suitable and well-defined endpoints. However, although the microbiome's potential as a component of risk assessment is widely recognized, critical technical limitations and knowledge gaps need to be addressed before the evaluation of microbiome interactions with food additives, pesticide and veterinary drug residues and other food contaminants are incorporated into regulatory activities.

What is the way forward?

Future perspectives on the topic

Latest trends have placed the microbiome as the target of dietary interventions to promote health or as a mediator in human disease due to alterations caused by different types of compounds (e.g. food additives, residues of veterinary drugs and pesticides, and environmental pollutants). However, the information supporting any claim requires careful and critical interpretation. While for the vast majority of cases research has only provided

[24] Resistome refers to the repertoire of antimicrobial-resistance genes within microbial communities (Kim and Cha, 2021).

Understanding the relative role and underlying mechanisms of the microbiome in health and disease will enable the update of chemical risk assessments and the development of evidence-based methodologies and frameworks to evaluate microbiome-related data.

Now that we have the possibility to evaluate the dynamics of microbial ecosystems, we also have significant potential to study the microbiome in food systems (ingredients, and foods and the different environments along the food production chain). These can include:

- establishing food or ingredient microbiome fingerprints at different production stages;
- early identification of abnormal shifts in starter cultures, products, and the environments of food production sites; and
- up and downstream monitoring of pathogenicity signatures and the resistome.

statistical associations between microbiome disturbances and health or disease, there is a need to prove causality (in other words, demonstrate the causal link between changes in the microbiome composition and function and physiopathological alterations in the subject). This would be the demonstration that, indeed, the microbiome contributes to either maintaining or disrupting human homeostasis. Moreover, further investigation about causal links could also indicate that microbial changes are a consequence of disease, not the cause. Once proven, it will be necessary to understand the dimension of such contribution.

Scope for future research

One of the most basic and still essential need in microbiome science is the lack of a consensus for the definition of a healthy microbiome. However, establishing what constitutes a healthy microbiome is challenging. Factors such as diet, lifestyle, genetics and surrounding environments influence how the microbiomes evolve, resulting in high interindividual variability. Also important

is to define dysbiosis and distinguish normal fluctuations in microbial composition and function from alterations of concern.

Still evolving analytical technologies and experimental methodologies need standardization and best practice guidelines to provide consistent, comparable and reproducible results. Moreover, for chemical risk assessment, there is a need to define fit-for-purpose experimental models, including the use of appropriate low-doses of test compounds (e.g. food additives, residues of veterinary drugs and pesticides) and exposure periods.

Although most research has targeted the bacterial component of the microbiome primarily, additional efforts are needed to study non-bacterial members such as viruses, fungi, archaea and protozoa. Further research is also necessary to elucidate all the substantial amount of generated data by omics technologies. It includes identifying new microbiome members, characterization of genes, metabolic pathways, proteins and metabolites.

To connect the microbiome with health and disease, it is critical to demonstrate causality and characterize biologically relevant microbiome disturbances. This will require the identification and validation of suitable microbiome-related biomarkers and endpoints.

These are knowledge gaps limiting the capacity to fully exploit the microbiome as a tool to promote food quality, and improve food safety processes, including incorporating microbiome data in chemical risk assessment and informing regulatory decisions.

Collaborations are key to moving forward

Microbiome science is inherently a multidisciplinary field. Most of the breakthrough advances have been possible thanks to coordinated efforts in the form of big projects with the participation of large multinational consortia (e.g. Human Microbiome Project).

To address the food microbiome as an additional component in chemical risk assessment and define possible framework, it would be necessary to convene a multidisciplinary group of experts (risk assessors, microbiome scientists, and regulators).

The current and strong interest in the microbiome is sometimes leading to overstatements, conveying the idea that it is a universal solution for almost everything. However, such statements needs a stronger scientific basis. Therefore, it is necessary to promote evidence-based, consistent and accurate communication strategies considering the *status quo* on microbiome knowledge and associated uncertainties. This is not only a challenging task, but also an opportunity to engage the public with stakeholders within the agrifood systems.

Due to the broad number of potential applications of the microbiome in agrifood systems, the complexities of the topic, and the need for consensus approaches, it would be beneficial and productive to involve all stakeholders, including academia, research organizations, industry and regulatory bodies. Many activities can be derived from such interactions, including the definition of topic-specific research needs, promotion of research collaborations, development of best practices, development and implementation of food safety applications (e.g. HACCP programs), and capacity development and so on. Given the consensus-driven nature and mission of FAO, the organization has the capacity to promote engagement activities and serve as a driving force in the dialogue about the microbiome in agrifood systems. As a first step forward, FAO is reviewing the scientific literature to define the *status quo* and knowledge gaps in understanding the interrelations of food additives, microplastics, residues of veterinary drugs and pesticides, the gut microbiome and human health. FAO's intention is to update and expand the literature research to other relevant substances and microorganisms as new information becomes available. Recognizing research needs and areas of improvement will ultimately allow laying down the path towards defining and implementing microbiome-related applications to support food systems and policy activities

8. Technological innovations and scientific advances

Drones are being used to monitor conditions in cultivated fields.

Technological revolution is transforming the agrifood systems. Scientific advances are being employed to chase the fundamental goal of producing more food with less – lower use of agrochemicals, reduced water utilization – in addition to improved land use and benefiting farmers economically. Remote sensing technologies (drones, satellites, and so on), new and improved technologies with analytical and traceability functions, innovations that allow data to be moved between the field and computational cloud, and technologies that allow processing of large volumes of information have ushered in the age of digital agricultural revolution (Delgado *et al.,* 2019; FAO, 2019; Lovell, 2021; World Bank, 2019).

Innovations and technological advancements in the food industry are also rapidly evolving the food safety arena (FAO and WHO, 2018a). New and emerging technologies in food production, processing and packaging are providing better tools for improving traceability, detecting contaminants in food and for investigating outbreaks. Below a few select technologies and innovations that have implications for food safety are briefly described in no particular order. The full breadth of opportunities and challenges associated with these technologies and innovations are not fully understood, and some of them still remain in their infancy.

Packaging

Appropriate packaging is designed to preserve the quality of food and makes it easier to transport, store and display at retail stores. Packages can also be used to communicate the nutritional content and potential safety issues associated with the food product inside to consumers through written texts or labels affixed on the outside. Loss of food quality does occur during storage or distribution due to various biological or chemical processes, and appropriate packaging can help to slow down these processes. Preserving food quality is not only linked to protecting the health of consumers against foodborne illnesses but also contributes to food security by minimizing food loss and waste. Some of the key food safety issues associated with food packaging are discussed in **Chapter 6**.

Active packaging and intelligent packaging are two new concepts that have emerged in response to the fast pace of globalization, longer distribution chains, greater awareness of food waste as well as changing consumer preferences. Active packaging is intended to extend the shelf-life of food products via the addition of various components to the packaging material. These components (oxygen and ethylene scavengers, moisture regulators, controlled release of antioxidants and antimicrobial agents, among others) either absorb or release substances in response to changes in the ambient environment both inside and outside the package thereby maintaining the quality and safety of food products.

Intelligent packaging includes materials that can monitor the condition of packaged food as well as the environment inside the package, alerting manufacturers, retailers or consumers when a product has been compromised or contaminated, for instance, indicating food spoilage by a change of colour of the package (BBC News, 2021). Intelligent packaging can also include "smart" labels that can track products as they move through the supply chain, confirm that products have not been tampered with and allow quick identification of products in a supply chain in case of contamination. Smart labels can also provide additional information that are not present on the physical label such as the sourcing of the food products and allergen information, among others.[25]

Nanotechnology

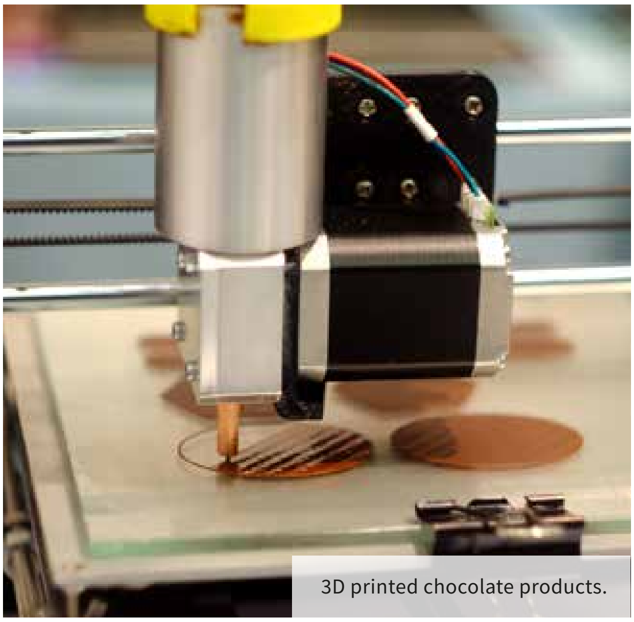
While this technology itself is not new, the use of nanotechnology in the food industry has started to garner renewed attention by offering a slew of novel applications and benefits in food packaging, processing, nutrition as well as safety. For instance, the technology can be used as nanocarriers to encapsulate and deliver nutrients like vitamin supplements and other food additives such as anticaking agents and antimicrobial agents. Nanocomposites can improve the mechanical strength and barrier properties of food packaging materials. Nanotechnology also has potential in food nanosensing, as part of active packaging, which can be used to monitor for pathogen detection, thereby improving food safety and quality (Singh *et al*., 2017). There is also potential for low-cost nanofilters in wastewater treatment to improve the quality and safety of water used in agriculture, aquaculture and for human consumption (FAO and WHO, 2012).

There is ongoing research about the fate of nanoparticles in the human body and any potential safety issues associated with them when ingested. In addition, the disposal of such materials at the end of their life cycle is another area of concern – whether nanomaterials are degradable, interact with/accumulate chemicals in the environment, among others (EFSA Scientific Committee *et al*., 2018; FAO and WHO, 2010; FAO and WHO, 2013). Low absorption and accumulation of titanium dioxide (food additive E171) nanoparticles after ingestion has been reported by a recent safety assessment carried out by the EFSA Panel on Food Additives and Flavourings (2021).

3D printing of food

The first instance of using additive manufacturing or 3D printing to produce edible forms from liquid or semi-solid food materials was reported in 2007 (Malone and Lipson, 2007). Most 3D printers for food applications are extrusion based, i.e. a moving nozzle extrudes an edible formulation or "ink" in a pattern predetermined by a 3D model (Godoi, Prakash and Bhandari, 2016). Some equipment also allows for the simultaneous printing and cooking of food (Blutinger *et al*., 2021; Gibbs, 2015). Apart from some of the more common materials (chocolate, cheese, sugar, starch-based food products) used for 3D printing, other alternative raw materials, such as seaweed, insect flour, fruits and vegetables, among others, are also gaining attention.

There are several food-based applications that 3D printing can render itself to – from confectioners printing desserts to creating edible food commodities from food waste (Banis, 2018; Garber, 2014). 3D printing can also diversify and personalize food products by allowing the mixing of several different ingredients, including encapsulated probiotics and vitamins, through co-extrusion printing. As the popularity of plant-based diets grow, 3D bioprinting can be used to create "meat"-like textures with plant-based ingredients (Moon, 2020). A recent advancement now allows 3D bioprinting of steak using a culture of live animal tissues, which can propel the field of cell-based food products even further (Bandoim, 2021). Taking 3D-printing of food a step ahead, now four-



3D printed chocolate products.

[25] Smart labels include QR codes, Electronic Article Surveillance (EAS) tags and specially configured Radio-frequency identification (RFID) tags (Bhoge, 2018).

dimensional food printing is under development. The principal applications of 4D printing are changes in colour, shape or flavour of food in response to stimuli such as pH, heat, moisture and so on. For instance, Ghazal *et al*. (2021) reported colour changes in a 4D-printed potato-starch based meal from anthocyanins responding to pH stimulus.

However, the widespread commercialization of this technology, either for domestic use or at the retail level, will require thorough assessment of potential food safety risks, and there is currently limited scientific research on the various food safety aspects of 3D-printed foods. Some potential food safety issues involve the migration of chemicals from the 3D printer to food. To reduce such concerns, it would be important to use food-grade materials to construct parts that come in contact with food (Azimi *et al*., 2016). The ability to thoroughly disassemble and clean a 3D printer will help reduce risks of microbiological contamination from the equipment and prevent cross-contamination issues (Severini *et al*., 2018).

Handheld devices

Food-sensing technologies on portable analysers can identify various contaminants in food in real time making it quicker than laboratory-based testing. It also enables people, who are not food safety professionals, to operate the devices; for instance, farmers can check for pesticide residue levels on their crops, or supermarkets can check for various contaminants before displaying produce for retail (Chai *et al*., 2013; EC, 2019; World Bank, 2019).

Point of care diagnostics allow consumers to carry out instant on-site testing of their food for certain ingredients, such as food allergens (like eggs, gluten or peanuts). With food allergies becoming an important public health issue, these devices can also be used in clinical settings where rapid, low-cost detection of food allergies can be performed. Since many allergic individuals often suffer from more than one food allergy, a range of allergen detection is a likely desired feature of such devices (Albrecht, 2019; Neethirajan *et al*., 2018; Rateni, Dario and Cavallo, 2017).

However, some devices may be limited by their inability to detect substances beyond a certain depth from the surface. In certain cases, results from screening tests may require further confirmation through validated instrumental analysis, a protocol not always followed. Moreover, a lack of international standards on threshold detection limits can also be a challenge.

Distributed Ledger Technologies (DLT)

Blockchain, which is one of most well-known uses of DLT,[26] comprises an extensive set of encrypted blocks of shared data that are strung together chronologically (Karthika and Jaganathan, 2019; Mistry *et al*., 2020; Nakamoto, 2009). This data is a record of transactions that is shared among members of a network, allowing greater access to information and preventing manipulation (Atzori, 2015; Cai and Zhu, 2016; Underwood, 2016). The decentralized nature of such databases enables all members participating in a network to validate and record digital data with no central authority over them.

The application of DLT, Blockchain in particular, in the food sector is an emerging area and holds much promise in food safety control (Li *et al*., 2020; Pearson *et al*., 2019). Food traceability is a major application with Blockchain providing a mechanism to securely record every step of a food product's journey through a supply chain making it easier to trace it from origin to end-point (Aung and Chang, 2014; Pearson *et al*., 2019). Enhanced transparency and traceability afforded by such technologies can reduce the response time when contaminated foods are discovered, making it easier and faster to selectively recall food products (Li *et al*., 2020; Yiannis, 2018). According to a major retailer in the United States of America, upon implementation of Blockchain technology, time taken to track the origin of a mango went from one week to 2.2 seconds (Kamath, 2018; Unuvar, 2017). By ensuring food traceability, Blockchain technology can also build consumer trust in food safety. In addition, it may be even possible to prevent or suppress fraud in some food supply chains (Cai and Zhu, 2016; Li *et al*., 2020; Yiannis, 2018).

However, it is important to point out that the ability of DLT itself to judge data quality is limited. Data can be entered from untrustworthy sources or may be incorrect, allowing erroneous data to be permanently recorded. The decentralized nature of DLT make its governance different from existing governance structures that have hierarchies. Governance of a digital domain can be complex; however, the successful implementation of DLT will depend on constructing an appropriate governance structure, particularly when it comes to issues pertaining to data rights, privacy and protection (van Pelt, 2020). Another important aspect is the need for interoperability, that enables seamless flow of data across disparate networks,

26 The terms Blockchain and Distributed Ledger Technologies are often used interchangeably in published literature.

in the food industry. The lack of this aspect can lead to information asymmetry and fragmentation within food supply chains that may employ a number of different DLTs. The need to preserve the decentralized properties within the boundaries of a single network complicates the notion of interoperability (Deshpande *et al*., 2017). In addition, high energy usage of certain types of Blockchains due to requirements for substantial computational power may complicate implementation given the current emphasis on environmental sustainability (Kaplan, 2021). Therefore, more assessment studies that help provide deeper understanding of the various environmental perspectives associated with these new and emerging technologies are needed (Köhler and Pizzol, 2019).

Internet of Things (IoT)

Various sensors (for temperature, humidity, pH, and so on) embedded into a vast network of devices that are spread across different aspects of a food chain connect and share data on a platform called the Internet of Things (IoT). The IoT platform integrates the data received from various sources, enables further analytics to be performed, followed by extraction of valuable information as per requirements which can then be streamed or shared with relevant recipients remotely (Bouzembrak *et al*., 2019). The application of this can be observed in food traceability where food distributors can track and document the journey of food products while ensuring that they have been stored at the right temperature along the way (Cece, 2019). At the consumer level, smart appliances connected to IoT are revolutionizing kitchens, for instance, smart refrigerators can scan and categorize food items and store them efficiently. They can also guide homeowners to organize their groceries and help plan their meals to minimize food loss (Landman, 2018).

Remote sensing

Today, high-resolution satellite imagery and drones carrying cameras and sophisticated sensors are revolutionizing agriculture by allowing food producers to remotely collect valuable information in real time, such as crop health, growth and maturity, soil conditions, as well as monitoring unanticipated weather conditions. On the back end, machine-learning algorithms can scan the images to provide deeper analytic data. Remote sensing also allows early detection of pest damage and disease outbreaks thereby providing opportunities to prevent overuse of agro-chemicals (pesticides, fertilizers, antibiotics) by facilitating targeted treatment of crops (Delgado *et al*., 2019; Raza *et al*., 2020; World Bank, 2019). Such a way of farming, also called precision agriculture, requires a technological network over which multiple instruments interact with each other, which is where IoT comes into play.

Linking geographic information systems with predictive risk-assessment models can help to forecast when, where and under what conditions microbial or chemical contamination of crops are likely to occur, thereby taking a functional role in early warning systems and preventing food safety issues downstream (Mateus *et al*., 2019).

Big data

Put simply, big data refers to a large volume of data gathered rapidly from a variety of sources. In food safety, this data can be from databases, sensors, handheld devices, social media, omics profiling, among many others (Donaghy *et al*., 2021). Big data can alert us to food safety risks in the food supply chain through new technologies like IoT, whole genome sequencing, next-generation sequencing, and Blockchain. These technologies generate large amounts of highly variable data that require tools to process the information to enable effective and timely decision-making, particularly in situations such as source identification during foodborne illness outbreaks, analysing food safety risks based on climate data, and so on (Donaghy *et al*., 2021; Marvin *et al*., 2017).

However, the use of big data in food safety is not straightforward as food safety information and data tend to be scattered across multiple sectors – food, health and agriculture. Food safety data traditionally collected through monitoring and surveillance can be limited and not always harmonized among different regions. The application of big data in food safety will require establishment of appropriate platforms for collection, storage and analyses of a diversity of data along with implementing safeguards for data rights and usage (Marvin *et al*., 2017).

Artificial Intelligence (AI)

AI incorporates advancements in machine learning to detect and predict patterns based on large data sets. New AI-based algorithms applied to conventional forecasting techniques can strengthen and enhance foresight capabilities of the actors in a food chain. AI can help track products from farm to consumers, forecast market fluctuations, facilitate autonomous farming, predict health code violations, and even be tailored to carry out foodborne disease surveillance.

AI also brings the power of machine learning and decision making to IoT thereby playing a major role in the growth of IoT applications and deployments in the food industry. For instance, AI-powered IoT (sometimes referred to as Artificial Intelligence of Things or AIoT) can improve operational efficiency through predictive analytics, such as by indicating when equipment needs maintenance or is closer to end-of-life and requires replacement, thereby enhancing risk management and maintaining performance. AIoT can help detect defective ingredients during food processing; in food manufacturing plants AIoT can ensure that workers are complying with food safety regulations, among many other applications (Friedlander and Zoellner, 2020). However, while this technology holds promise for food safety, it is not without risks – human bias, data inaccuracy, as well as security issues arising from cyberattacks – and should therefore be adopted keeping controls in place.

Automation

In an effort to better manage the risks that human workers can pose to food safety, advancements in robotics technology, coupled with AIoT, can be used to improve food safety, for instance by preventing cross-contamination issues. While previously robots were mainly limited to last step packaging tasks, today they are being increasingly used to handle unpackaged goods (Mohan, 2020). Soft robots, built from softer and flexible materials, to facilitate efficient handling of delicate food commodities without bruising, are being employed by some food producers to harvest fruits, by food manufacturers to run automated warehouses and by processing plants to handle a variety of food products (Jones *et al.*, 2021). To ensure that the robots themselves are not contributing towards contamination, an additional set of robots have been developed to wash down the entire working area in such processing plants (Jarrett, 2020; Newton, 2021). Collaborative robots, or cobots, are a new generation of robots made to work alongside humans, under limited supervision. Cobots can be used for tasks that are carried out in areas which pose health hazards for human employees or are mundane and repetitive while ensuring adequate and consistent quality control (So, 2019).

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Automation used in agriculture.

Scientific advances improve risk assessment of chemical mixtures

The provision of scientific advice by FAO and WHO is the foundation for the development of international standards by the Codex Alimentarius (FAO and WHO, 2018b). As science is constantly evolving, it is important to keep pace with these advancements to maintain and improve the reliability, robustness and relevance of food safety risk assessments, which in turn facilitate the establishment of appropriate regulatory frameworks and food safety standards.

Methodologies used for food safety risk assessments largely depend on the purpose of the assessment as well as the quantity and quality of scientific data available on the substances being evaluated at the time. This implies that food safety risk assessments are in continuous evolution to match the state of scientific knowledge at a given time period and this is explained in the context of food safety risk assessments for combined exposure to chemical mixtures.

Assessment of risks of combined exposure to chemical mixtures is a notion that has been developing over the last few years. While risk assessments of chemical hazards in food usually tend to evaluate individual compounds,[27] humans are typically exposed to multiple low-levels of chemicals (not all of which pose appreciable negative

[27] Such assessments evaluate a number of risks associated with chemical food hazards: the nature of adverse health effects (known and potential); estimates of risk in terms of probability of occurrence and severity of adverse health effects; identification of the population at risk (general, children, pregnant women, etc.), and uncertainties related to the available data, such as limited toxicological data, food consumption, exposure estimates and so on.

health impacts), with various sources including food and water contributing to these exposures (Drakvik *et al.,* 2020).

In 2019, FAO and WHO convened an expert consultation to develop guidelines for a pragmatic step-wise decision-making process for undertaking risk assessment for combined exposure to multiple chemicals (FAO and WHO, 2019). The experts agreed that if a substance under consideration was not part of an established chemical group previously considered, the Joint FAO/WHO Meeting on Pesticide Residues (JMPR) or the Joint FAO/WHO Expert Committee on Food Additives (JECFA) would then determine if there was need to include it in a risk assessment of combined exposure to multiple chemicals. Both JECFA and JMPR are expected to pilot the agreed-upon guidelines prior to the general implementation of the methodology (FAO and WHO, 2019). A number of other organizations, including the European Food Safety Authority (EFSA), Organisation for the Economic Co-operation and Development (OECD) and the United States Environmental Protection Agency have also published guidance and methodologies for combined exposure to chemical mixtures (EFSA Scientific Committee, 2019; OECD, 2018; US EPA 2000; 2003; 2008; 2016).

As the evaluation of chemical mixtures is an evolving area, it is vital to keep monitoring it and to update, as appropriate, the risk assessment processes, to ensure soundness and relevance of the advice that is provided.

What is the way forward?

Technological innovations are transforming the agrifood sector, including the field of food safety. Digitalization, scientific innovations, and technical advancements can facilitate international trade that is faster, more cost-effective, with greater market access and inclusivity, increased food safety along food chains, and reduced vulnerabilities to fraud. However, emerging technologies, by definition, come with both opportunities and challenges, and a critical view is needed to balance the benefits with the risks. Promotion of standardization and best practices, access to reliable and curated reference databases, communication of lessons learned, and transparency in data sharing across stakeholders will be needed to implement and apply emerging technologies and innovations. Rapid advances in technology often outpace the development of appropriate regulations needed to provide oversight. In addition, technological advancements will continue to provide opportunities to collaborate and have access to large amounts of diverse data from a wide variety of sources within the food sector. With rules on the governance of this data often unclear and inadequate, it raises trust and transparency concerns regarding data rights, privacy, sharing and may provide opportunities for misuse (Jacobs *et al*., 2021).

Translation of cutting-edge technologies across the global agrifood systems is not uniform. Excluding those that lack access and affordability can reinforce and accelerate inequalities. If adoption of such technologies requires substantial investments and capacity development, low- and middle-income actors in the food chain can get left out. For instance, if retailers required all suppliers to adhere to real-time traceability for food safety by implementing blockchain technology, it would raise supplier entry costs, and those unable to meet these requirements can get excluded from market access. Countries most affected by foodborne illnesses, where innovations in analytical tools might be most beneficial, often do not have access to these technologies or sufficient resources to realize their development. To promote equitable implementation of scientific advances, the international community will need to contribute more to help LMICs close the technological divide. This can be done through measures such as investments in infrastructure – roads, electricity, post-harvest storage facilities and so on – which can be some of the major constraints faced by farmers, developing capacities and training in technical expertise to facilitate understanding of new technologies as well as increasing user capabilities.

Finally, it is worthwhile to iterate that science is central to food safety. Development and application of sound scientific principles underpin the formulation of appropriate food safety regulatory frameworks and policies that are needed to safeguard public health amid ever-changing agrifood systems. The interconnection between science, risk assessment and risk management in food safety has always been complex, and it is even more so in an era with rapid scientific advances and technological innovations

9.
Food fraud – reshaping the narrative

Testing for potential contaminants in turmeric.

Food fraud, an uncomfortable & unfortunate part of agrifood systems

Food fraud comprises a variety of intentionally deceptive modes of conduct carried out with the purpose of cheating the system for an economic advantage.[28]

Food fraud has been a concern since historic times.[29] Fraudsters use creativity and resources to place goods that are not what they seem on the market. They operate in a manner that does not draw attention to their activities with the aim of avoiding detection. In doing so, they deceive the system as a whole and undermine control mechanisms. By intentionally violating the explicit and implicit claims made on foods, they destabilize the relationship we all have with food, thus negatively affecting our confidence in foods and our future expectations.

Recent scandals have brought food fraud to the forefront of public discourse and the topic is of concern to consumers, the business sector and policy makers alike. In addition, food fraud remains a constant threat to the interactions and relationships within agrifood systems and affects the outcome of agrifood system interactions, one of which is food safety. The economic burden (Bindt, 2016) of food fraud is two-fold: i) economic damage and ii) unfairness between market actors.

Despite technological advancements in communication, analytics and value-chain traceability, there exist no easy solutions for this complex problem.

Overall, the current narrative is one of ever-increasing levels of food fraud incidences and of agrifood systems undermined by criminal elements accompanied by calls for urgent reaction without much consideration of what might be done and how. The narrative further fails to separate the impact of the crime itself from the impact of the crime on our emotional reactions to it (Levi, 2008).

Using foresight thinking to adjust the narrative

The thinking shared here has built on a foresight approach and aims to move the conversation about food fraud beyond the current narrative that seems to be circling around a limited number of themes. We will start by expanding the picture to consider a variety of system elements that are central to analysing the problem of food fraud and subsequently recombine these diverse strands of thinking with the aim of contributing to a discourse supporting a realistic assessment of the issue.

We start from the basic premise that there will never be an agrifood system without attempts at food fraud. However, we feel that with better overall understanding of the problem and how to maintain a judicious level of

[28] Food fraud differs from bioterrorism in that bioterrorism intends to cause harm and/or achieve high visibility resulting in public unrest or panic.

[29] Efforts to regulate food fraud are contained in the Hammurabi code of laws, a Babylonian code of law from ancient Mesopotamia, dated to about 1754 BCE.

preparedness, we will contribute to minimizing the risk it poses and maintaining trust in our food (FAO, 2021).

In the following chapters we start by discussing whether the widely shared narrative of ever increasing instances of food fraud due to complex supply-chains is substantiated and will then move on to looking at those principles our food control systems rely on to create trust. We further continue by looking the role legislation has in increasing trust and addressing food fraud. Finally, we return to the notion of trust in social interactions and have a look at the role of the consumer within the food systems context.

The arguments for increased incidences are not based on solid evidence

Arguments supportive of an increase in food fraud are built on one or a combination of the following: recent scandals, an increase in recorded numbers (European Commission b, n.d.), an increase in academic publications, an increase in analytical results, and the increasing complexity of global supply chains.

These strands of argument feed into our fear of loss of control and make for great stories; however, a more careful look at the numbers might be pointing towards a different conclusion.

First, neither does the data cited as a proof of increasing instances of food fraud depart from a common baseline, nor is the methodology applied in determining the economic burden of food fraud harmonized (Bindt, 2016). In relation to data, one would also need to add that the hidden nature of the crime makes it near impossible to capture data reliably (Reilly, 2018).

Second, the argument of food fraud increasing as a result of complex food chains and globalization would deserve a closer analysis. Fraud in relation to foods was severely punished as far back as Babylonian times (Yale Law School, 2021), and publications demonstrating the level of adulteration of foods using chemical analytical methods in the early 19th century (Shears, 2010) illustrate that this crime of opportunity has been accompanying business activities regardless of the level of globalization and supply chain complexity.

As an alternative to these arguments, we propose to view the increase in requests, e.g. those submitted to the recently[30] established European Union Administrative Assistance and Cooperative System for Food Fraud for cooperation concerning suspected cases of fraud in the agrifood chain (European Union, 2020), as a consequence of raised awareness and willingness to contribute to a system put in place to address food fraud rather than a proof of increase in numbers.

We further propose to consider the increase in published analytical data identifying food fraud as an indication of the redirection of analytical resources within an agrifood system towards this necessary body of work and therefore as a contribution to more transparency and identification of cases that have so far gone unremarked.

Our food controls are built around the notion of trustworthiness of the agrifood system actors

Over the past century, the continued advancement of analytical techniques, our knowledge about food safety hazards, the shifting of the public agenda to the relationship between diet and health, and reactions to very prominent food safety scares resulted in a focus on the protection of consumers from food safety risks and less from fraud. This is mirrored in the fact that public health and facilitation of trade are the desired policy outcomes of food control systems (FAO and WHO, 2019).

Food safety, a central outcome of a functioning food control system, results from practices and controls involving all actors of the system with a major responsibility for following good practices born by the business sector. Over the years and based on experience, oversight has moved away from distrust and punishment towards an approach of learning and improvement in that producers and processors are expected and encouraged to adopt practices as appropriate towards the common goal of safe food. Oversight activities are carried out based on the notion that most actors want to and are doing their best to play by the rules. This food control system approach creates an environment of predictability which in turn supports trade, public health and builds consumer trust.

While this successful model builds upon the common notion that all stakeholders want to play according to a set of agreed-upon rules, practices and shared responsibility,

[30] The system was established in 2016.

food fraud does the opposite: it simultaneously benefits from the established trust mechanisms while undermining them thereby collapsing the multifaceted system of shared responsibility down to the actor(s) committing the fraud. As a result of this, the safety and quality of our foods relies on decisions and actions made by the fraudsters, which in turn can enhance food safety risks even if food fraud is committed with the goal of economic gain only.

This situation arguably puts a strain on food control systems because fraudsters see it as an opportunity to benefit from the efforts conducted by others to build trust: fraudsters disregard the ethical principles that have made the system trustworthy. Despite this, we would argue not to lose trust in the system, but to continue to work to maintain it and ensure that it is resilient to such attacks.

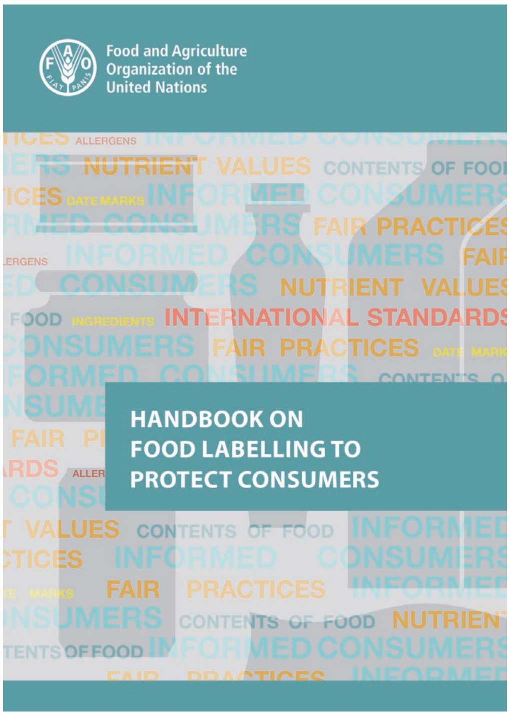
Regulation is a central part of trust-building in agrifood systems

Governments are in the unenviable position of having to develop policies and legislation to face this risk to agrifood systems that is hard to measure and predict.

The good news is that countries, regions and the international community are responding to the challenge food fraud presents. This provides an opportunity to learn from approaches and experiences adopted by others. In this section, we will present five regulatory strategies, from which countries can draw from to address food fraud and increase trust in their food systems. These strategies are based on i) food safety and quality frameworks, ii) consumer protection legislation, iii) contract law, iv) criminal law framework, and v) public-private collaboration (Roberts, Viinikainen & Bullon, forthcoming).

This grouping is simply intended to provide an orientation for developing national strategies that have common threads; however, there is considerable overlap and interdependence between each strategy. Additionally, these five categories are not comprehensive, and countries may have other approaches applicable to food fraud. Implicit in this section is the recommendation that national governments cannot fully address food fraud by just enacting a single law or a single strategy. Food-systems thinking about multiple strategies and coordinated effort amongst government agencies and with the private sector will be required for governments to successfully address food fraud and increase trust in agrifood systems.

Regardless of the overall strategy chosen, countries may find it useful to define "food fraud" in their legal frameworks, potentially relying on the defining elements of intentionality, deception and undue advantage. While a legal definition for food fraud is not strictly necessary to combat food fraud – essentially all actions that would be classified as "food fraud" are already prohibited in most if not all national legal frameworks – an agreed definition



may still carry significant benefits in clarifying the regulators' intent and be conducive to galvanizing action and support for the chosen regulatory strategies.

Food safety and quality is the "traditional" home of legislation countering food fraud, especially, but not limited, when the fraud poses a health risk. Many countries regulate food fraud within the framework of food safety and quality legislation, including rules on standard-setting, labelling and quality control. These can contribute to preventing food fraud, and also to establish legal grounds for surveillance, control, enforcement and even prosecution. The main limitation under this approach is that it may be less effective in cases where food fraud does not pose a direct health risk, as the system is built to capture certain, mostly known, issues endangering food safety, which may not be equally applicable to catch what the fraudsters are doing.

Consumer protection legislation offers a number of options for governments to protect consumers from food fraud. The crux of the legal protection in this subject area is that consumers should have the right no to be deceived by products and services which do not meet their expectations, to receive accurate and sufficient information regarding the product or service they want to purchase, and to seek redress against fraud and other unfair trade practices. Relying on consumer protection legislation, consumers may try to remedy food fraud directly by suing the offending food operators for fraudulent practices. Limitations of this approach comes from the capabilities and knowledge of consumers in relying the tools at their disposal, and the knowledge and capacity of consumer protection agencies to recognize and react to food fraud.

Contract law offers another strategy. Food supply chains are normally composed of vertical and horizontal chains of contracts connecting various core value-chain actors from producers to consumers, as well as contractual relations among operators of support services (e.g. purchase of inputs, financial agreements) (FAO, 2020). It is often within the context of these supply chain contracts, that the fraudulent behaviour occurs: one contractual party has no intention to follow the contract, but rather intentionally provides a product that does not match with its description in the contract and tries to mislead their counterparty as to this fact. As such, food fraud would most often be a violation of the underlying contract, bringing the topic within the scope of domestic contract law and allowing for contract law enforcement. As with consumer protection legislation, the real possibility to protect one's rights under such enforcement may be the limiting factor.

Criminal and administrative codes can also define food fraud infringements and sanctions that complement the regulatory framework. The inclusion of food fraud into criminal codes reflects the uniqueness of this problem and its potential harmful effects. While criminal law does provide a valid avenue for the prosecution of food fraud, which is often a form of fraud criminalized in national criminal codes, care should be taken not to expand the use of criminal enforcement to other forms of infractions related to food safety and quality standards. It is because food fraud occurs at the nexus of criminal and non-compliant business behaviour that conceptualising it as a crime – where certain requirements of severity and intentionality are established as required by national legislation – is important for effective control.

Private sector regulatory strategies for addressing fraud in global food value chains, but also at domestic level, have emerged. There remains ample room for strategic use of private regulatory initiatives to control food fraud, especially with regards to transnational contracts. Self-regulation and co-regulation strategies, and private-public coordination opportunities for controlling food fraud in national and international food value chains, including the development of best or good practices by food companies, are especially ripe for exploration and consideration.

With all these options, and more, regulating food fraud to increase trust and choosing and implementing the optimal legal strategy requires thoughtful analysis, process orientation, and skilful implementation. It also requires consideration of the interrelationships between food fraud and public health, economic factors, fair commercial practices and consumer interests. The chosen regulatory approach to food fraud would also depend on the type of legal system that exists in a particular country (such as civil or common law), the existing legal and institutional frameworks and available resources. Above all, successful strategies to combat food fraud depend on strategic cooperation at all levels of governance along the food supply chains.

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Employee inspects bottles of olive oil.

Beyond the technical: considering the notion of trust in social interactions

Even though food fraud undermines trust, we need to remind ourselves that trust is a result of highly differentiated socioeconomic systems (Bachmann, 2001). Our globalized supply chains exist and function precisely because of trust; we cope with uncertainty through trust. In fact, in socioeconomic systems where there is little trust, interactions are limited to levels of control that are not conducive to growth because everything must be within eyesight. Societies are constantly producing trust through institutional and other mechanisms (Zucker, 1986) and our economy is a result of enduring patterns of social practices. In layman terms, one could say that it is made up of a fuzzy logic of shared beliefs rather than calculation.

Within this socioeconomic context, consumers are considered the weakest actor in an agrifood system when food fraud is concerned. Their role is the one of the ultimate trustors of the system who consumes the foods coming out of a value chain. In the context of an agrifood system where consumers can choose which foods to buy, they carry a share of responsibility by being able to put their money where their trust is.

In the case of most frauds, consumers cannot identify whether a food has for example been adulterated or whether the label accurately represents what is in the packaging. Therefore, their trust in what they buy relies heavily on the overall regulatory framework from which their foods derive and the commitment by the producing/processing sector to abide by standards.

From every technical progress, societal change, and regulatory achievement comes an increased demand for agrifood systems to deliver at the next level of expectations. Foods, in addition to nutritional and health demands, are carriers of societal global values relating to the environment, production practices, working conditions and so on.

Further to this, increased knowledge by agrifood system actors appears to also create a demand for more control over food attributes, which in turn places demands on the food sector to meet these demands of value attributes.

This increase in attributes of course requires additional controls for guaranteeing that foods meet these criteria and labels are not selling empty promises. However, these additional attributes provide additional surfaces for food fraud opportunities.

Instead of viewing this as a never-ending game of enabling fraud, we need to remain on the path of building resilient agrifood systems and argue against the demand for more control and more data with a statement provided by the social sciences which links back to the previous “fuzzy logic” description: Potential trustors need good reasons instead of precise data for their decisions.

What is the way forward?

It is a sobering thought to accept that we will not eliminate fraud from our agrifood systems, and that fraudsters are free riders whose business model thrives optimally where trust systems exist.

One might even argue that adverse situations that put strain on systems ensure that the systems stay alert and are thus better prepared for adverse events. Recognizing that this thought is theory only, we emphasized that the final call must be left to those bearing the responsibility of minimizing the economic damage, potential health consequences, and overall erosion of trust that fraud leaves in its wake.

A suggested way forward would be to avoid hasty reactions to every new food fraud scandal that hits the news, and instead to analyse how national and regional approaches can be developed using an appropriate combination of the regulatory strategies, including those introduced in this brief.

We also caution against relying exclusively on data and data-based techniques as a solution for solving food fraud. Data on its own does not provide more clarity and is not a solution for the fact that fraud is linked to behaviour patterns inherent to human behaviour. We would rather recommend looking beyond data as a solution and considering social variables as an equally valid element of a discourse on food fraud.

In the restructuring of a food control system to better address the fraud, the tendency has been to include additional layers of administrative burdens on agrifood system actors that only result in slowing down the successful mechanisms in place that support trade and ensure public health.

As already alluded to, heightened awareness and vigilance and continued contributions to building resilient agrifood systems are our best chance at ensuring that the damage of food fraud can be managed

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10.
Conclusions

Foresight plays an important role in identifying emerging food safety challenges and opportunities that will continue to arise as the global context evolves with ongoing transformation of the agrifood systems.

As transformation of the way we produce, distribute and consume food is underway, there is need for effective and proactive food safety management that keeps pace with the changing global context, to ensure food safety-based vigilance throughout the agrifood systems. Therefore, the application of foresight in food safety has never been more pertinent. Foresight can be used to shed light on emerging areas that have not received adequate attention, for instance, by highlighting the impacts of climate change on food safety (FAO, 2020), a topic not as well-known as other effects of climate change. As science evolves, foresight will enable relevant food safety authorities to stay abreast of the latest advancements. At the same time, it is important for risk assessment processes to keep pace with scientific progress in order to continue to guide the development of relevant and reliable food safety policies, including for emerging issues such as new food sources. With the rapid evolution of technological innovations, foresight provides the opportunity to adequately evaluate the benefits and risks associated with them, thereby allowing the development of appropriate adoption and implementation strategies. An overview of some of emerging areas of interest, as identified through the FAO food safety foresight programme, has been provided in the various chapters in this report.

Amid intensification of food production, there is increased attention to the issues of sustainability and resource depletion, which are driving the popularity of the concept of circular economy. While implementation of circular economy within agrifood systems can bring with it many benefits – maximizing the value of natural resources, reducing food waste, regenerating natural systems, and more – it can also raise the potential risk of introducing (or re-introducing) and concentrating food safety hazards within the system, an area that is explored in this report through the brief on recycling of plastics.

Rising awareness about the adverse environmental impacts of food production, climate change effects, and population growth are not only driving innovations that will shape our future agrifood landscape, but are also influencing consumer preferences and the resulting dietary shifts. New food sources (such as insects, seaweeds, and so on) and new food production systems (e.g. for cell-based food production), are gaining global interest among consumers for meeting both human and planetary health goals. Development of regulatory safeguards needed to provide appropriate oversight call for keeping pace with this fast-expanding food sector of new food sources and food production systems. Understanding the unique food safety implications that this area can bring will help to establish the necessary guidelines and standards needed to fully realize the potential of this sector.

The role of microbiome structures and dynamics across the agrifood systems on the impacts on human and animal health is increasingly being understood.

There is recent literature that offer new insights into the associations between microbiomes and a range of different human diseases as well as their possible implications for modulating our exposure to different chemical hazards. Our growing understanding of the role of microbiomes for our health also calls for better integration of this component into food safety risk assessment processes. In addition, as microbiome assessment lies at the intersection of both biological and chemical risk assessments, it also provides opportunities to collaborate among these two disciplines.

Technological innovations, such as Blockchain, and Artificial Intelligence, among others, can be transformative for food safety, and in turn for agrifood systems. To facilitate this, basic infrastructure, regulatory framework and enforcement procedures, better data protection and governance need to be put in place. Moreover, such advancements also need to be brought to areas where they are needed the most. With inequality on the rise globally, putting both social and economic development in jeopardy, access and usage gaps with regards to scientific advances and technological innovations can be major stumbling blocks to an equitable distribution of science and innovation applications.

Foresight will enable emerging issues to be looked at through a food systems lens by encouraging a holistic way of evaluating both opportunities and challenges that can have varying impacts on food safety, and through it on agrifood systems.

The global community increasingly agrees that food systems thinking and the importance of One Health demand a holistic approach to addressing emerging challenges to the agrifood systems, rather than through siloed responses. In addition, the changing global contexts of the agrifood systems are highlighting the importance of acknowledging the growing interconnectedness, complexity and multidimensionality of food safety. Foresight provides an avenue to explore emerging opportunities and challenges in their totality, including all variables influencing them, thereby allowing food safety authorities to develop a multisectoral view of the changing dynamics within and for food safety. This is in line with the increased recognition of the One Health approach (Joint Tripartite [FAO, OIE, WHO] and UNEP Statement, 2021), that affirms the inextricable linkages between the health of human, animal and ecosystems and aims to address complex multidisciplinary issues to improve public health and livelihoods, safeguard natural resources and transform agrifood systems. In addition, efficient science-policy interfaces support forward-looking approaches that are needed to create effective multi-stakeholder dialogues on the benefits and trade-offs associated with pursuing specific strategies. Foresight can help bridge science and policy by utilizing the former to inform a range of food chain-related decisions that enhance the latter.

FAO is well-placed to collect, analyse, and disseminate information on various emerging issues from numerous fronts, and it can also provide support to countries in implementing their own foresight activities.

FAO’s Corporate Strategic Foresight Exercise (CSFE) was instrumental in providing a set of 18 key current and emerging interconnected socioeconomic and environmental drivers that are impacting agrifood systems and in turn are affected by the systems. These insights from CSFE were considered in the formulation of the Strategic Framework of FAO, as it was developed in the context of recent international developments, emerging global and national trends, and major challenges in the food and agriculture sectors (FAO, 2021a). FAO’s Strategic Framework supports and enables the 2030 Agenda through the transformation to MORE efficient, inclusive, resilient and sustainable agrifood systems for *better production, better nutrition,* a *better environment,* and a *better life*, leaving no one behind. Science, technology and innovation have been highlighted as critical elements for this transformation.

The importance of proactive identification, through foresight approaches, of new and emerging issues with implications for transformation of agrifood systems, has been underscored in the outline of the new FAO Science and Innovation Strategy (FAO, 2021b). Since food safety plays an integral role in transformation of agrifood systems, FAO's Strategic Priorities for Food Safety (currently under development) highlights the importance

of foresight in food safety decision-making by facilitating better identification of emerging issues that may pose potential food safety risks as well as those that may bring opportunities. Therefore, the importance of foresight has been stressed to not only help fill in knowledge gaps but also promote future policies for the adoption of emerging innovations and foster preparedness to address future challenges in the agrifood systems.

Limited resources, user capabilities, technical skills, and financial support are among the factors that can affect the capacity of countries to engage in foresight exercises. In order to cultivate this capacity, significant investments in terms of training and development of institutional capabilities will be needed, together with encouraging a shift in mindsets – from reactive to anticipatory – at various tiers of public administration. FAO's global perspectives on emerging issues in food and agriculture coupled with extensive cross-border reach and the capacity to deliver global public goods make it uniquely placed to serve as a neutral platform for the collection, analysis and dissemination of information that is independent and trusted. Therefore, results from foresight exercises, carried out by the Organization at a global level, can be distributed to a wide audience, including countries with limited access to the know-how and capacities to carry out foresight exercises of their own. Moreover, effective foresight approaches rely on information gathered from a wide range of sources. FAO can not only draw from expertise across the full agrifood spectrum within the Organization, but also through cooperation with a broad network of external partners – academic and research institutions, national authorities, and the private sector – who provide valuable additional insights into various aspects of the food chain.

In conclusion, foresight can help us understand how new trends and drivers, either within or outside the agrifood systems can affect the systems in general, and food safety in particular. However, it is important to acknowledge that foresight does not predict the future, but can allow us to be better placed to navigate both opportunities and challenges, enabling resilience and agility, and ultimately enhancing strategic preparedness through long-term thinking

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10. Conclusions

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Food safety is a keystone of agrifood systems and all food safety actors need to keep pace with the ongoing transformation of agrifood systems towards the 2030 Agenda for Sustainable Development, while preparing to navigate the potential threats, disruptions and challenges that may arise. Foresight in food safety facilitates the proactive identification of drivers and related trends, both within and outside agrifood systems, that have implications for food safety and therefore also for consumer health, national economy and international trade. Early identification and evaluation of drivers and trends promote strategic planning and preparedness to take advantage of emerging opportunities and address challenges in food safety.

In this publication, the FAO food safety foresight programme provides an overview of the major global drivers and trends by describing their food safety implications including climate change, changing consumer behaviour and preferences, new food sources and food production systems, technological advances, microbiome, circular economy, food fraud, among others.

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