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# A FoodSafeR perspective on emerging food safety hazards and associated risks

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The recently launched FoodSafeR initiative is a cooperative and coordinated approach to the identification, assessment, and management of emerging food security challenges and associated risks—both chemical and microbial. The FoodSafeR consortium includes global stakeholders across governmental, inter-governmental, academic and industrial institutions involved in food safety, research, and production. Consortium members have led in-depth discussions on identifying, assessing and managing chemical and microbial food safety issues resulting from climate change, emerging microbial and chemical contaminants, and evolving dietary preferences. Food safety research often is episodic in nature, increasing after a crisis and then decreasing when there are no major problems. Timely communications about and a central source containing data on previous outbreaks were identified as crucial issues to reduce the harm that could result from a food safety issue. In the course of the discussions, both new and old microbial and chemical hazards were identified for inclusion in a central database. The database could be used to develop artificial intelligence (AI) models to explain existing and predict emerging food safety risks. The FoodSafeR hub continuously collects and merges government, academic and private sector data to enable all stakeholders to better understand emerging risks, both chemical and microbial, and where they are found. As the database expands, climate change impacts on food safety can be documented and then integrated with public health data to rigorously assess the contributions of food safety to public health risks. The overall goal is to enhance global data sharing, improve food safety standards, and ensure the production of safe, accessible food for all populations thereby reducing the economic burden of foodborne illnesses, enhancing food security, and promoting sustainable food systems. The goal of this paper is to alert the global food safety community of the availability of this new resource and to provide information on the types of data it contains while encouraging others to contribute data that would broaden the information available and enable more timely and accurate identification of potential food safety issues throughout the world.

KEYWORDS

**agrifood system, climate change, emerging contaminants, microbial contaminants, chemical contaminants, risk assessment, mycotoxins, heavy metals**

# 1 Introduction

There is an on-going urgency to improve the safety and security of our food globally (FAO, 2024). Threats to food safety include, among others, climate change, the integration of emerging novel raw and recycled materials into agrifood systems, changing dietary preferences, and requirements of susceptible population subgroups (FAO, 2022a,b; Welch et al., 2024). The major goal of the FoodSafeR project, which began in October 2022 and is funded by the European Commission, is to identify, assess, and manage emerging chemical and microbial food safety risks. One of FoodSafer's first activities was to organize a workshop whose participants were international experts in the areas of microbiological and chemical food safety, food security hazards, and risk assessment from international institutions, universities and regulatory agencies (Supplementary Table S1). Generally, discussions were based on independent responses to a seven-question questionnaire (Supplementary Table S2) distributed prior to the meeting and returned and compiled before the meeting. Questionnaire responses and meeting discussions were synthesized for this paper to provide a state-of-the-art perspective on international food safety issues. Included are some potential responses to the problems and information on the role that FoodSafeR can play in the process.

# 2 Food safety hazards

Food safety hazards are generally well known in scientific circles and both microbial and chemical hazards are important. The amount of contamination is not usually as well understood and varies widely by location and type of food consumed. Table 1 is a list of the hazards discussed at the Workshop.

Prior to this report, findings related to stakeholders'/experts' opinions of food safety/security policies in the EU with global perspective have been limited. The most comprehensive studies were conducted over a decade ago (van Kleef et al., 2006; Sargeant et al., 2007; Van Boxstael et al., 2013). In a somewhat more recent online survey (Lupo et al., 2016), 80 stakeholders' perceptions, attitudes, and practices toward risk prevention in the food chain were assessed in more detail. Among these stakeholders, 60% thought that pathogenic microorganisms were the most important hazard and 24% suggested that climate change was the most important challenge to food safety. In response to these hazards, 73% felt that food chain-related problems were preventable and had a positive attitude toward risk prevention measures, with 75% reporting they had recently experienced some hazards and described risk reduction measures that had been adopted. Overwhelmingly, incentives to implement risk reduction measures were considered policy obligations, e.g., enforcement of regulations, with public health consequences. Other identified barriers to food safety risk reduction included budgetary constraints, and doubts about the food safety measures' effectiveness. More recent multi-stakeholder expert opinions of critical drivers of agrifood systems and related trends can be found in a series of publications titled "*Trends and Challenges for the Future of Food and Agriculture*" (FAO, 2022b) from the Food and Agricultural Organization of the United Nations (FAO).

## 2.1 Real and perceived risks

Food safety is the third most important trait, behind cost and taste, considered by a European consumer when purchasing food (European Union, 2025). The European Food Safety Authority (EFSA) reports that >5,000 foodborne outbreaks, i.e., incidents in which two or more people develop the same disease following the consumption of a common food (EFSA et al., 2023), occur annually in Europe and cause approximately 45,000 cases of illness. The European Rapid Alert System for Food and Feed (RASFF) and the FAO/World Health Organization (WHO) International Food Safety Authorities Network (INFOSAN) report hazards rather than illness, with hundreds of notices per year regarding contamination by microbes, chemicals, allergens (mostly unreported milk, soy, egg, and peanut in products; WHO and FAO, 2023), and physical hazards, e.g., glass or plastics. A great deal of additional science- and data-based information is available publicly, with the databases listed in Supplementary Table S3 providing an excellent starting point for more in-depth analyses.

## 2.2 Microbiological hazards

During the discussions, a number of microbes (bacteria, fungi, viruses, and parasites) were identified as potential hazards, with bacteria most commonly mentioned (Table 1). Some were widespread,

TABLE 1 Food safety hazards discussed at the FoodSafeR workshop.

| Type of risk | Risk agent |
|---|---|
| Bacteria | *Bacillus cereus*, *Campylobacter jejuni*, *Clostridium* spp. (e.g., *C. botulinum*, *C. perfringens*), Coliform and multidrug resistant bacteria, *Cronobacter sakazakii*, toxin-producing *E. coli* (e.g., STEC, O157:H7 and O116: H25), *Listeria monocytogenes*, *Salmonella* spp., *Shigella* spp., *Staphylococcus aureus*, *Streptococcus* Group B, and *Vibrio* spp. (e.g., *cholerae*, *parahaemolyticus* and *vulnificus*) |
| Fungi | *Alternaria*, *Aspergillus*, *Claviceps*, *Fusarium* |
| Parasites | *Anisakis*, *Cryptosporidium* spp., *Cyclospora cayetanensis*, protozoa |
| Viruses | Hepatitis A & E viruses, noroviruses |
| Natural toxins | Mycotoxins (e.g., *Aspergillus* toxins including aflatoxins and ochratoxin A, ergot alkaloids, and *Fusarium* toxins including deoxynivalenol, fumonisins, T-2, HT-2 and zearalenone), phycotoxins (e.g., ciguatera toxins), plant toxins (e.g., pyrrolizidine alkaloids and tropane alkaloids) |
| Toxic elements | Arsenic, cadmium, lead, mercury and other heavy metals |
| Chemicals | Allergens, bisphenol A, drug residues, environmental inhibitors, ethylene oxide, flame retardants, food additives, food processing contaminants (e.g., acrylamide), micro- and nano-plastics, mineral oils, plasticizers, per- and polyfluoroalkyl substances (PFAS), perfluorooctane sulfonate *(PFOS)*, persistent organic pollutants (e.g., dioxins), pesticide residues (e.g., fipronil and neonicotinoids), and volcanic ashfall |

e.g., *Listeria*, *Salmonella*, and multi-drug resistant coliform bacteria, while others were limited to one or a few foods, e.g., *Vibrio* on shellfish and *Cronobacter* on baby formula. Fungi were viewed as hazards primarily as toxin producers. Multiple viruses also were mentioned including: hepatitis A and E viruses, noroviruses, new Ovine Pestivirus (a close relative of classical Swine Fever Virus), West Caucasian Lyssavirus, and avian influenza virus.

*Salmonella* and *Campylobacter* contamination of food items, especially poultry, was viewed as particularly serious for Low- and Middle-Income Countries (LMICs) where both the availability of and demand for chicken is increasing rapidly (EFSA, 2024b; European Union Reference Laboratory for Salmonella, 2024). *Salmonella* contamination of food items, especially poultry, has been a leading cause of foodborne illnesses globally (European Union Reference Laboratory for Salmonella, 2024; Kirk et al., 2014). The Joint FAO/WHO Expert Meetings on Microbiological Risk Assessment (JEMRA), when providing advice to Codex on updating Guidelines for the Control of *Campylobacter* and *Salmonella* in Chicken Meat (CXG 78-2011), noted that no single control measure sufficed to effectively reduce either the prevalence or the level of contamination by these pathogens. Instead, control strategies require multiple intervention steps that will be difficult to implement globally, and especially in LMIC broiler production chains (FAO, 2023c; FAO and WHO, 2024a).

### 2.2.1 Detection methods

Limited analytical capacity for foodborne pathogen detection combined with incomplete monitoring of emerging risks often limit preventive detection and risk management, with a disease outbreak often the trigger for a closer safety evaluation. Culturing potentially contaminated materials and identifying the microbes present is the current testing standard for many bacteria and fungi. These tests often take time and their utility depends on the ability to accurately identify any microbes that grow.

Foodborne contamination with non-bacterial microbial agents, e.g., viruses and parasites, was thought to be under-reported, as there are relatively few tests for these microorganisms. The lack of rapid, easily-implemented diagnostic tests might be a result of lesser regulatory emphasis or research focus for these microbial hazards.

Multiplex PCR (polymerase chain reaction) systems, through metagenomic studies, and Illumina and Nanopore Sequencers, through whole genome sequencing (WGS), can be used to detect and identify microbial contaminants, but they are not yet considered high throughput. WGS can resolve the identities of very closely related foodborne pathogens. For example, WGS can distinguish closely related *Escherichia/Shigella* species, and differentiate toxigenic strains of *E. coli* (Chattaway et al., 2017; Devanga Ragupathi et al., 2017; FAO and WHO, 2022; Therrien et al., 2021). WGS technology has rarely been used for source attribution or microbial risk assessment (Franz et al., 2016). FoodSafeR will test WGS for monitoring and detecting coliforms, antimicrobial resistant (AMR) bacteria, and emerging zoonotic viral strains in ready-to-eat foods of animal origin in the EU food supply chain.

## 2.3 Chemical hazards

Chemical food safety hazards were clustered into six classes: (i) toxic heavy elements (As, Cd, Pb, Hg); (ii) perfluoroalkyl and polyfluoroalkyl substances (PFAS, especially PFOA and PFOS); (iii) natural toxins, including mycotoxins (aflatoxins, deoxynivalenol, ergot alkaloids, fumonisins, citrinin, HT-2/T-2, and emerging/modified toxins), plant toxins (pyrrolizidine and tropane alkaloids), and phycotoxins; (iv) pesticides, e.g., neonicotinoids, fipronil, nanopesticides, and biocides; (v) micro-/nano-plastics and plastic-associated contaminants, e.g., bisphenol A and plasticizers; and (vi) other chemical contaminants, e.g., acrylamide, ethylene oxide, flame retardants, and mineral oils. Pesticide residues topped the list of EU food safety alerts in 2022 (Food Safety Magazine, 2023).

Natural toxins (especially mycotoxins), PFAS, toxic heavy elements, and pesticides were the chemical hazards of highest interest. Conference participants identified arsenic as the heavy element of greatest concern associated with rice, fruits, vegetables and seafood as potential contaminant sources, although other heavy metal contaminants, e.g., Cd, Pb and Hg, could be important in some of these foods. PFAS were of concern in processed foods and food contact materials. Chemical mixtures have been important topics of discussion for both EFSA and the FAO/WHO Joint Expert Meeting of Food Additives (JECFA). A total diet study identified mycotoxins, pesticides and PFAS of public health concern in the typical dietary patterns in four African countries (Ingenbleek et al., 2019a, 2019b, 2020; Vaccher et al., 2020). Finally, food allergens, drug residues, and volcanic ashfall were all highlighted as global hazards, with the FAO flagging allergens as the second most common cause of recalls of foods traded globally.

Mycotoxins were perhaps the single most important topic of meeting discussions, which was not unexpected due to the recent increase in global attention given to these widespread naturally occurring contaminants (Krska et al., 2022). This attention when coupled with enhanced surveillance and monitoring for these toxins by the EU of imported commodities (https://food.ec.europa.eu/safety/rasff_en), intra-regional trade disputes in East Africa (The East African, 2023; TradeMark Africa, 2023), and product recalls globally have increased mycotoxins' public profile.

### 2.3.1 Detection methods

Over the past decade, numerous technical advances have been made in the detection and quantification of (emerging) chemical contaminants. State-of-the-art Liquid Chromatography–Tandem Mass Spectrometry (LC–MS/MS) is a sensitive targeted platform that can simultaneously detect and quantify over 1,200 contaminants, including mycotoxins, plant toxins, pesticides, veterinary drugs and other pharmaceuticals, in less than 45 min (Steiner et al., 2020; Sulyok et al., 2020). LC–High Resolution Mass Spectrometry (LC-HRMS) can screen and analyze food for non-targeted chemical contaminants and their metabolites, e.g., biotoxins, pesticides, and plant toxins. Although not necessarily high throughput, LC-HRMS is essential for emerging toxin/metabolite screening and quantification as it can detect contaminants not expected to be in a particular material. This property is particularly important in a climate change context (FAO, 2020) as novel compounds may be created as plants and microbes adapt to a changing environment. In contrast, the use of a method restricted to targeted analytes would miss both novel and unexpected contaminants.

Other novel high throughput methods also have emerged, including infrared spectroscopy for routine determination of mycotoxins in crops; and magnetic solid-phase extraction (MSPE) based gas chromatography-tandem mass spectrometry for insecticide residue determination in vegetables (Freitag et al., 2022; Iammarino et al., 2022). In the area of food fraud, isotope ratio mass spectrometry (IRMS) is now used for organic authentication of multiple food products. Portable spectroscopy devices coupled with chemometrics and AI also can be used. Similar methods also can be used to identify adulteration with toxic chemicals, e.g., addition of lead chromate and metanil to turmeric to give a more vibrant yellow color. FoodSafeR leverages the strengths of these chemical detection methods for pro-active food monitoring, the prediction of potential problems, and to forestall future outbreaks.

## 2.4 Some recent problems

In Europe each year, foodborne hazards, including bacteria, parasites, toxins (and other chemical hazards) and allergens, cause some 23 million cases of illness and 5,000 deaths (European Commission, Directorate-General for Research and Innovation, 2020; WHO, 2019; WHO Foodborne Disease Burden Epidemiology Reference Group, 2015). This record leaves European citizens neither fully confident in nor trusting of current food supply systems. These problems often are triggered by isolated events such as a zoonotic agent or a carcinogenic mycotoxin and are likely to increase in coming years due to climate change and shifts toward more plant-based diets. Major food safety problems in Europe include substitution of lead chromate for turmeric spice (Erasmus et al., 2021), which is currently under study as a FoodSafeR project. Another prominent European issue was an outbreak of Shiga toxin-producing *E.coli* (STEC) in 2011 that sickened nearly 4,000 people and resulted in 53 deaths (EFSA, 2011a). Similarly important problems have occurred in the United States, e.g., cyanide contamination of Tylenol® (Markel, 2014; Petros, 2022), *E. coli O157:H7* in fast food hamburgers (Rangel et al., 2005), and *Salmonella* in peanut butter (Cavallaro et al., 2011; CDC (US Centers for Disease Control), 2009) and eggs (Kuehn, 2010). These problems have resulted in billions of losses of euros and dollars and at practical levels have resulted in changes in the ways that foods are packaged, labeled and distributed. In general, responses to food safety crises include:

- Product recalls: Products suspected of being contaminated were recalled to prevent further illness, with emphasis on high-risk food items, e.g., ground beef, eggs, and ice cream.
- Stricter regulations: New regulations such as mandatory Hazard Analysis Critical Control Point (HACCP) plans for meat processing, improved sanitation requirements, and increased pathogen testing for various foods. New legislation requiring stricter food labeling, packaging, e.g., tamper-evident packaging for Tylenol®, and food safety measures, e.g., BSE regulations in the UK.
- Public awareness campaigns: From agencies such as CDC, FDA, and WHO to educate consumers about safe food handling practices and the risks associated with certain pathogens.
- Enhanced inspections and monitoring: Closer scrutiny of food production plants and farms, especially following significant outbreaks of pathogens like *E. coli*, *Listeria*, or *Salmonella*.
- International cooperation: For outbreaks with global implications, increased international interaction between public health authorities, e.g., WHO and CDC, and national regulatory agencies particularly regarding food chain monitoring and food imports.

These events often drive consumer perceptions of food safety and must be managed with care to educate the public while avoiding panic responses.

Zoonoses and extreme weather events in Europe in 2021, compounded by the COVID-19 pandemic, made underlying vulnerabilities apparent in our global food systems (iPES Food, 2020) and were an important wakeup call. Food safety management systems established over the past decades in European farming and food businesses, and in European food safety governance need to be adapted to make them more resilient to changes altering global food systems, and yield proactive risk management strategies that can future-proof EU agrifood systems.

### 2.4.1 Microbial contaminants

In the 27 countries of the European Union, microbiological contamination accounts for >95% of national food safety violations and 37% of Rapid Alert System for Food and Feed (RASFF) notifications. Microbial hazards endangering consumer health include infectious bacteria such as *Salmonella*, pathogenic *E. coli* and *Listeria monocytogenes*, and viruses such as norovirus and hepatitis A and E (WHO Foodborne Disease Burden Epidemiology Reference Group, 2015). Historically, the focus of countermeasures has been on mitigation of zoonotic pathogen transmission via animal-based foods. Yet multiple crises have shown that food systems of non-animal origin can suffer from unexpected risks, e.g., the sprouts-associated *E.coli* (STEC) O104:H4 outbreak in Germany and France (EFSA et al., 2023). Climate change-based events, e.g., heavy rainfall, can lead to higher contamination in plant food sources and extensively housed farm animals. Microbiome studies of microbiota highly adapted to conditions of modern food production have identified re- and cross-contamination scenarios resulting from unexpected microbial persistence that lead to an emerging risk for microbial transmission at the processing level (Zwirzitz et al., 2021).

The lack of monitoring for viruses remains a major weakness (particularly for family-driven outbreaks) and little progress has been made in this area in recent decades. A wide range of viruses were reported in 2019, with norovirus and hepatitis A and E being the most prevalent. Overall, outbreaks caused by foodborne viruses led to many illnesses. Some viruses, such as hepatitis E, are role models for emerging foodborne viruses (Harrison and DiCaprio, 2018); with the prevalence of hepatitis E cases increasing 10× between 2005 and 2015 (Aspinall et al., 2017). The epidemiology of the infection spread is not completely understood and new sources of transmission have been identified in recent years.

### 2.4.2 Chemical contaminants

Chemical contaminants in food remain an important foodborne public health concern in Europe (Eskola et al., 2020). In particular, chemical contaminants unintentionally present in food, such as environmental and food process contaminants, e.g., furans, and natural toxins (especially mycotoxins and plant toxins), can pose public health concerns if their concentrations exceed regulatory limits. Even so, the average European food consumer can be exposed to a cocktail of (potentially) genotoxic-carcinogenic contaminants, including mycotoxins, whose synergistic effects at regulatory limit levels are not well understood (EFSA, 2007; Mulder et al., 2015). Evidence is increasing that unexpected biotoxin occurrence patterns due to climate change and combined health risks from exposure to a mixture of chemical contaminants, both increase health risks for consumers (Eskola et al., 2020). Advancing existing prediction tools for mycotoxin (co-) occurrence to increase forecast accuracy, especially for grains, through a big data and machine-learning approach is an active research area and an important part of the FoodSafer project (https://www.foodsafer.com).

Emerging plant toxins, e.g., pyrrolizidine alkaloids, are serious food quality and safety concerns according to recent EFSA reports (EFSA, 2011b, 2013). Plant toxins may function as genotoxic carcinogens in humans, but too little data currently are available to draw firm conclusions. Tropane alkaloids, however, clearly can induce anticholinergic poisoning (EFSA, 2013). Plant toxins can enter the food chain via animal feed, seeds, cereals, tea, herbal infusions and herbal dietary supplements (Di Martino, 2025; Mulder et al., 2014, 2015). Plant toxins are expected to emerge in yet unknown areas and situations due to the increasing globalization of the food supply chain, climate change, online shopping, and continuing changes in consumer preferences and behavior.

## 3 Pre-food-processing food safety risks

Food safety often is perceived as an issue that occurs only after food processing has begun, with pre-harvest pre-food-processing issues considered very important, but often overlooked. How plants are grown or animals are raised often matters significantly in determining the potential, probability, and nature of food safety risks that can be encountered. Thus, food safety should be considered throughout the agro-ecosystem ranging from farmer's fields and livestock to food processing, transport, storage, and use of finished foods.

### 3.1 Good agricultural practices

Managing crops according to Good Agricultural Practices (GAPs) is essential for food safety. Farmers in the United States can be certified as complying with GAPs and are rewarded with broader market access for doing so (NASDA, 2022). Agricultural reform policies targeted at altering agrifood systems, increasing crop resilience, meeting local production constraints, and ensuring sustainability may alter GAPs. GAPs prevent improper use of pesticides and other agricultural chemicals that can contaminate soil, water and crops in ways that make the availability of non-contaminated food almost impossible. Failure to safely manage insects and plant pathogens can result in production losses and contamination with naturally occurring noxious substances, e.g., mycotoxins, that are all but impossible to remove once present. When decontamination is possible, it is expensive, reduces product value, and restricts potential uses. Sometimes contaminated crops or products are destroyed, which often reduces food security, compromises trade and tarnishes reputations. Altered and more extreme weather events associated with climate change are expected to increase pest and pathogen hazards. More climate-resilient varieties or even alternative better-adapted crops may be required in the long-term to adequately respond to these challenges on a global scale.

### 3.2 Water

Only 3% of Earth's water is fresh. This small fraction of the total water supply is divided for uses in agriculture (70%), industry (23%), and municipal/residential (7%) purposes (FAO, 2023a), and is frequently overlooked in food safety systems. Clean water is critical for safe food production in farm, household, and commercial settings (Abia et al., 2023; Anyaegbunam et al., 2024; UNICEF, 2023). Many countries, especially in Africa and Asia, already have access to too little fresh, potable water (FAO, 2023a; FAO and WHO, 2023b), with water pollution exacerbating local water scarcity (Li et al., 2022). Common waterborne diseases from contaminants such as typhoid, cholera, *E. coli O157:H7*, and *Shigella* will increase in response to climate change (Semenza and Ko, 2023). Contaminants in irrigation water (Uyttendaele et al., 2015b) easily carry over to fresh fruits and vegetables with leafy greens, such as lettuce, usually the most problematic. Water, Sanitation and Hygiene (WASH) programs in developing countries focus on household and commercial uses, but often neglect water used for irrigation. Contaminated/polluted irrigation water can lead to unsafe food through plant uptake of contaminants such as heavy elements, on-farm agrochemicals, and pathogenic microorganisms (European Commission, Joint Research Centre et al., 2022; Rather et al., 2017). Clearer descriptions of potential contaminants of typically used water sources and their associated consumer risks are needed to better match available water sources with intended uses or reuses without compromising safety.

Fortunately, water used in food production can usually be reused. The Codex Committee on Food Hygiene (CCFH) recently revised annex documents for using and reusing water that focus on where potable water is most needed (FAO and WHO, 2024a). The FAO/WHO Joint Expert Meeting on Microbiological Risk Assessment (JEMRA) and WHO provided guidelines (FAO and WHO, 2019; WHO, 2022b) for the use and reuse of water in various food sectors with advice on fit-for-purpose microbiological criteria. JEMRA guidance documents (FAO and WHO, 2021, 2023a, 2023b) and documents from the USDA and US-FDA are readily available on water safety for fresh fruits and vegetables, and on the production and processing of dairy, fish and fishery products.

## 3.3 New foods and technologies

Global agriculture needs new technologies that enable access to new food sources and/or production systems. These foods could result from precision fermentation, the introduction of now underutilized plants, or incorporation of new protein sources, e.g., insect proteins. Similarly, novel and existing processes could extend product shelf life by inhibiting microbial growth through "cold pasteurization," with little or no impact on the organoleptic and nutritional properties of the processed material. To succeed, these innovations must be used to produce and preserve food that is accessible to most of the world's population and not just those living in developed countries. Evidence-based safety assessments accompanied by broad education and communications efforts about a technology's safety, efficacy and benefits will be needed from both the public and private sectors.

## 3.4 Fires, floods, etc.

Forest fires produce toxic organic pollutants through combustion, e.g., polychlorinated dibenzo-*p*-dioxins, or by mobilizing toxic elements in the soil. Subsequent floods can then transport these pollutants to uncontaminated areas. Warmer water reduces salinity and facilitates the methylation of mercury, which increases the uptake of methylmercury and other toxic elements by fish and shellfish. This type of contamination increases health risks due to chronic exposure to these contaminants in food.

## 3.5 Environmental inhibitors

Environmental inhibitors inhibit nitrogen oxide release and methanogenesis. They improve production efficiency of crops and livestock by limiting nitrogen loss from farmland, and by reducing methane emissions from ruminants, rice paddies, or manure, and collectively reduce negative environmental impacts of crops and livestock. Food safety issues associated with these inhibitors are difficult to assess and manage due to the lack of internationally harmonized regulatory approaches, agreed definitions of environmental inhibitors, and food safety data for some substances or their carryover residues (FAO, 2023b).

# 4 Monitoring and regulation

Pre-emptive monitoring is the most effective means of controlling and reducing/eliminating food safety hazards. Hazards can enter and accumulate anywhere in the food chain. The earlier contaminated materials are identified the more quickly they can be treated or removed, and effective prospective testing, i.e., the data bedrock of risk management, remains critical. Data from targeted crops/countries/regions are essential to localize and delimit assessments. Implementation of passive monitoring and horizon scanning tools by food operators and competent authorities makes it easier for them to conduct self-checks and issue mandatory hazard alert notifications. Involving National Reference Centers that participate in international programs, such as the WHO Chemical Risk Assessment Network (WHO, 2021), in pro-active/foresight food monitoring was clearly envisioned by workshop participants. A FoodSafeR target activity is to detect and monitor microbial risks in alternative food networks and in novel or little regulated food production systems.

## 4.1 Testing methods

Widespread screening requires high-throughput testing methods. Improved analytical methods could alter existing guidelines or regulatory limits and the codes of practice to prevent, mitigate and manage food safety risks. These improved methods and validation data should be available to all stakeholders. The application of high-throughput identification techniques for chemical and microbial analyses has been increasing (Ayeni et al., 2022, 2024), with further experimentation and innovation in progress. Continual technological advancements however, can make it difficult for private companies and regulatory authorities to keep up with improvements in protocols and the procurement and maintenance of the necessary equipment.

## 4.2 Source of contamination identification

Source attribution of foodborne illnesses is fundamental for the identification, prioritization, and measurement of the impact of interventions to reduce a foodborne illness' burden (Pires et al., 2009). Source attribution also is important in identifying previously undetected or emerging food safety hazards. Identification efforts usually are slower than pre-emptive monitoring as the cause of the problem may not be known. Hazard identification can be particularly difficult if there is chronic toxicity or if similar illnesses can be caused by unrelated hazards. High throughput methods can complicate analyses by identifying multiple potential causes and thereby obscure one or a few critical causal agents. These identifications can be further complicated if the effects can be partitioned among or attributed to co-exposure to multiple chemical substances from food and/or environmental exposures.

## 4.3 Models

Predictive microbial models enhance the understanding of microbial behavior in food systems and usually can account for various environmental conditions (Koutsoumanis et al., 2016).

Quantitative Microbiological Risk Assessment (QMRA) and Poultry Food Assess Risk Model (PFARM) are important models of microbial risks to food safety. QMRA is widely used in North America, especially for assessing water-borne illness risk from drinking water (Brouwer et al., 2018; WHO, 2016, 2023a). PFARM is a risk assessment simulation tool pioneered in 1995 for Salmonellosis due to *Salmonella* contamination of poultry (Oscar, 2023). QMRA and PFARM are both promising models for estimating changes in microbial contamination in foods and water, across the farm-to-fork chain. The FoodSafeR consortium does not focus on the poultry value chain, which is targeted in the Holifood project (holifoodproject.eu); however, QMRA and PFARM may have wider uses in assessing emerging microbial hazards in the food supply. New models are needed to handle the large amount of data generated as high throughput genetic and chemical detection methods become better developed.

### 4.3.1 Early warning systems

Early warning systems can evolve from improved modeling. Climate-change associated events—droughts, floods, excessive heat, and changes in weather patterns—are expected to increase in frequency. Many of these events lead to food contaminated with mycotoxins or phycotoxins (Mu et al., 2024), or with microbiological hazards. Both FoodSafeR and HoliFood are developing novel approaches to improve the prediction of emerging food safety hazards and associated risks.

## 4.4 Regulatory programs

Institution and enforcement of regulations on food safety and management are accepted norms in most of the developed world. Outside the EU, the United States and a few other developed countries. Adoption of external regulations commonly means that data, if any, on local diets or local contamination patterns were not considered. Such regulations are common in LMICs that export food to a developed country. These adopted regulations often are based on those in the EU or US, or from global standards, guidelines, and codes of practice such as those of Codex Alimentarius, e.g., maximum limits (ML) for mycotoxins (Magamba et al., 2017; Meneely et al., 2023; Tueller et al., 2023). Exported products must meet thresholds specified by the importer, which usually means that only the highest quality food in the LMIC can be exported (Uyttendaele et al., 2015a). Food of lesser quality is retained for local consumption, thereby increasing the exposure of the local population to potential food safety hazards, e.g., mycotoxins (Matumba et al., 2015).

Over the past decade, the World Bank (2022) and donor countries have focused on improving food safety for domestic consumers in exporting countries and not just on food for export. This shift in focus is particularly important in sub-Saharan Africa, which is disproportionately impacted by foodborne hazards (Batch et al., 2025). LMIC policy changes often rework Codex food safety guidelines and codes of practice to reflect critical LMIC conditions. Policies for agrifood systems must be flexible so that they ensure resilience, and that local production and sustainability are adequately addressed. The draft guidelines for food hygiene control measures in traditional food markets, completed by the 54th session of the Codex Committee on Food Hygiene (FAO and WHO, 2024b) and adopted by the Codex Alimentarius Commission in November 2024 are an example of such policy changes.

Food regulatory programs in which decisions are based on a food safety risk analysis are a pre-requisite to FoodSafer's objectives and need competency development and capacity building initiatives to develop sustainable programs. In LMICs with nascent or evolving food safety authorities, capacity building efforts also should include collecting local data on dietary intake, food consumption, and the occurrence of food hazards to ensure adequate local information is available.

## 4.5 Food fraud

Food fraud is defined by the Global Food Safety Initiative (GFSI, 2014) as "including the subcategory of economically motivated adulteration. It is deception of consumers using food products, ingredients and packaging for economic gain and includes substitution, unapproved enhancements, misbranding, counterfeiting, stolen goods or others." FoodSafeR recognizes the importance of food fraud, but is not active in this area since food fraud is not always a food safety risk. For example, the substitution of horse meat or kangaroo meat for beef, is an act of fraud that usually has an economic basis, but does not always alter food safety risks (Woodward, 1982; European Commission, Directorate for Food Safety, 2014), although contamination with clenbuterol or other veterinary medications may present a risk if the meat is consumed in a large enough quantity (Rubio-Lozano et al., 2020). Other food frauds, such as melamine in milk powder (Chan et al., 2008; Xiu and Klein, 2010) or mineral oil in cooking oil (Reuters, 2021) had both economic and health related implications. A detailed study of food fraud in China found that most food fraud there had an economic basis and occurred most commonly at the producer level (Zhang and Xue, 2016).

# 5 Needs to improve food safety

Engagement/partnering between the academic community, government and the private sector is needed to ensure that food safety considerations are integral to new food/feed source identification, development and production systems. To further expand the linkage, partners from Ministries of Health and Regional Agencies, e.g., those in the Emerging Risk Exchange Network (EREN) of EFSA, and National Food Safety Agencies and/or Committees, should be included in the project. Five major food research-oriented companies are part of the FoodSafeR consortium (https://my.foodsafer.com/auth). Their inclusion is consistent with the European Commission's strategy to encourage collaboration between researchers in industry and academia. To create a stable public/private collaboration, data from internal industrial monitoring and research projects must be anonymized, reduced to its essentials and entered into public databases. Industry-engaged research and newly identified problems generate findings that drive new systems and policies and benefit consumers. Scientific advice and risk assessments provided by the Joint FAO/WHO risk assessment bodies [JEMRA, Joint Meeting on Pesticide Residues (JMPR), JECFA] are often underutilized. These international bodies can provide advice tailored for regions or countries, interpret technical data, and guide policy and regulatory discussions.

## 5.1 Existing gaps in food safety

Beyond the identification of potential food safety hazards is the identification of strategies/tools that can be used to manage the risks (Table 2; EFSA, 2024a). LMICs sometimes lack human resources and/or physical infrastructure needed to implement effective risk management measures.

Funding for research and surveillance programs, and awareness of publicly perceived risk levels influence the resources devoted to any particular risk management program (Leslie and Morris, 2020; Leslie et al., 2023). Relative attention can depend on the target consumers and food culture, media influence, intentionality and severity of the risk as well as the public's immediate focus within the context of current issues/events. If there are many other 'public health issues', food safety issues might be perceived as less important (Feliciano et al., 2022; Todd, 2020; Wu et al., 2021). FoodSafeR provides a central platform for tackling global food safety issues through the development of a virtual format as an open and accessible tool kit for global stakeholders.

### 5.1.1 Microbial gaps

*Salmonella* and *Listeria* are frequent microbial risks in North America and Europe, but the spectrum of potential pathogens and contaminants expands significantly in the less tightly-controlled food processing and supply chains in Africa and Asia where open informal markets often dominate. In these informal markets there is insufficient adherence to good hygiene practices, and deficiencies in the awareness, capacity, and enforcement of existing, often inadequate, food safety regulations (Kirezieva et al., 2015; Kussaga et al., 2014). Similar problems can exist in developed countries with supplementary health products and food sold through e-commerce and in packaging-free stores where higher levels of cross-contamination can occur (Di Martino, 2025).

More broadly, lapses in Good Manufacturing Practices, Good Handling Practices, Good Hygiene Practices, and Hazard Analysis and Critical Control Points increase the risk of microbial contamination as do increased microbial resistance and limited surveillance and analytical capacity. Climate change impacts, e.g., drought- and temperature-related shifts in the distribution, prevalence

TABLE 2 Strategies for mitigating food safety hazards and risks in different regions of the world.

| Continent | Strategies and tools for reducing food safety risks (*including strategies already in place and new strategies to be implemented*) |
|---|---|
| Africa | *Access to clean, fit-for-purpose water and routine water quality (safety) tests<br>*Public sensitization to food hygiene, good food safety practices, and fecal disposal<br>*Strengthening/building food safety and management regulations |
| Asia | Partnering with the research community, consumers and food companies to integrate food safety considerations in the development of new food sources and production systems<br>*Adopt effective testing methods for detecting emerging hazards in a timely manner, e.g., Liquid Chromatography-High Resolution Mass Spectrometry for (non-) targeted analysis of chemical contaminants in food; multiplex polymerase chain reaction (PCR) methods to rapidly detect microbial contaminants; and Next-Generation (e.g., Illumina and Nanopore) sequencers for Whole Genome Sequencing and Metagenomics |
| Europe | *Passive monitoring (e.g., self-checking and mandatory notifications for food operators; un/planned control, RASFF and follow-up of non-compliance products by food safety authorities) and horizon scanning tools<br>*Pro-active and effective foresight food monitoring<br>*Application of genomic tools for identification of pathogens<br>*Agricultural reform policies (e.g., targeted at resiliency, local production, self-sufficiency, sustainability)<br>*Identification and development of new food and feed sources (e.g., oceans as a source for food and feed) and production techniques<br>National Reference Centre for emerging chemicals and risks (e.g., FAO/WHO identification of emerging risks in food, early assessment of safety, and risk monitoring) that should be linked to representatives from the Ministry of Health and Regional Agencies in the EREN (Emerging Risk Exchange Network of EFSA), and the National Food Safety Organizations<br>Refocus on marine biotoxins, food fraud, and food supplements |
| North America | *Regulatory activities and follow-up<br>*Predictive tools and systems [e.g., Quantitative Microbiological Risk Assessment (QMRA), Poultry Food Assess Risk Model (PFARM)]<br>*Leverage detection methods (e.g., whole genome sequencing)<br>Exploit the Food Safety Modernization Act (FSMA)<br>Perform survey data evaluation<br>Support USDA's Core network<br>Exploit Food Emergency Response Network (FERN) alerts<br>Good Agricultural Practices (GAP) and new plant breeding methods |
| Global agencies | *Better use of scientific advice and risk assessments provided by the Joint FAO/WHO bodies (JEMRA, JECFA)<br>*Awareness raising and food safety risk communication<br>*Hazard analysis, risk profiling, guidelines, and codes of practice for preventing, mitigating and managing the risk, including the use of web-based tools |

*Response provided by more than one workshop participant.

and virulence of foodborne pathogens, are expected to escalate the risk of microbial contamination of food and feed (Duchenne-Moutien and Neetoo, 2021; Morgado et al., 2021; Springmann et al., 2016).

### 5.1.2 Chemical gaps

Parallels to many of the microbial risks also are found when considering chemical risks (Onyeaka et al., 2024; Rather et al., 2017). Inadequate hygiene practices, unenforced or unenforceable regulations, uncontrolled informal markets, and overdependence on plant-based products in the Global South all pose food safety risks. Inadequate agricultural production systems including indiscriminate use of antibiotics and pesticides, drug residue accumulation, food fraud (e.g., horse meat sold as beef), and food processing contaminants are human-generated risks. As extreme climate-change associated events intensify and become more frequent, droughts, floods, heat waves, and harmful algal blooms will increase the susceptibility of many food products to chemical contamination (Krska et al., 2023). The impact of climate change on food safety cannot be explicitly assessed, but increased contamination of food with organic pollutants and natural toxins seems likely.

## 5.2 Risk management and assessment

Availability of data on both well-recognized hazards and emerging hazards whose threats to food safety are not yet well understood or fully characterized limits risk management. Ideally, standardized data are shared through open access food safety databases and alert systems so that threats from different substrates can be easily compared and integrated.

Food safety and hygiene education underlie control of food safety hazards. In some countries, and in particular LMICs, sensitization to food hygiene, good food safety practices, and fecal disposal are needed. Basic public health measures are essential for improved food safety, but cannot be assumed. For example, the WHO/UNICEF Joint Monitoring Program reported in 2019, that 43% of schools globally lacked access to basic handwashing facilities with soap and water (WHO, 2020).

In multiple African countries, the very low level of knowledge of food safety issues negatively impacts the attitudes of local food producers and consumers (Batch et al., 2025; Cudjoe et al., 2022; Makinde et al., 2020; Onyeaka et al., 2021). These attitudes are reflected in data (WHO, 2022a) on sickness and death due to consumption of unsafe food. Implementing hazard identification methods and simple food control options, are first steps for managing risk in much of Africa. Benchmarking food safety performance indicators enables comparison of different management systems, and provide a first evaluation of their microbiological performance (Jacxsens et al., 2010).

## 5.3 Real world exposure

Real-world exposures require evaluating the threat posed by a mixture of microbes and chemicals of both biological and synthetic origin. However, most risk assessments focus on a single contaminant or, perhaps, several structurally similar compounds, e.g., PFAS. Merging often disparate assessments can be critical to determining the real food safety risk. Emerging risks often are difficult to assess due to a lack of quality occurrence data. Without clear identifiable symptoms, a significant threat may remain only marginally detected for years. Yet singular environmental events such as floods, droughts, heat waves, and plant or animal disease epidemics, can pose food safety risks. Event frequency has a role in the risk assessment, which implies a need to understand the consequences of a change in the frequency of the event. For example, how are data on climate change (event frequency and severity changes) and data on plant and animal health simultaneously incorporated into a risk assessment model to derive better predictions of risks that might emerge.

Risk responses require adequate data on the occurrence, type and level of a threat be combined with dietary intake/food consumption data. Short-term risk responses might be as straightforward as limiting the distribution of a particular shipment of a commodity. Long-term risk responses require the assessment of more data and models that can help interpret them. Biomarkers that assess human and animal exposure times and levels are important, especially for hazards such as mycotoxins and pesticides that commonly pose long-term risks, or risks when consumed recurrently at sub-acute levels. Validated biomarkers can assess dietary consumption, or exposure, without the bias of self-reported dietary intake.

### 5.3.1 Integrating food contamination data with foodborne disease surveillance systems

An integrated surveillance system for food contamination and foodborne diseases is vital for protecting public health, ensuring food safety, and upholding consumer confidence in the food supply chain (FAO and WHO, 2004). The WHO Alliance for Food Safety (WHO, 2024a) aligns efforts to integrate surveillance of food contamination and foodborne diseases. Such a system enables early detection of food contamination and foodborne diseases, which in turn enables identification and mitigation of potential public health risks before widespread outbreaks occur (FAO, 2023c). It also empowers public health authorities for swift responses to emerging threats through tailored interventions (WHO, 2023b). Finally, these systems generate data on the prevalence and pattern of food contamination and foodborne diseases, and ground the development of effective prevention and control strategies (FAO and WHO, 2004). Such data also enables authorities to identify trends in foodborne illnesses and to pinpoint potential sources of contamination. Most importantly, however, an integrated surveillance system fosters collaboration and coordination among diverse stakeholders that is essential for a unified response to food safety challenges and to meet WHO's foodborne disease surveillance target by 2030 (WHO, 2024b).

## 5.4 Education and communication

Education about the safety and acceptability of innovative food products and processes, should be part of focused communication efforts. These efforts should explain the technology used in food production and how it was assessed for safety and efficacy. These proactive efforts should reduce or eliminate situations in which acceptable food alternatives, e.g., foods derived from biotechnology, encounter consumer resistance resulting from mis-information campaigns that are commonly spread through social media.

Consumers and food safety authorities in the EU and internationally need to be educated to understand that as food markets become further intertwined with one another, the risks of contamination and novel foodborne illness increase (Walls et al., 2019). The digital/web-based FoodSafeR repository for food safety information will provide data and context for communications across all facets of the food production network.

Risk communication strategies are effective tools whose implementation usually determines their impact. Risk communication from trusted sources, ranging from government agencies to academia, food processors, wholesalers and retailers is critical for the correct interpretation of a risk (Bhardwaj et al., 2023). Programs in which government and food distributors work together to reduce the risk of widespread panic should a food-safety issue be detected and risk management required. National food safety programs need effective projects and channels for communicating risks to consumers, food industries, food authorities and policy makers. Depending on the nature of the problem, those who respond to risks must have been previously sensitized to the potential problems and be capable of responding rapidly. Longer-term risks may have an extended response time, depending on the nature of the efforts required to remedy the risk. In LMICs, illiteracy can compound problems and risk communication messages often need to be conveyed through pictorial and oral messages in local languages.

### 5.5 Food safety as a priority

Adequately funding food safety efforts must be a priority that is not pushed aside in favor of more research to increase productivity (Stelzl et al., 2023). Unsafe food should not be consumed when there is a risk, but instead should be repurposed for alternate uses; e.g., biofuel production or feeding black soldier flies (Heuel et al., 2023). Increasing food safety while reducing food loss/waste, will reduce demand for increased production, result in a more sustainable agrifood system, increase income across the system, enhance food security, and enable more trade. Increased food safety will reduce the economic burden of foodborne illness and the Disability Adjusted Life Years (DALYs) of a population, and enhance stakeholder understanding of the positive and negative consequences, of producing, selecting and keeping food safe for consumption.

## 6 Conclusion

FoodSafeR is focused on making food safety everyone's business. Natural causes, human actions or inactions, climate change, and food handling processes can all impact food safety (FAO, 2022a). Proactive early warning and detection systems for rapid identification of problems and causes utilizing big data and AI will reduce food safety risks and strengthen policies that cater to resilience, self-sufficiency and sustainability. Improved information sharing across the international food network, and the use of innovations in science and technology, especially Big Data, to facilitate data-driven management of problems by a diverse range of stakeholders (Jin et al., 2020; Lee et al., 2014; Vasanthakumar et al., 2023) top the list of critical responses to these challenges.

The FoodSafeR Digital Hub can build awareness and engagement among stakeholders in the agrifood system. Within this Hub, trusted sources of information, guidelines and advice regarding emerging hazards can be collated, integrated with FoodSafeR project outputs, and collective efforts to address emerging food safety risks identified. Organized approaches to identify, assess and manage food safety hazards and risks, including frameworks, tools, methods, strategies, models, and guidance and training materials, will reinforce resilience in the agrifood system. These FoodSafeR materials can be readily distributed to stakeholders to address emerging and identified food hazards. Meeting participants were confident that current and emerging microbiological and chemical food safety hazards could be addressed transparently through coordinated actions of the public and private sectors as modeled in the FoodSafeR project.

## Author contributions

JFL: Methodology, conceptualization, Writing – original draft, Formal analysis, Writing – review & editing. CNE: Writing – review & editing. MW: Writing – review & editing. CE: Conceptualization, Writing – review & editing. OM: Writing – review & editing, Visualization. MU: Writing – review & editing. WY: Writing – review & editing. SoW: Writing – review & editing. SO: Writing – review & editing. JL: Writing – review & editing. DR: Writing – review & editing. SC: Writing – review & editing. KZ: Writing – review & editing. VL: Writing – review & editing, Conceptualization, Investigation. FW: Writing – review & editing. RB: Writing – review & editing. ED: Writing – review & editing. StW: Writing – review & editing. SG: Writing – review & editing. MS: Writing – review & editing, Conceptualization. RK: Funding acquisition, Formal analysis, Writing – review & editing, Project administration, Writing – original draft, Methodology, Conceptualization, Investigation.

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OM was employed by IRIS Technology Solutions Ltd.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

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