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COMPREHENSIVE REVIEW

Megatrends and emerging issues: Impacts on food safety

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Abstract

The world is changing at a pace, driven by global megatrends and their interactions. Megatrends, including climate change, the drive for sustainability, an aging population, urbanization, and geopolitical tensions, are producing an increasingly challenging environment for the provision of a safe and secure food supply. To ensure a robust, safe, and secure food supply for all, potential food safety impacts associated with these megatrends need to be understood, and mitigation and management plans must be implemented. This paper outlines the relevant megatrends, discusses their potential impact on food safety, and suggests steps to help ensure the production of safe food in the future. Megatrends are increasingly driving resource depletion, reducing the vitality of plants and animals, increasing the geographical spread of animal and plant pathogens, increasing the risk of mycotoxins, agrichemical residues, and antimicrobial-resistant pathogens contaminating foods, and threatening to destabilize food systems and the food regulatory network. Science-based actions, adopting continual and dynamic risk assessments, alongside the use of more sensitive and accurate methods for the detection of contaminants, may counter these challenges. The use of artificial intelligence, robotics and automation, the enhancement of food safety cultures, the continued education and training of workforces, and the implementation of risk-based food regulations will help ensure preventative controls are in place. As low-income countries and smallholder farmers are more likely to be exposed to the impact of these megatrends and less likely to have resources to counter them, geographical social inequality, unrest, and population migration are likely to be exacerbated unless urgent action is taken.

KEYWORDS
food regulation, food safety, food safety communication, food safety culture, food security, global megatrends

1 | INTRODUCTION

The world around us is changing rapidly, and among the myriad of challenges this presents is the challenge of ensuring that all people have access to a safe and secure food supply. In 2017, King et al. published an article highlighting global trends and their impact on food safety and security (King et al., 2017). Since then, the world has experienced a global pandemic, more frequent heatwaves and climate-driven environmental events, and increasing political tensions, all of which have highlighted vulnerabilities in the food supply chain. Rapid advances in digital platforms, artificial intelligence (AI), low-cost high-throughput gene sequencing, nanotechnology, and synthetic biology are changing how food is produced, assessed, and delivered to consumers. There have also been dramatic shifts in expectations from governments and consumers on diverse issues, such as pesticide residue limits in foods, the use of plastics, and the importance of environmental sustainability. Megatrends describe global dynamics that are likely to impact countries and their populations. Many approaches have been used to identify megatrends, with different entities identifying slightly different megatrends (Naughtin et al., 2024). Nevertheless, while the naming and grouping of issues differ, many of the identified megatrends overlap (Naughtin et al., 2022; Noonan et al., 2024; United Nations Economist Network, 2020).

Although not identified as a megatrend, food security is a growing global concern. Food security exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food to meet the dietary needs required for a productive and healthy life (Security, 2009). With the world's population anticipated to exceed 9 billion people by 2050, there is a growing realization that food systems will have to radically transform to meet the challenge of producing sufficient, nutritious food (Godfray et al., 2010). Food safety is a critical component of food security as it ensures that food is free from pathogens or toxins that may cause either acute or chronic illnesses in consumers. In fact, international organizations such as the Food and Agriculture Organization (FAO) have stated that if it is not safe, it is not food (FAO, 2019).

While food is safer now than it has ever been in the past, in the face of a rapidly changing world driven by new and evolving megatrends, it is crucial to stay vigilant for potential or emerging food safety issues. To ensure a robust, safe, and secure food supply for all, potential food safety impacts and hazards associated with these changes need to be understood. Some megatrends may increase the risk of pathogens or toxins entering the food supply chain either by increasing the potential for food to become contaminated or by limiting or reducing the options available to eliminate or manage a hazard. Conversely, some trends and evolving research may present opportunities to help manage or mitigate current, new, or emerging risks. It is also important to appreciate that new food safety challenges and existing issues are evolving as the food industry responds to minimize the risks and address the impacts of different megatrends. An obvious example of this is the change in dietary patterns seen in some parts of the world as consumers increase their consumption of plant-sourced foods and add plant-based substitutes for animal-sourced foods to reduce their risk of chronic diseases and lower the carbon footprint of the food supply. Further, to improve environmental sustainability, novel foods such as cell-based meats, insect-based products, and upcycled foods are increasingly being promoted, and like all new foods, it is important to understand the risks that may be associated with them and how they may be reduced to an acceptable level. The frequency of food fraud is also escalating with the increase in online shopping, more frequent food supply chain disruptions, and the shifting focus of governments toward what they perceive to be more pressing economic and geopolitical issues.

A better understanding of the drivers for change and their potential impacts will enable scientists, governments, and the food industry to work on implementing mitigation and management plans and take actions to limit or prevent the negative consequences of change or to realize the positive opportunities they represent. This paper presents an overview of the current global megatrends impacting our food systems and discusses the associated food safety challenges and potential mitigation strategies. With this information, individuals, organizations, and governments will be better informed and better placed to act to ensure a safe food supply in the future.

2 | METHODOLOGY

The global trends presented in this review were determined by identifying the repeating trends discussed in the most recent reports from the United Nations Economist Network (United Nations Economist Network, 2020), the European Strategy and Policy Analysis System (ESPAS) (Noonan et al., 2024), and Australia's National Science Agency (CSIRO) (Naughtin et al., 2022). These megatrends are presented in Table 1.

The final selection of global megatrends, the associated food safety risks, and the mitigation strategies explored in this literature review was guided by the authors' extensive knowledge and experience, as well as the perceived impact of the different megatrends on food safety. In addition,

TABLE 1 Global megatrends identified by different international organizations.

	UN Economist Network (2020)	ESPAS (2024)	CSIRO (2022)
Climate change	×	×	×
Demography (aging population, population size)	×	×	×
Urbanization	×	×	
Digital technologies (AI, hyperconnected population)	×	×	×
Addressing inequalities	×	×	×
Geopolitical shifts		×	×
Economic challenges		×	×
Managing health		×	×
Drive for environmental sustainability (biodiversity, resource efficiency, alternative energy sources)		×	×
Threats to democracy		×	

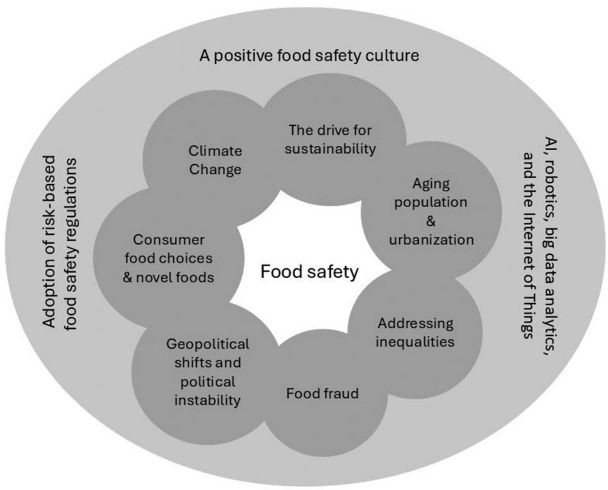

FIGURE 1 The global megatrends impacting food safety (inner ring) and strategies that may help to mitigate these challenges (outer ring).

the increasing importance of developing a positive food safety culture (FSC), the use of AI, robotics and automation, and a move to risk-based food safety regulations were presented as overarching mitigation strategies for the risks highlighted (Figure 1).

To determine the impact of the global trends on food safety, a literature search was carried out using the terms safety, food, and "food safety" in conjunction with relevant terms for each global trend. For example, terms used for population demographics included population, demographics, elderly, and "older adults," and for the trend, geopolitical shifts, and political instability, terms included geopolitical, politics, instability, trade, conflict, "foreign policy," and war. Research articles were included if they were published between 2017 and October 2024. In addition to published research, gray literature from recognized agencies such as the Food and Drug Association (FDA), the World Health Organization (WHO), and the United Nations was included. Articles discussing food security were largely excluded from this review.

3 | MEGATRENDS, ASSOCIATED FOOD SAFETY RISKS, AND MITIGATING FACTORS

In this section, we provide an overview of six global megatrends and four smaller trends that are increasingly impacting the safety of global food systems. The megatrends discussed are climate change; an aging population and urbanization; AI, robotics, big data analytics, and the Internet of Things (IoT); geopolitical shifts and political instability; addressing inequalities; and the drive for sustainability. The smaller trends discussed are increasingly diversified consumer food choices and the increase in novel foods; increasing food fraud; the increasing importance of developing a positive FSC; and a move toward the adoption of risk-based food safety regulations. Tables summarizing the key food safety risk factors and mitigation strategies are presented at the end of each relevant section.

3.1 | Climate change

Of all the global megatrends, climate change poses one of the most significant threats to the health of the planet and its human population. The impacts of climate change on the food system and food security have been well documented; however, there is less information on its implications for food safety (Mirón et al., 2023). Climate change and an associated drive for sustainability and protection of the environment are also influencing food choice and food production methods as evidenced by the increasing interest in foods and ingredients derived from insects, precision fermentation, plants, or cells via cellular agriculture, all of which are perceived to have a lower environmental impact than diets containing a high content of meat and dairy produced using traditional methods (Willett et al., 2019). The risk factors and mitigation strategies associated with these dietary changes are presented later in this review.

3.1.1 | Food safety risks

Climate change has been linked with an increased occurrence, persistence, virulence, and potential toxicity of disease-causing microorganisms. Warmer air temperatures and drier weather patterns will enhance the survival of pathogens, broaden their habitable regions along with those of pathogen-carrying vectors, such as flies and ticks, and increase the frequency of their distribution via vectors such as wind-borne dust (Duchenne-Moutien & Neetoo, 2021). Climate change will also contribute to the spread of disease by driving the migration of wildlife and humans. Increased ambient temperatures have already been associated with higher rates of salmonellosis and campylobacteriosis in Europe, Canada, and the United States (Misiou & Koutsoumanis, 2022). Extreme weather events, including heavy rainfall, flooding, and droughts, can lead to an increased risk of microbial, chemical, and fecal contamination of crops, land, and waterways (Duchenne-Moutien & Neetoo, 2021). Adverse weather events have also been associated with an increased proliferation of foodborne pathogens in soil and waterways, as well as their increased wind-borne spread. The presence of *Salmonella* spp. and *Escherichia coli* O157:H7 on fresh produce, including alfalfa sprouts, lettuces, tomatoes, broccoli, celery, squash, and green onions (Duchenne-Moutien & Neetoo, 2021), has been reported to have been caused by contact with contaminated water, and an outbreak of listeriosis in Australia associated with rock-melons (cantaloupe) is believed to have been due to pathogen transfer via a dust storm (WHO, 2018). Increased seawater temperatures have been linked with the geographical spread and increased frequency of harmful algal blooms, as well as the spread and increased incidence of foodborne illness caused by ingesting raw seafood contaminated with *Vibrio vulnificus* or *Vibrio parahaemolyticus* (Misiou & Koutsoumanis, 2022).

An overall shift in the geographical range, frequency of events, severity of impact, and types of fungi and pest infestations on plants is expected owing to temperature changes and extreme weather events, which reduce plant vitality by decreasing soil quality through erosion, nutrient leaching, and a reduction in their microbial populations (Gomez-Zavaglia et al., 2020; Misiou & Koutsoumanis, 2022). Related to this is an expected increase in the exposure of humans and animals to mycotoxins either directly through the ingestion of contaminated crops or foods or from the consumption of meat or milk from animals exposed to aflatoxin-contaminated feed (Godde et al., 2021; Van der Fels-Klerx et al., 2019).

To counter the challenges highlighted above, an increased use of pesticides is probable. However, the effectiveness of pesticides is likely to be decreased due to increased precipitation levels and warmer temperatures, further driving their use and exacerbating the risk of pesticide residues getting into waterways and foods (Delcour et al., 2015). Hence, robust agricultural practices around the use of agrichemicals will need to be implemented to reduce the risk of increasing residue levels in foods and the development of pesticide resistance in plants, which may pose a human health risk (Sivaperumal et al., 2022) as well as a threat to the health of beneficial insects.

While microbial resistance to pesticides and antibiotics is a pressing global concern, it is of greatest concern in lower- to middle-income countries where regulations around the use of agrichemicals and antimicrobials are often limited. Antimicrobials are used extensively in livestock production, aquaculture, and the agriculture sector to protect against pathogenic microorganisms. As climate change drives higher levels of disease, it is anticipated that increased antimicrobial use will lead to an increase in both antimicrobial residues in foods and the number of antimicrobial-resistant pathogens (MacFadden et al., 2018), and this trend is considered unlikely to be countered by increasing consumer demand for organic foods. Consumption of foods contaminated with antimicrobial-resistant pathogens poses a serious food safety risk. Soil and waterways can be reservoirs for antimicrobial residues and antimicrobial-resistant pathogens (Kaiser et al., 2022), and adverse weather events will increase their dissemination to food. To address these issues, robust global regulations and education about optimal agricultural practices around the use of agrichemicals and antimicrobials are warranted.

In many regions around the world, soils, due to either their natural geology or industrial impacts, contain heavy metals, particularly arsenic, cadmium, lead, and mercury, which in 2015 were estimated to cause over 1 million illnesses and 9 million disability-adjusted life years (Gibb et al., 2019). Rising temperatures have been associated with the increased occurrence of heavy metals in the food chain owing to an increase in their absorption rate by plants, as reported for arsenic in rice plants (FAO, 2020a). As rainfall events become more frequent, heavy metals such as lead, cadmium, and methylmercury (MeHg) will increasingly enter rivers and oceans (Wijngaard et al., 2017), and hence, their accumulation in marine animals will continue at an ever-increasing rate (Schartup et al., 2019).

While the considerations presented above strongly suggest that climate change will lead to an increase in foodborne illnesses, in the EU, cases of campylobacteriosis and salmonellosis were stable between 2016 and 2020 (Mirón et al., 2023), which, in part, was attributed to the effectiveness of food safety measures established by the food industry and public health authorities. However, in the absence of the funds or technological support to implement such controls, there is concern that the cases of foodborne illness will undoubtedly increase, especially in low- to middle-income countries, further exacerbating global inequalities in health outcomes.

3.1.2 | Mitigation strategies

Food safety risks can arise at any stage of the food supply chain, and climate change will impact each stage differently. Farm-to-fork risk assessment models may help identify and manage climate-impacted food safety risks for different food groups (Chhaya et al., 2022). For example, Van der Fels-Klerx et al. (2019) combined the individual models and datasets available for maize and milk production to create a modeling framework that enabled the potential impact of climate change on aflatoxin formation at each stage of maize production and the consequential contamination of dairy products consumed in Europe to be estimated. In addition, AI and big data analytics are increasingly being used to predict food safety risks associated with various climate scenarios and extreme weather events (Karanth et al., 2023). These applications and the effectiveness of these approaches will rapidly improve over time. Food safety risk assessment tools, including lifecycle assessments, will facilitate the implementation of environmentally sustainable mitigation steps to address food safety risks (Feliciano et al., 2022), including the early prediction of potential weather events, and the development of strategies to share information on climate-related food risks and their control at national and international levels (Lake & Barker, 2018). It is, however, essential to acknowledge that due to economic, technological, political, and cultural factors, the ability of individuals, companies, and countries around the globe to implement control measures varies widely. To date, discussions on—and, in some cases, trials of—approaches to mitigate emerging food safety risks have mainly focused on approaches that are more suited to wealthier economies. It is, however, vital to recognize that many options will not be technologically feasible or economically viable for all countries, especially low- and middle-income countries, countries where there is a predominance of smallholder farmers, and countries where wild food collection sustains populations or has cultural significance for Indigenous peoples.

Examples of mitigation strategies for climate change include alterations to the way livestock or crops are bred, reared, cultivated, or genetically modified to support, promote, or develop drought- and temperature-tolerant or disease-resistant cultivars and species (Gomez-Zavaglia et al., 2020). Innovative gene-editing technologies have the potential to create plant species with enhanced disease resistance, which may improve production rates, help control the spread of invasive species, and reduce the use of pesticides (Brookes & Smyth, 2024). Indoor crop production under more human-controlled conditions, often referred to as Controlled Environment Agriculture (CEA), has experienced significant growth worldwide. In the United States alone, CEA operations—which include greenhouses, vertical agriculture, hydroponics, aquaponics, and other controlled production methods—increased by more than 100% from 1476 operations in 2009 to 2994 in 2019. Installing suitable sun protection and ventilation options can minimize climate-induced physical stress for plants and animals. Establishing computerized, AI-driven water management systems can improve the efficiency of irrigation systems that optimize plant hydration. Soil analysis systems can assess soil quality and support optimal enrichment. Collectively, these strategies may reduce animal and plant stress, which can enhance disease resistance in the primary stages of the food supply chain, thus helping to reduce the number of foodborne pathogens, the incidence of foodborne disease, and the use of antimicrobials and pesticides. However, barriers to the widespread adoption of these climate change adaptations are numerous (Maldonado-Méndez et al., 2022), including a lack of money, technology, infrastructure, and regulatory oversight, as well as a limited awareness by some farmers of the issues and the importance of responding to them. For example, rising global temperatures will put increasing pressure on the cold chain, potentially leading to an increased risk of foodborne pathogen growth. The dairy industry in low- and middle-income countries is one sector that is at notable risk if the cold chain is compromised, as raw milk and pathogen numbers are more likely to exceed acceptable levels as the temperature of the raw, unpasteurized milk increases (Feliciano et al., 2020). Consequently, urgent action is needed to understand the potential risks associated with climate change-related disruptions to the cold chain, to educate farmers and authorities, and to develop appropriate and affordable mitigation strategies.

A good example of what research and education/training can achieve is seen in the work carried

TABLE 2 Food safety risks and mitigation strategies associated with climate change.

Climate change
Food safety risks: - Increased proliferation of foodborne pathogens in soil and waterways. - Enhanced survival and expansion of the habitable regions of pathogens and pathogen-carrying vectors. - Increased distribution of pathogens via vectors such as wind-borne dust and migration of wildlife and humans. - Decreased plant resistance to pathogens by decreasing soil quality through erosion, nutrient leaching, and a reduction in their microbial populations. - Increased risk of microbial, chemical, and fecal contamination of crops, land, and waterways through adverse weather events. - Increased exposure to mycotoxins by consuming contaminated crops, meat, or milk products. - Increased use of pesticides while the effectiveness of pesticides decreases and an increased risk of pesticide resistance in plants and pesticide residue in food. - Increased use of antimicrobials, leading to an increase in antimicrobial residues in foods and the number of antimicrobial-resistant pathogens. - Increased presence of heavy metals in plant-based food and seafood.
Mitigation strategies: - Robust regulations and increasing efforts to provide education and training on best agricultural practices in the use of agrichemicals and antimicrobials. - Farm-to-fork risk assessment models to help identify and manage climate-impacted food safety risks for different food groups. - Use of AI and big data analytics to predict climate-related food safety risks. - Changes to breeding, rearing, cultivating, or the genetic modification of livestock and crops. - Science-based guidance documents, policies, regulations, and monitoring of agricultural and/or food production processes to support food safety for new or emerging consumer dietary trends. - Installation of sun protection, ventilation options, and AI-driven irrigation systems to reduce climate-induced stress for plants and animals and enhance disease resistance. - The development of appropriate and affordable mitigation strategies to address potential cold chain disruptions.

out by Bradford et al. (2018), who assessed the food safety risk posed by the formation of mycotoxins in inadequately dried goods in low- and middle-income countries and subsequently introduced the concept of the "dry chain." This approach focused on achieving and maintaining the optimal dryness of dried foods throughout the food supply chain and stressed the importance of the initial postharvest drying process and low-moisture storage (Bradford et al., 2018).

A summary of the food safety risks and mitigation strategies associated with climate change is presented in Table 2.

3.2 | An aging population and urbanization

Global demographics are changing as the population increases and ages. By 2050, it is anticipated that the population will reach 9.7 billion people (United Nations, n.d.), with one in six people aged 60 years or over by 2030 (WHO, 2022). Historically, an aging population has been associated with higher-income nations. However, this trend is changing, with an anticipated two thirds of the global population over 60 years old expected to live in low- and middle-income countries by 2050. The global population is also becoming more urbanized due to natural population growth, rural–urban land conversion, and migration patterns, with the portion of people living in urban areas anticipated to increase from 53% to 70% between 2020 and 2050.

Globally, urbanization has been associated with improved public health through increased income levels and better living standards (Zhang et al., 2022). Conversely, consumers with a limited income may experience food insecurity if they become reliant on purchasing rather than producing food (Macalou et al., 2023). There is also concern that food production and supply may be compromised due to a loss of farmland to accommodate urban expansion (Macalou et al., 2023), although the magnitude of this impact is unclear (Wang et al., 2021).

3.2.1 | An aging population

Food safety risks

Older adults can experience various physical, physiological, and cognitive changes, which can lead to poorer health status (WHO, 2022). Consequently, older adults are more likely to be malnourished and have a weakened immune system, increasing their susceptibility to foodborne illnesses. In the United States, it has been projected that with an aging population, the incidence rate of listeriosis will increase from 2010 levels of 0.25 per 100,000 population to an incidence rate of 0.32 per 100,000 population in 2030 (Pohl et al., 2017).

Older adults' sense of smell, taste, and eyesight also diminish with age, potentially impacting their ability to judge whether a food is safe to consume (Kosa et al., 2019). Food insecurity may also be an issue for older adults who are often on a fixed weekly income, which may mean they are more likely to stockpile food or eat spoiled food or food past its "use by" date, which introduces a food safety risk. Critically, older adults frequently do not perceive themselves as being at higher risk of contracting a foodborne illness, and indeed some individuals believe they are less susceptible due to previous life experiences (Berger et al., 2023).

Mitigation strategies

Recent studies have identified the need for targeted food safety education, highlighting food safety risks and safe food handling practices for older adults and their caregivers (Berger et al., 2023; Evans & Redmond, 2019). The food industry has started to recognize the needs of older adults by producing modified-texture, flavorsome foods rich in macro- and micronutrients. It is of interest to speculate whether regulators in the future may be tempted to treat food designed for older adults in the same way they regulate foods for infants, who are also recognized as being a vulnerable population with specific nutritional needs. However, targeted food formulation and regulations can increase food costs substantially, such as is the case for infant formula manufacturers. Hence, it is critical to ensure that any changes developed to enhance the safety of foods designed for older adults do not make these foods unaffordable for those on a limited budget.

3.2.2 | Urbanization

Food safety risks

The impact of urbanization on food safety is less direct than on food security, and to date, its effect on the rates of foodborne illness is unclear. It would, however, seem logical to assume that the impact of urbanization on food safety rates will differ globally due to cultural and economic reasons. For example, it is known that in low- and middle-income countries, wet markets and street vendors provide access to fresh food, including meat, seafood, fruit, and vegetables for an increasingly urbanized population. Unfortunately, wet markets, especially those with live bird stalls (Soon & Abdul Wahab, 2021), are also associated with providing foods that may not have the same level of food safety assurance as food from larger food producers and retailers, due to the presence of live animals and their subsequent slaughter in open-air environments, the holding of meat with little or no temperature control, limited access to handwashing and cleaning facilities, and limited regulatory oversight, including on how the food was grown or produced.

Another impact of urbanization is the greater tendency of urban residents, compared to rural residents, to eat away from home at restaurants or street vendors or to have food delivered (Gargiulo et al., 2022). In many low- and middle-income countries, the street food industry provides a critical source of income for the vendors; however, food and beverages prepared and sold in these environments can pose a serious health risk. Microbial contamination may occur due to inadequate sanitation and handwashing, the handling of higher-risk foods, or the use of contaminated water for food or beverage preparation and cleaning (Mulyodarsono & Kristopo, 2024).

Demand for home food delivery services, including meal kits and "dark or ghost kitchens," expanded rapidly during the COVID-19 pandemic, but research on the food safety implications of these services is limited (Hakim et al., 2022; Maneerat et al., 2024). There are, however, numerous potential food safety risks associated with home-delivered meal kit delivery services, which is not surprising given the nature of the industry, the lack of targeted regulations, and the potential for inadequate temperature control of perishable high-protein foods (Maneerat et al., 2024). For example, a 2017 study of US-based online food vendors offering direct delivery of raw meat, poultry, game, and seafood products to consumers reported that nearly half of the food items arrived with a surface temperature above the recommended maximum of 4.44°C (40°F).

Urban agriculture has been proposed to be a way to help offset the productive land lost due to urbanization. Such food production systems range from low-budget home, community, and roof-top garden plots to capital-intensive vertical agriculture, aquaponic systems, or insect farms. In some situations, the reduced transport required for urban-grown produce may lead to less food spoilage and potentially safer foods. Indoor agriculture is also considered to have a lower risk of the produce being contaminated with pathogens as the produce is not exposed to wildlife, variable climate-related weather patterns, or airborne contaminants (FAO, 2022). Nevertheless, vertical farming grows predominantly leafy greens and herbs in a compact, warm, and humid environment that is conducive to the growth of many pathogens, if appropriate control measures are not followed (Tan et al., 2024). For example, microbial contamination can occur if inadequately treated irrigation water is used.

Soilless and vertical agriculture, in particular, have been recognized for their water-preserving efficiency, in part through the reuse of wastewater (Stanghellini & Katzin, 2024). However, reused wastewater in urban agriculture is a key risk factor for foodborne pathogens, with numerous foodborne disease outbreaks linked to the irrigation of fresh produce with inadequately treated wastewater (Adegoke et al., 2018). In addition to foodborne pathogens, reused wastewater can contain nutrients, antibiotic residues, and antibiotic-resistant genes, which can negatively impact human health if they enter the food supply chain. In this regard, it is concerning that many vertical farm growers have been reported to have a negative perception of microbial water testing due to its perceived cost, a lack of understanding of the need for testing, and a concern that false positives will affect their reputation (Hamilton et al., 2023).

It has also been reported that if soil used in vertical farming is sourced from urban areas, it can be contaminated by heavy metals, pesticides, and persistent organic pollutants (Tan et al., 2024). Of course, plants grown in vertical farms can still be affected by pests; hence, monitoring is required, and potentially, pesticides may need to be used, which can lead to pesticide residue on the crops. The infrastructure in vertical farms can also be a potential food safety risk, with mercury vapor released from urethane-based lighting materials reported to have been found on plants (Tan et al., 2024) and concerns that if repurposed older buildings are used for vertical farming, crops may be exposed to building materials, including asbestos and microplastics (FAO, 2022).

The food safety risks associated with "open" urban agriculture systems also include the presence of foodborne pathogens and toxin contamination from heavy metals, pesticides, and nitrates (Buscaroli et al., 2021) associated with historical land use (FAO, 2022). Heavy metal concentrations in plants grown in urban settings have also been correlated with air pollution levels and the distance of the plants from heavy-use roads (Antisari et al., 2015).

Mitigation strategies

Different strategies have been proposed to counter food safety risks associated with urbanization. In 2021, the WHO released interim guidelines to reduce food safety risks in traditional wet markets, including the risk of zoonotic diseases (WHO, 2021). Banning the slaughter of live birds, improving access to sanitation and handwashing facilities, monitoring food safety practices, and promoting food safety messages for vendors and customers were among the key recommendations (Soon & Abdul Wahab, 2021; WHO, 2021) to decrease the food safety risks posed by such markets. Running food safety education programs has also been proposed to help reduce the risk of foodborne illnesses from street food as it has been reported that there are notable gaps between street vendors' food safety knowledge, self-reported practices, and observed practices (Nordhagen, 2022). Education programs that address the contextual and physical barriers to change and provide suitable food safety equipment have been reported to result in better adoption of food safety practices than food safety education alone (Madjdian et al., 2024). Similarly, the adoption of good food safety practices in the preparation and delivery of home-delivered meal kits and for meals prepared in "invisible" kitchens is key to protecting customer health, but whether such services currently comply with food safety regulations or whether more specific regulations or efforts are required to enforce them is unclear (Hakim et al., 2022; Maneerat et al., 2024).

Appropriate treatment of wastewater is critical to ensuring food safety, with access to adequate and affordable treatment, storage, and distribution technologies and infrastructure being a barrier to the safe reuse of water, especially in low- and middle-income countries (Faour-Klingbeil et al., 2023). Even in higher-income countries, the perceived high costs of water reuse systems can be a barrier to their adoption (Mesa-Pérez & Berbel, 2020). The WHO has developed a risk assessment framework and guidelines for the safe use of reclaimed wastewater, but government support will likely be required to facilitate the adoption of these practices by growers (FAO & WHO, 2021). Well-run urban agricultural systems also offer opportunities for safer food, but their widespread adoption and the amount of food they can contribute to the global food supply are likely to be limited due to a lack of access to suitable land for urban gardens and the high capital investment, running costs, and energy demands of the more intensive operations (Hardman et al., 2022).

A summary of the food safety risks and mitigation strategies associated with an aging population and urbanization is presented in Table 3.

3.3 | AI, robotics, big data analytics, and the IoT

AI, robotics, big data analytics, and the IoT are in many parts of the world becoming rapidly interwoven throughout food supply chains. AI technology enables computers and computerized robots to simulate human intelligence, and current applications include natural language processing, voice recognition, machine vision, and fast data analysis. "Big data" refers to the wide variety of diverse data that can be compiled and analyzed, and IoT is a framework that supports the accumulation and management of data from a growing network of physical devices, sensors, vehicles, and other objects connected to the Internet.

TABLE 3 Food safety risks and mitigation strategies associated with an aging population and urbanization.

An aging population and urbanization
Food safety risks: - Older adults are more susceptible to foodborne illnesses due to their weaker immune systems. - A reduced sense of smell, taste, and sight could potentially impact food safety assessment. - Increased risk of foodborne illness from wet markets and street food in lower-income countries. - Food safety risks from home delivery foods due to a lack of targeted food regulations and temperature abuse. - Potential for pathogen, heavy metal, or pesticide contamination in fresh produce grown in vertical agriculture. - Food contamination by pathogens, antibiotic residues, and antibiotic-resistant genes from inadequately treated wastewater. - Increased presence of pathogens, heavy metals, pesticides, and nitrates in “open” urban agriculture.
Mitigation factors: - Targeted food safety education for older adults and their caregivers. - Implementation of food safety regulations to meet the needs of older adults. - Global guidelines and government support to regulate food safety practices in places such as wet markets and around the use of reclaimed wastewater. - Food safety education programs for wet market and street food vendors that address contextual and physical barriers to change and provide suitable food safety equipment. - Targeted regulations and monitoring for home delivery services and “dark” kitchens.

3.3.1 | Role in improving food safety

When combined with AI, big data analytics can support production efficiencies, increase food safety predictive capabilities, help identify emerging and future food issues, and identify potential solutions to food safety challenges. For example, many aspects of agricultural production are being automated with AI and robotics, including planting, weeding, harvesting, sorting, and grading of fresh produce before processing and packaging (Botta et al., 2022). Drones and sensors gather real-time data to inform field-specific irrigation, nutrient application, and pest control. These forms of precision agriculture help optimize resource use, improve crop quality, increase productivity, and make food safer by identifying adverse events at an early stage. AI will also play an increasing role in predicting climate-driven changes in weather patterns and events and associated food safety risks, thereby creating the opportunity for growers to take preemptive actions to reduce risks to the safety of their crops. In addition, potential food safety risks can be identified by modeling microbial population dynamics and growth for different climate scenarios and weather events. Food safety risk assessments conducted using AI’s capacity to analyze vast amounts of real-time data quickly can ensure that timely food safety mitigation strategies are implemented (Karanth et al., 2023). For example, pilot studies by the FDA determined that AI screening of imported seafood shipments could increase their chances of detecting violative shipments by approximately 300%. Monitoring growing and storage conditions can also help determine when conditions favor the growth of mycotoxin-producing fungi and enable actions to be taken to ensure that contaminated products do not enter the human or animal food supply chain. Similarly, climate data sources and satellite imaging of phytoplankton density can predict the development of harmful algal blooms and provide information that enables regulatory authorities and seafood harvesters to take timely and appropriate actions (Davidson et al., 2021).

Biosensor technologies, computer vision systems, and wireless sensor networks enable AI surveillance of production systems and food supply chains and help identify food safety risks at critical control points (Mu et al., 2024). In the meat industry, computer vision systems are used to scan animal carcasses for pathological lesions or fecal contaminants, and AI technology is monitoring staff hygiene and sanitation practices. AI-driven analytical tools can also screen suppliers of raw materials to ensure best practice food safety standards are applied and can help minimize the risk of food fraud or misinformation (Qian et al., 2023). AI temperature control and monitoring systems can help ensure food temperatures stay within safety limits as food moves along the supply chain to the retail sector.

Distributed ledger technology (DLT), such as blockchain technology, provides a secure system for data collection from all participating food organizations as food moves from farm to fork (Singh et al., 2023). Although the adoption of DLT within the food supply chain is still limited, its widespread use will reduce the risk of food safety outbreaks by embedding food safety checks and contract requirements within the system (Singh et al., 2023). In a food safety outbreak, AI can rapidly analyze diverse data sources and help reduce the scale of an issue by quickly identifying the source of food contamination and facilitating the recall of all relevant food products. The ability of AI to scan unstructured text, restaurant reviews, reports, blogs, and social media platforms has been shown to identify a foodborne disease outbreak faster than conventional epidemiological approaches (Mu et al., 2024). Opportunities for rapid qualitative and quantitative data analysis offered by AI can also support and enhance an FSC, consider the impact of environmental factors, and improve business processes by reducing waste, increasing efficiency, and ensuring quality and performance.

However, AI systems and advanced food safety and data collection technologies are expensive and resource intensive. Skilled personnel are typically required to set up and maintain the systems, limiting adoption by street vendors and smaller-scale producers in rural areas and low- and middle-income countries (Karanth et al., 2023). Other obstacles to the wider adoption of these technologies include the limited availability of food safety data in a standardized, usable format, privacy concerns about sharing company data, the potential punitive use of data if shared (Qian et al., 2023), the generation of bias and reinforcement of stereotypes, and concerns among food handlers about being monitored.

3.3.2 | Role in decreasing food safety

As discussed above, recent advances in digital technology have largely been viewed as critical to ensuring a reliable and safe food supply. However, some experts have cautioned against an overreliance on AI and big data analytics for food safety prediction. The use of unreliable data or data from limited sources or a lack of scientific knowledge to correctly interpret the data means that AI has the potential to over- or underestimate risks and provide incorrect information. Hill et al. (2017) warned against using predictive food safety models to "predict" outbreaks or the potential burden of a foodborne illness due to the potential for numerous false positives to obscure a rarer true food safety risk (Hill et al., 2017). Rather, it is recommended that AI-driven models be used to identify potential scenarios associated with higher food safety risk. While some of these concerns will dissipate with the evolution of generative AI and increasing access to data, it is generally agreed that expert validation of AI-derived results will be required for the foreseeable future. Concern has been expressed that with the increasing digitalization of food safety monitoring and controls, the risk of cybersecurity attacks and forged digital documentation is increasing with an enormous potential to disrupt food systems and adversely impact food safety and security (Singh et al., 2023).

A summary of the role of AI, big data analytics, and the IoT in improving food safety and the associated food safety risks is presented in Table 4.

3.4 | Geopolitical shifts and political instability

Geopolitics refers to geographical influences on international relations and power dynamics. Given the globalized food supply chain, geopolitical shifts can significantly impact food safety and security. Political instability and conflict such as the current wars in Ukraine and the Middle East immediately impact food safety and security for local communities. If the countries involved are food-exporting nations, these concerns can radiate worldwide as export supply chains are disrupted and countries in conflict prioritize domestic food production. For example, Russia's invasion of Ukraine in 2022 impacted global energy, grain, and fertilizer supplies and increased food prices (Tollefson, 2022).

3.4.1 | Food safety risks

The destruction of infrastructure during times of conflict including the disruption of the power supply, storage facilities, and transportation can increase the potential for food spoilage and the growth of microbial contaminants (Lüthi & Ray, 2024). Fighting elevates the risk of contamination of water supplies, agricultural land, and food products. When primary production in regions experiencing conflict relies on imported fertilizers and pesticides, reduced amounts or inferior quality products may have to be used. Ineffective agrichemical use coupled with a reduced capacity for quality controls and food safety inspections may result in agricultural products, such as grains or dried and processed foods, having a higher risk of contamination from mycotoxins, pesticide residues, or environmental contaminants. In times of political instability or conflict, food safety systems may also not be as well maintained as during settled times, due to a lack of qualified food safety specialists and inspectors and governmental focus being directed elsewhere. In a worst-case scenario, food supply and food safety can be weaponized as a means of spreading food insecurity and foodborne illnesses.

Even in the absence of direct disruptions, governments may impose food sanctions to influence the outcomes of conflict. Putting tariffs on food products has the potential to disrupt established trade relationships and fragment the global food supply chain. When food supplies are disrupted, countries and companies need to negotiate new trade relationships and new supplier agreements. In doing so, food safety procedures and standards may become compromised to minimize supply chain disruptions. Even in the absence of overt conflict, some nations have been

TABLE 4 The role of artificial intelligence (AI), robotics, big data analytics, and the Internet of Things (IoT) in improving food safety and the associated food safety risks.

AI, robotics, big data analytics, and IoT
Role in improving food safety: - Precision agriculture will help make food safer by identifying adverse events at an early stage of production. - AI-generated predictions for climate-related weather events and changing weather patterns and their potential impact on food safety will allow growers to take preemptive actions to reduce risks. - AI-conducted food safety risk assessments using real-time data can ensure timely food safety mitigation strategies are implemented. - More advanced technology can help identify food safety risks at critical control points along the food supply chain. - Distributed ledger technology can provide a secure data collection system as food moves from farm to fork and reduce the risk of food safety outbreaks by embedding food safety checks and contract requirements within the system. - Rapid AI analysis of data sources can reduce the impact of a food safety outbreak by quickly identifying food contamination and facilitating a product recall.
Role in decreasing food safety: - AI may over- or underestimate food safety risks or provide incorrect information when using unreliable data or data from limited sources, or if there is a lack of scientific knowledge to correctly interpret the data. - Predictive food safety models may “predict” numerous false positives that obscure a rarer true food safety risk. - The risk of cybersecurity attacks and forged digital documentation may increase with the digitalization of food safety monitoring and controls.

operating with an increasingly nationalistic, protectionist focus, which has the potential to adversely impact regulatory communication channels and food safety (Bednarski et al., 2025). Similarly, a lack of appetite for equivalence or harmonization of standards creates barriers and adds complexity, which increases the risk of food safety-related events. Countries may be less inclined to share information or take action against new or emerging food safety risks. The sharing of new research and technological advances that support safe food production, especially in the context of climate change, may also be compromised by a lack of global collaboration.

Access to adequate food is a basic human right, and countries are obligated to protect this right for their people (OHCHR & FAO, 2010). Given the global nature of the food supply chain, international collaboration, trust, and information sharing are essential for maintaining a resilient food supply (Duong & Chong, 2020) and are critical to ensuring food safety. Without trust between countries and organizations, there may be less equitable access to the knowledge and resources to help address food safety risks. Further, the production of high-end technological tools and innovations relies on a relatively small pool of nations and organizations that supply the raw materials, provide the manufacturing processes, and support the distribution of these products.

3.4.2 | Mitigation strategies

Trust is a vital component in the sharing of knowledge and resources to help address food safety risks. It is therefore imperative that governments, researchers, and the food industry work to safeguard food safety systems and surveillance by continuing to maintain constructive working relationships and partnerships with international counterparts. It is also imperative that entities continue to build trust in one another and proactively collaborate on shared concerns. By working together to promote food safety and sharing knowledge and know-how, progress can be made to ensure a safe food supply for all.

A summary of the food safety risks and mitigation strategies associated with geopolitical shifts and political instability is presented in Table 5.

3.5 | Addressing inequalities

Inequalities between populations can be broad-reaching and interlinked, including differences in income and education levels, living standards, health status, gender inequality, and climate justice (United Nations Economist Network, 2020). Reducing these inequalities can improve health and life expectancy, increase education levels, and ensure a better quality of life. Furthermore, reducing gender and education inequalities and ensuring climate justice led to better income equality.

3.5.1 | Food safety risks

Food insecurity can range from low food availability or unaffordability to an overabundance of food with low nutritional value or limited access to healthy foods. Regardless of its form, food insecurity is directly linked to income inequalities and poorer health outcomes.

TABLE 5 Food safety risks and mitigation strategies associated with geopolitical shifts and political instability.

Geopolitical shifts and political instability
Food safety risks: - Reduced food safety and security for countries in conflict and globally through disrupted food supply chains. - Food sanctions can impact food insecurity in areas of conflict. - Tariffs on food products have the potential to disrupt established trade relationships and fragment the global food supply chain, introducing inefficiencies and increasing reliance on less familiar or less regulated food sources. - Disruption of the power supply, storage facilities, and transportation can increase the potential for food spoilage and the growth of microbial pathogens. - Increased contamination of water supplies, agricultural land, and food products. - Reduced use of fertilizers and agrichemicals may impact plant and animal health and increase their susceptibility to disease. - Reduced capacity to maintain food safety systems and conduct food safety inspections for products such as grains or dried and processed foods may lead to a higher risk of contamination from mycotoxins, pesticide residues, or environmental contaminants. - Supply chain disruptions and food safety could be weaponized during times of conflict. - When negotiating new trade relationships and supplier agreements, food safety procedures and standards may be compromised to minimize supply chain disruptions. - International communication channels about food safety practices and risks can be affected when nations take a nationalistic, protectionist approach to food policy. - A lack of equivalence or harmonization of food safety standards creates barriers and adds complexity to the supply chain, which increases the risk of food safety-related events. - Countries becoming increasingly unwilling to share information and take actions to minimize food safety risks.
Mitigation strategies: - Safeguarding food safety systems and surveillance. - Maintaining constructive international relationships and partnerships. - Supporting ongoing collaboration and trust-building between countries. - Sharing information and resources to reduce food safety risks.

Lower-income regions, such as sub-Saharan Africa and Southeast Asia, experience the highest levels of food insecurity and malnutrition globally. A reduced food intake, poor nutrient absorption, and poor food choices due to concerns about the safety of fresh produce can lead to malnutrition, which can increase an individual's susceptibility to foodborne illnesses (Nordhagen et al., 2022). Access to safe food is also linked to income levels, meaning that lower-income families and regions have a higher risk of foodborne illnesses (HLPE, 2023). This is due, in part, to lower- to medium-income countries having limited funding to establish and maintain robust food safety systems and effective surveillance and mitigation programs. Hence, foods presenting a higher food safety risk are less likely to be identified, foodborne outbreaks are less likely to be identified, and food fraud may occur more frequently. Further, there may be insufficient resources to maintain a cold chain from farm to fork, including continuous electricity and adequate refrigeration units, which increases the risk for the growth of pathogenic or spoilage microorganisms.

3.5.2 | Mitigation strategies

Strategies to mitigate food safety risks typically require financial investment, especially if they require the adoption of some of the advanced technologies suggested to address climate-related food safety risks. Therefore, supporting a nation's economic development is a key factor in improving food safety (Lin et al., 2010). International collaborations, including the sharing of new research and technical innovations for safe food production, transport, and storage options, can help address food safety inequities between higher- and lower-income countries. It is, however, critical that collaborators appreciate that each community is likely to face different food safety issues and barriers to change, including access to technology and funding; therefore, when collaborating with local communities, it is essential to work with the community to create solutions tailored to the local environment. Efforts should be focused on addressing the most important local food safety risks with cost-effective, locally driven, sustainable solutions.

A summary of the food safety risks and mitigation strategies associated with inequalities is presented in Table 6.

3.6 | The drive for sustainability

Global food security and environmental sustainability are interlinked. As the sustainability of our environment becomes compromised, the consistent production of nutritious, safe food is similarly compromised. Therefore,

TABLE 6 Food safety risks and mitigation strategies associated with inequalities.

Addressing inequalities
Food safety risks: - Food safety concerns about fresh produce can lead to malnutrition, which can increase an individual's susceptibility to foodborne illnesses. - Lower- to medium-income countries may not have the funding to establish and maintain robust food safety systems and effective surveillance and mitigation programs. - Food safety risks or outbreaks and food fraud are less likely to be identified. - Insufficient resources to maintain a cold chain from farm to fork increase the risk for the growth of pathogenic or spoilage microorganisms.
Mitigation strategies: - Supporting a nation's economic development. - International collaborations and the sharing of information, research, and technologies for safe food production, transport, and storage. - Collaboration with local communities to create solutions that fit the local environment. - Focus on addressing the most important local food safety risks with cost-effective, locally driven, sustainable solutions.

protecting the environment and the Earth's ecosystems is critical. Issues impacting the sustainability of the environment and consequently food safety risks include climate change (as discussed above), deteriorating water and soil quality with the build-up of heavy metals and plastic waste in the environment, increasing resource scarcity, and reduced biodiversity.

3.6.1 | Reduced resource availability and biodiversity preservation

Access to healthy soil and a clean and abundant water supply is fundamental for a productive and safe food supply. Yet, globally, the agricultural sector faces resource scarcity, reduced water quality and accessibility, and poorer quality soil. Overpopulation, industrialization, climate change, and pollution are driving water shortages, depleting fossil fuels and minerals, and reducing biodiversity. Historical and present-day industrialization and urbanization have also decreased the quality of our soils and waterways. Diverse global ecosystems, which include a wide variety of microorganisms, fungi, plants, and animals, help cleanse water, provide shelter, protect against the effects of climate change, and ensure food security (FAO, 2020b). A high level of biodiversity supports plant pollination, maintains soil health, and helps control pests and parasites. However, the intensification of our existing food production systems is compromising global biodiversity.

Food safety risks

The agriculture sector uses nearly 70% of global freshwater withdrawal, with groundwater supplying approximately 25% of all water used for irrigation (United Nations, 2024). Where there is insufficient water or the available water is of poor quality, food safety can be compromised. For example, an increase in preharvest drought stress in peanuts has been correlated with an increase in their aflatoxin concentration (Martins et al., 2023). Limited access to safe drinking water and inadequate sanitation practices in Asian countries and sub-Saharan Africa can expose individuals to the risk of bacterial diseases such as cholera (Girotto et al., 2024). In addition, contaminated water used in agriculture has resulted in numerous food safety outbreaks associated with fresh produce (Gurtler & Gibson, 2022).

Mineral fertilizers, such as phosphorus, nitrogen, and potassium, are essential for healthy plant growth. Access to these resources is becoming more restricted due to increases in their cost, driven by a limited supply and an increasing demand, especially in lower-income countries (Avşar, 2024). The biodiversity literature predominantly focuses on the impact on food security rather than specific food safety risks. Nevertheless, reasonable assumptions can be made about potential food safety risks. In a monocrop scenario, the diversity of microorganisms in the soil decreases, thus compromising soil health. A poor soil nutrient profile and reduced moisture levels also negatively affect the soil's microbial population and reduce the resistance of plants to pests, diseases, or fungi colonization, with the increased presence of fungi increasing the risk of mycotoxin production (Samaddar et al., 2021). Therefore, farmers are likely to become more reliant on the use of fertilizers and pesticides to maintain crop health. As previously mentioned, in these situations, crops are more likely to become contaminated with fertilizer or pesticide residues.

Mitigation strategies

New regulations are being implemented, and alternative production practices are being researched to address the issues of resource scarcity and contamination risks. For example, the United States and Europe have reacted to a perceived food safety threat from disinfection byproducts associated with the use of chlorine in water treatment and as a sanitizing agent for food processing environments by reducing the allowable levels of chlorate and perchlorate in foods (European Commission, 2020). However, care is needed to ensure that reduced chloride use does not increase the risk of uncontrolled microbial contamination.

A shift toward a circular economy (CE) offers an opportunity to address resource scarcity. Rather than following the predominant linear economic model of take–make–dispose, a resource or product's lifespan is extended by repairing, recycling, redesigning, or reusing the product, and production byproducts are no longer seen as waste but as a potential resource. The use of treated wastewater, recycling of packaging material, soil preservation, and food waste valorization are all examples of a CE applied to the food system. However, as alternative CE production models are explored, new food safety risks may arise, and known hazards may accumulate along the food supply chain. For example, ink or printing residues in recycled paper-based packaging may contaminate food with mineral oil saturated (MOSH) or aromatic hydrocarbons (MOAH).

Food production is resource intensive; therefore, food waste at any point along the food supply chain represents a significant loss of those resources. A 2021 report stated that globally, 40% of food produced each year goes uneaten (WWF-UK, 2021). By adopting the CE principles within the food supply, food waste can be reduced, and the use of resources consumed during food production can be optimized. Valorizing unmarketable but edible food and food byproducts provides a potential means of retaining food for human consumption; however, there is limited research exploring the associated food safety risks (Socas-Rodríguez et al., 2021).

Many food byproducts, such as fruit and vegetable pomace, have a high moisture content and support microbial growth. Furthermore, if these byproducts are dried, any bacterial or fungal spores, pesticides, heavy metals, and toxins in the food are concentrated. Routinely assessing the food safety risks associated with different byproducts and investigating potential strategies to manage these risks will help protect consumer health as the food system transforms into a more CE. A "safe-by-design" approach has been suggested whereby food safety risks at each stage of product development are considered, and targeted interventions can address emerging issues (Focker et al., 2022). Specific legislation regulating the suitability and safety of upcycled foods may also help facilitate effective food safety assessment of byproducts and potentially enable the industry to expand the range of byproducts suitable for valorization (Socas-Rodríguez et al., 2021).

3.6.2 | Plastic packaging

Single-use plastic is used extensively throughout the food supply to protect food from external elements that can cause spoilage or make it unsafe, and by extending its shelf life, it can help limit food waste and reduce the carbon footprint of the food supply chain (Matthews et al., 2021). Unfortunately, plastic packaging waste can contaminate oceans, waterways, and the soil, breaking down into micro- and nanoplastics and releasing chemicals that may be hazardous to microorganisms, plants, sea life, animals, and ultimately human health (Li et al., 2024).

Food safety risks

There is increasing concern that microplastics can act as vectors for heavy metals, microbial pathogens, viruses, and antimicrobial-resistant bacteria (Zhi et al., 2024). The main source of microplastics in the human diet is believed to be animals, particularly marine species that have ingested them or animals containing them, as microplastics and their concentration can be biomagnified up the food chain, as well as plants that have absorbed microplastics from the soil. Food and beverages can also become contaminated with microplastics from packaging, takeout containers, plastic coffee or tea bags, and disposable coffee cups (Li et al., 2024). Recent studies have shown the presence of microplastics in human stools, blood, and other tissues (Li et al., 2024). Although the human health impacts of microplastics are still uncertain, they have been detected in multiple systems in the body and may trigger inflammatory responses and oxidative stress, cause tissue alterations, and affect the immune system (Islam & Cheng, 2024). Microplastic exposure is also suspected to adversely impact human reproductive outcomes, as well as digestive and respiratory health (Chartres et al., 2024). The abundance of microplastics in human feces has been positively correlated with inflammatory bowel disease, while other studies suggest links with endocrine disruptions and neurological diseases (Zhi et al., 2024). Despite the evidence collected to date, suggesting the possible adverse impacts that microplastics could have on human health, there is still debate about the level of risk that micro- or nanoplastics found in foods pose to human health (Chartres et al., 2024).

Mitigation strategies

Sustainable approaches to help address microplastic pollution in the environment are being explored. Upstream solutions focus on preventing plastics from entering the environment, with some countries prohibiting the use of certain single-use plastics or the addition of microplastics to cosmetics and beauty care products (Islam & Cheng, 2024). The problem can also partially be addressed by designing wastewater treatment plants with more advanced filtration technologies that can more effectively remove microplastics. However, initial investment costs may make this option prohibitive for low- to medium-income countries. Incentivizing plastic recycling is also a logical preventative step, but currently, most countries do not have the necessary infrastructure to be a truly effective option (Wong et al., 2020). While some researchers are calling for a ban on all single-use plastic packaging, such as food packaging, the current reliance of the food industry on the use of plastic packaging suggests that such a ban is unlikely to be widely adopted in the short term. A sensible alternative approach may be for the packaging industry to focus on the development of innovative packaging technologies and plastic waste collection strategies to reduce the potential for microplastics contamination from food packaging.

The use of recycled food packaging also poses challenges, as it can contain higher levels of non-intentionally added substances (NIAS) compared to virgin packaging, which can potentially migrate into food and impact human health (Etxabide et al., 2022). The NIAS in recycled packaging include residues from the food or other substances the packaging contained before entering the recycling stream. Effective sorting and decontamination processes for used plastic packaging, dilution, the use of functional barriers, and only recycling plastic wastes generated from industrial processes for which its previous use is known are strategies being used to mitigate the food safety risks associated with recycled plastics (Nguyen et al., 2024). The development of packaging materials that contain antibacterial agents (sometimes within nanoparticles) designed to enhance product shelf life or inhibit pathogens has received much scientific interest; however, it seems likely that regulatory and consumer pressure regarding the health risks posed by these antimicrobials and environmental concerns on their recyclability will limit their widespread adoption.

A summary of the food safety risks and mitigation strategies associated with the drive for sustainability, including reduced resource availability, biodiversity preservation, and plastic packaging, is presented in Table 7.

3.7 | Increasingly diversified consumer food choices and the increase in novel foods

A shift toward a more plant-based diet containing predominantly grains, fruits, vegetables, legumes, and nuts has been promoted to reduce the risk of chronic diseases and lower the carbon footprint of the food supply. In addition, there has been a rapid increase in the availability of plant-based foods mimicking dairy, meat, or seafood products, insect-based foods and ingredients, and cell-based (cellular agriculture) meats, fish, and dairy products, which may offer alternative food production approaches with a lower environmental impact than traditionally produced meat and dairy products. Collectively, these dietary changes have the potential to introduce new hazards. Novel foods may come with new food safety issues, including pesticide contamination, concentrated levels of natural toxins or mycotoxins, novel pathogens, the re-emergence of "old pathogens," and new allergen profiles.

3.7.1 | Food safety risks

Agrichemicals are thoroughly evaluated for their safety before being approved; nevertheless, an increase in the consumption of plant-based foods is likely to increase the concentration of their residues in the diet. Of particular concern is the presence of a cocktail of pesticide residues. The toxicity of pesticides has traditionally been evaluated individually, and combined exposure may result in cumulative effects (Yang et al., 2024). For example, in 2023, the European Food Safety Authority (EFSA) reported that 44.3% of 87,863 food samples tested from the EU market contained more than one pesticide, 26.4% contained multiple pesticides, and a single raisin sample contained 39 different pesticides (Carrasco Cabrera et al., 2023). In line with these findings, the United States Pesticide Programme reported that 57.5% of the 10,127 samples contained more than one pesticide, and a peach and a winter squash sample each contained residues from 19 different pesticides (USDA, 2022). Although the levels for each of these 19 pesticides did not exceed established tolerance values, their combined effects are unknown. While concern about agrichemical residues in food is likely to fuel the growing demand for organically produced foods, it has yet to be conclusively demonstrated that they are safer than conventionally grown food produced in accordance with established food regulations.

Plant-based foods can also contain a wide range of natural toxins, such as antinutrients, glycoalkaloids, quinolizidine alkaloids, cyanogenic glycosides, or mycotoxins such as aflatoxins and deoxynivalenol (DON), depending on growth conditions, geographical location, plant variety, and processing or storage conditions (Rietjens & Eisenbrand, 2023). Furthermore, co-harvesting weeds can cause accidental contamination by naturally occurring plant toxins, such as genotoxic and carcinogenic allylalkoxybenzenes and 1,2-unsaturated pyrrolizidine alkaloids, being present in some teas or botanical food supplements at levels that raise a food safety concern (Rietjens & Eisenbrand, 2023). Switching plant varieties for economic or product shortages may result in food fraud or exposure to natural toxins, as has occurred in teas, where Chinese

TABLE 7 Food safety risks and mitigation strategies associated with the drive for sustainability.

Reduced resource availability and biodiversity preservation
Food safety risks: - Contaminated drinking water and water used for agriculture can lead to food safety outbreaks. - Reduced soil nutrient, moisture, and microbial content reduces plant's resistance to pests and diseases. - Decreased access to agrichemicals to maintain crop or animal health can make them more suspectable to diseases. - An increased reliance on the use of agrichemicals can increase the risk of residues getting into foods. - New food safety risks may arise from alternative circular economy (CE) production processes.
Mitigation strategies - Creating and implementing new or updating existing regulations to address food safety risks. - Adopting a CE model for wastewater, packaging material, soil preservation, and food waste. - Routinely scanning for emerging food safety risks and investigating solutions as the food system changes. - Following a "safe-by-design" approach to food safety.
Plastic packaging
Food safety risks: - Microplastics may act as vectors for heavy metals, microbial pathogens, viruses, and antimicrobial-resistant bacteria. - Humans are exposed to microplastics by eating animals and plants that have ingested or absorbed them and via plastic food and beverage packaging and containers. - Microplastics have been detected in multiple systems in the human body, may trigger inflammatory responses and oxidative stress, cause tissue alterations, and affect the immune system. - Recycled food packaging can contain higher levels of non-intentionally added substances that can potentially migrate into food and impact human health.
Mitigating factors: - The development of innovative packaging technologies and plastic waste collection strategies to reduce the potential for microplastic contamination from food packaging. - Designing wastewater treatment plants with more advanced filtration technologies. - Incentivizing plastic recycling. - Effective sorting and decontamination processes for used plastic packaging, and only recycling plastic wastes generated from industrial processes for which its previous use is known.

star anise (*Illicium verum*) was replaced by the Japanese variety (*Illicium anisatum*) containing the neurotoxin anisatin. Further, the accidental replacement of *Stephania tetrandra* with *Aristolochia fangchi* in herbal weight-loss preparations resulted in the unintentional exposure of young women to aristolochic acids, which are potent kidney toxins and carcinogens (Rietjens & Eisenbrand, 2023).

The mycotoxins mostly encountered in plant-based foods include aflatoxins, trichothecenes, zearalenone, fumonisins, ochratoxins, and patulin. Risk assessments by EFSA revealed that current levels of exposure to aflatoxin B1 and the trichothecene DON are a health concern for consumers (Schrenk, Bignami, et al., 2020). Aflatoxin B1, which causes liver tumors upon chronic exposure, is the most common and the most potent genotoxic and carcinogenic aflatoxin in foods. DON contaminates grains and cereal-based food and feed, causing vomiting and, upon long-term exposure, weight gain suppression, anorexia, and altered nutritional efficiency. Risk assessment of fumonisins, ochratoxins, and patulin is somewhat hampered by a lack of data. Nevertheless, for ochratoxin A, EFSA concluded that there might be a health concern depending on whether the genotoxicity underlying the kidney tumors would be the result of a direct instead of an indirect mode of action (Schrenk, Bodin, et al., 2020).

Cellular agriculture is also vulnerable to natural and man-made contaminants, although given that the technology is still in the early stages of development, and detailed production processes are often commercially sensitive, there are gaps in our knowledge of associated food safety hazards (Ong et al., 2021). Potential contaminants, including microorganisms, heavy metals, pesticide residues, and antimicrobials contained within the source animal cells, the growth medium, or supplements used in the production process, may introduce risks from added hormones, zoonotic pathogens, and carcinogens. The most significant food safety risk from insect production is determined by the quality of the feed used and if it is contaminated with mycotoxin or heavy metals (Traynor et al., 2024). Furthermore, both insect- and cell-based proteins have the potential to trigger allergenic immunoglobulin E (IgE) and non-IgE-mediated immune responses (Ong et al., 2021; Traynor et al., 2024).

TABLE 8 Food safety risks and mitigation strategies associated with consumer food choices and novel foods.

Increasingly diversified consumer food choices and novel foods
Food safety risks: - Risk of increasing concentrations of agrichemicals and natural toxins in plant-based diets and cellular agriculture. - Allergenic immunoglobulin E (IgE) and non-IgE-mediated immune responses can be triggered by insect- and cell-based proteins.
Mitigation strategies: - Clearly identifying risks and establishing effective controls associated with dietary changes and novel foods. - Good agricultural practices and science-based effective risk assessments, guidance documents, policies, and regulations are required to help manage any potential risks.

3.7.2 | Mitigation strategies

Collectively, modern plant-based and novel cell-based food chains have the potential to contain many natural and man-made toxins. To help manage any potential food safety concerns associated with new or emerging consumer dietary trends, it is imperative that the risks are clearly established, and effective controls are implemented. This will include the development of science-based guidance documents, policies, and regulations and the adherence to good agricultural and/or food production processes.

A summary of the food safety risks and mitigation strategies associated with increasingly diversified consumer food choices and novel foods is presented in Table 8.

3.8 | Food fraud

Food fraud is the economically driven act of altering, substituting, or misrepresenting food to deceive customers and organizations along the food supply chain. While a longstanding issue, the frequency of food fraud is escalating as online shopping increases and geopolitical tensions disrupt food supply chains (Fernando et al., 2024). Food fraud is a notable issue in sub-Saharan Africa, with most essential foods at high risk of being fraudulent (Chukwugozie et al., 2024). It may also occur in other regions where it remains an issue despite regulations and auditor requirements (Everstine et al., 2024).

3.8.1 | Food safety risks

Food fraud is of particular concern for dairy ingredients, seafood products, meat and poultry products, herbs, spices, seasonings, and milk and cream (Everstine et al., 2024). Food safety risks can arise from undisclosed additions to food products, such as melamine in infant milk powder products in China (Brooks et al., 2021) and formalin, an embalming chemical, reportedly added to protein-based foods in Ethiopia and Uganda (Chukwugozie et al., 2024). When the addition or substitution of ingredients is misrepresented or not declared on food labels, individuals with food allergens are also at risk. For example, undeclared soy may be added to meat products to increase protein content. Diversion-related fraud typically involves diseased or otherwise unfit meat for human consumption being sold, with shelf life, slaughter, and food safety records being falsified. In Nigeria, expired rice potentially contaminated with molds and microorganisms was repackaged and fraudulently sold (Chukwugozie et al., 2024). In higher-income countries, food safety concerns may originate from the substitution of olive, coconut, or mustard oil with cheaper, potentially toxic oils, such as Argemone oil from Mexican Poppy (Argemone Mexicana) or the artificial enhancement of spices with potentially carcinogenic Sudan dyes (Kumari et al., 2023).

3.8.2 | Mitigation strategies

A multitiered approach involving food regulations, surveillance processes, and enforcement systems, supported by interagency and international collaboration, is necessary to combat food fraud (Fernando et al., 2024). Centralized food fraud databases and assessment tools can help disseminate information about food fraud events, provide early warnings about potential threats, determine the risk factors and vulnerabilities of food supply chains, and highlight potential preventative actions. Various detection and analytical techniques, such as DNA sequencing and isotope fingerprinting, have been developed to assess the authenticity of foods. However, their use is largely confined to food laboratories and research facilities due to the need for expensive, potentially bulky equipment, trained staff, and data analytics tools. DLT, secure radio frequency identification tags, and QR codes can provide traceability of products as they move along the food supply chain. Although these technologies do not identify food fraud, they can ensure effective product recalls when issues are identified. The initial capital investment and technical expertise required to implement and maintain DLT mean that, to date, this technology has not been widely adopted

TABLE 9 Food safety risks and mitigation strategies associated with food fraud.

Food fraud
Food safety risks: - Undisclosed additions to food products. - Individuals with food allergies are at risk when the addition or substitution of ingredients is misrepresented or not declared on food labels. - Diseased or otherwise unfit food for human consumption may be sold with falsified food safety records.
Mitigation strategies: - Centralized food fraud databases and food fraud assessment tools. - Development and commercialization of detection and analytical techniques to assess the authenticity of foods. - Implementation of technologies used to improve traceability of products to ensure effective product recalls if food fraud is detected. - International support to ensure new technologies are accessible to lower-income countries and to establish farm-to-fork surveillance.

by the food industry. These barriers also make the technology prohibitive for small-scale operators and potentially restrict its use to premium products where customers can absorb the costs. The further development and commercialization of cost-effective tools to improve the traceability of food and assess the authenticity of food will help detect food fraud and mitigate the associated risks. Although recommended strategies to address food fraud in sub-Saharan Africa are similar to those already in place for other countries, they are not easily achievable due to the high levels of poverty and resource constraints, weak regulatory frameworks and enforcement capacity, limited access to the different forms of technology, and the lack of technical expertise to set up and maintain the systems (Chukwugozie et al., 2024). International support will be required to ensure that food traceability and monitoring technologies are accessible and to establish farm-to-fork surveillance.

A summary of the food safety risks and mitigation strategies associated with food fraud is presented in Table 9.

3.9 | Increasing importance of developing a positive FSC

The food industry, academia, and regulatory bodies are increasingly acknowledging that human behavior and an organization's culture play an integral and profound role in food safety. The role of organizational FSC as a determinant of the adoption of more effective food safety controls and food-handler behavior has received particular attention as a means of ensuring safe food beyond regulatory compliance, using social–behavioral determinants, such as emotions, experience, values, consequence, environment, knowledge, and need (Zanin et al., 2021). A conducive FSC may also boast wider benefits for an organization, leading to fewer food safety incidents, reduced costs related to food recalls, increased consumer confidence, and higher product turnover. In general, it is acknowledged that the key components shaping an organization's FSC include, but are not limited to, constructs such as leadership involvement, employee engagement, expectations, communication, resources and environment, competency, and performance (GFSI, 2018). Leadership is key across the FSC continuum whereby senior management has an obligation to demonstrate their commitment to fostering a positive food safety and quality culture by establishing, implementing, and maintaining food safety and quality culture objectives within the management system (Yiannas, 2023). An FSC should be interdisciplinary in nature, involving organization-wide collaboration, whereby specialist knowledge, tools, and techniques from different disciplines can be explored for potentially effective interventions.

Accurate and ethical assessment is a key step in the process of improving FSC through the phases of assessment and improvement (Nyarugwe et al., 2016). Each phase presents its own complexities and best practices, but without an authentic and reliable assessment, subsequent efforts to improve FSC will be ineffective and potentially harmful, whereas a clear and articulated FSC improvement pipeline (Figure 2) should be followed by industry to support requirement for continuous improvement (Lues, 2023).

The success of FSC initiatives lies in the foundation of respectful engagement with all stakeholders so that valid and reliable information can be collected to provide a clear understanding of an organization's current state, identify areas that need improvement, help in goal setting, and monitor progress (Griffith et al., 2017). As elsewhere in the food industry, AI is poised to make a dramatic impact on how data regarding a food company's FSC are gathered and assessed, as well as on the design and implementation of strategies to enhance food safety behaviors and related decision-making. The ethical dimensions of assessing FSC should not be underestimated, as neglecting these principles can significantly harm the organization and the legitimacy of the FSC discipline. Such ethical dimensions encompass aspects of mitigating risk and harm, observing moral and just engagement, and ensuring valid and reliable data.

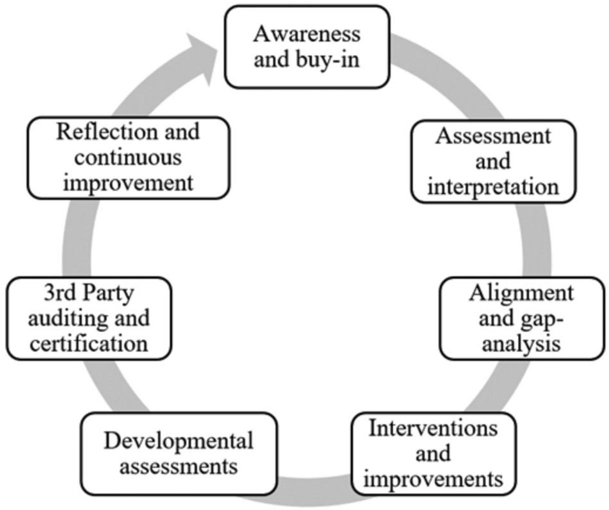

FIGURE 2 The food safety culture improvement and certification pipeline.

Ultimately, the aim of data collection is to identify gaps between the organization's current state and its desired state as required by food safety standards. A gap analysis requires in-depth reflection and consideration of the shortcomings identified, as well as how to align them with appropriate interventions by utilizing cognitive progression and design. Organizations are then positioned to align their findings with accurate and practical improvement strategies and interventions that consider the existing array of solutions already available in the public and scientific domains among consultants, scholars, scientists, and advisors in the food safety and broader organizational culture fields (Friedrich-Nel & Lues, 2024).

Startup companies, by their very nature, have a culture of taking risks; however, one of these risks should not be with food safety, and FSC should be seen as equally important for them as for established organizations. Therefore, companies creating new plant-based, cellular, insect-based, or other novel foods or ingredients should embrace the concept of FSC to strengthen consumer protections, reduce losses due to food safety incidents, and promote consumer confidence in the safety and quality of novel foods.

3.10 | Changing food regulations and the adoption of risk-based regulations

The main purpose of food regulations is to ensure that food is safe, nutritious, and properly labeled so that consumers can make informed choices. Food regulations can be official government regulations, policies, or guidance documents that serve as de facto standards or best practices for food industries. Food safety regulations may evolve due to technological advancements, changing consumer demands and preferences, and food safety modernization.

Currently, food safety evaluations and regulations can either apply a hazard- or risk-based approach. Hazard-based approaches typically only focus on the first of the generally accepted four steps of risk assessment: hazard identification, hazard characterization, exposure assessment, and risk assessment. At present, state-of-the-art hazard-based approaches are typically applied to the evaluation and regulation of genotoxic carcinogens or allergenicity (Mehta & Rietjens, 2023); however, in some jurisdictions, they may also be used for endocrine-active substances. Nevertheless, to avoid unnecessary risk management actions or consumer concerns, risk management should be based on risk and not on hazard identification, as exposure to a hazard below a certain level may not pose a risk, even for genotoxic carcinogens or allergens.

In response to the changing face of foods and expectations from regulators and consumers, food safety regulations have begun changing from a reactive, disease-triggered approach to a preventative, whole-food chain approach focused on achieving prescribed outcomes. This can be accomplished by using risk- and outcome-based food inspections, having more stringent requirements for tracking and tracing food products, and placing a regulatory emphasis on foods of greatest risk, that is, a risk-based approach, as informed by risk assessments and epidemiological evidence, all enhanced by an FSC. While it can be very challenging to directly link changes in food safety practices and regulations to reductions in food safety risks or improvements in health outcomes, it can be done. For example, in Canada, whole genome sequencing provided increased resolution to identify discrete clusters of *Salmonella* Enteritidis. Consequently, several outbreaks linked to frozen raw breaded chicken products were identified and ultimately led to a change in food safety policy that reduced the number of illnesses associated with these products (Morton et al., 2024). Advances in AI and the greater availability of low-cost high-throughput gene sequencing offer unparalleled accuracy and speed in pathogen detection and source attribution (Liberty, 2025) and will undoubtedly play an increasingly important role in ensuring food safety and the development of food regulations. Future research should focus on improving the scalability, affordability, and accessibility of genomic tools, particularly for resource-limited regions (Liberty, 2025).

Modernizing food safety can help to achieve better performance in the food industry, but new trends can also pose a risk. For example, with cell-based foods, it is hard for regulators to keep pace with all the advancements in the field, and right now, the industry is ahead of the regulators, which makes it difficult to achieve consistent and reliable timelines for approval that the industry desperately needs to become and stay viable. As global trends rapidly emerge, smarter regulations are needed, and regulators may have to evolve models to create regulatory standards at a faster pace to keep up with the rate of change happening in the marketplace. Regulatory frameworks need to be defined for emerging trends, and companies must stay up to date with regulations. Regulators need to train their staff on emerging technologies and trends that are coming down the pipeline. Food businesses also need to pay strict attention to the safety and quality of the foods that they produce. Promoting a strong and positive organizational FSC can go a long way toward achieving this goal.

In summary, updating regulations is crucial for maintaining a safe and reliable food supply chain, protecting consumers and the environment, and ensuring that food businesses operate an FSC that is fair, ethical, and science based. Both food companies and regulators need to keep pace with the emerging drivers and trends that food industries are adopting.

4 | CONCLUSIONS

The ability to produce safe food is becoming increasingly challenging. Multiple trends are simultaneously impacting food safety and global food security, and in the same way that the causes are multifactorial, so too must be the solutions. It is critical that the drivers impacting the safety of our foods are not looked at in isolation, but rather that multiple drivers, trends, and solutions are considered. Food producers, governments, and research organizations need to work together to consider the challenges and solutions through economic, technological, environmental, and social lenses. Critically, it needs to be appreciated that given the different settings in which risks may occur, it is unlikely that a single solution will be able to address the challenge presented by a single risk in a global context across time. It is critical that industry, regulators, and scientists strive to build resilience into our global food systems and develop a range of solutions that match the economic and technological resources available. The adoption of risk-based regulatory frameworks, the creation of a robust FSC, targeted research, and education and training will all play a role in addressing the looming food safety issues. The "best" solution will be adaptable, scalable, cost-effective, technologically feasible, and socially and environmentally acceptable. Creating solutions for low- to middle-income countries and those with a dominance of smallholder farmers will be particularly challenging. Regulators must strive to integrate food safety and food security considerations into guidance, and the food industry must endeavor to work more effectively with regulators and academia. In doing so, the food industry can better integrate its economic goals, processes, and people to reduce inequality and to help ensure the provision of safe food to all.

AUTHOR CONTRIBUTIONS

Margaret Thorsen: Investigation; methodology; data curation; writing—original draft; writing—review and editing. **Jeremy Hill**: Conceptualization; funding acquisition; writing—original draft; writing—review and editing. **Jeffrey Farber**: Writing—original draft; writing—review and editing. **Frank Yiannas**: Writing—review and editing. **Ivonne M. C. M. Rietjens**: Writing—original draft; writing—review and editing. **Pierre Venter**: Writing—review and editing. **Ryk Lues**: Writing—original draft; writing—review and editing. **Phil Bremer**: Conceptualization; methodology; supervision; project administration; writing—original draft; writing—review and editing.

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