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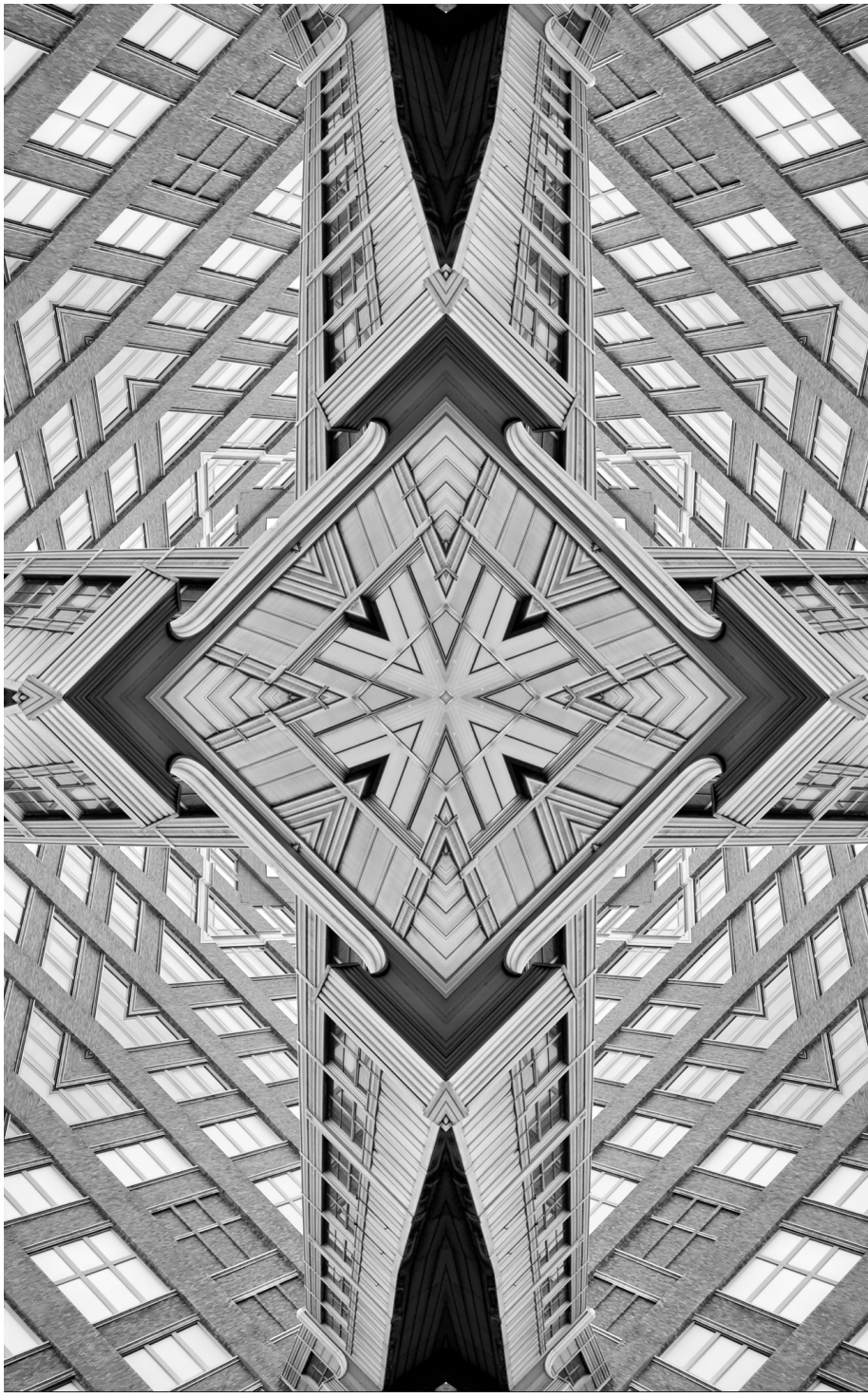

Food Safety in a Risk-Prone World: Strategies for Rapid Response and Resilience

Shoba Suri

Abstract

Globalisation has made the farm-to-fork journey complex, and with it comes the potential for food contamination in local contexts to spiral into global crises. A largely reactive food safety approach, the rapid growth in urbanisation, and climate change events are linked to the spread of food-borne illnesses, which affect hundreds of millions of people in low- and middle-income countries. This brief argues that building resilient food safety systems requires a proactive, whole-of-system approach, aided by technologies like Artificial Intelligence, Machine Learning, and Internet of Things. This would translate to the early identification, evaluation, and mitigation of food risks before they proliferate. The brief proposes strategies for a resilient food security ecosystem by drawing on influential frameworks and identifying systemic loopholes that need to be addressed.

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Introduction: Approaches to Food Safety

Food safety is a critical global public health concern: ensuring that food is free from biological, chemical, and physical hazards that could harm consumers.[1] With the globalisation of food supply chains, increasing complexity in food production, and rising consumer awareness, the need for robust food safety strategies has never been more pressing.[2] These challenges are compounded by emerging risks such as antimicrobial resistance, climate change impacts on food production, and the rapid expansion of global trade.

Food safety efforts have historically focused on reactive measures, such as responding to outbreaks or incidents of contamination. However, modern strategies for achieving food safety include technical, regulatory, and educational measures. This shift is driven by the recognition that food safety is not solely a technical issue but also a behavioural, cultural, and systemic one. International organisations, governments, and businesses play a pivotal role in establishing and enforcing standards, while education and shared responsibility among stakeholders ensure their effective implementation.

Some international standards (e.g., Codex Alimentarius) emphasise management systems, requiring organisations to adopt a Food Safety Management System (FSMS) that identifies and controls hazards.[3] Food businesses implement systematic controls such as Hazard Analysis and Critical Control Points (HACCP) and Good Manufacturing Practices (GMP),[4] which focus on critical production steps where hazards can be prevented or eliminated.

Such an approach highlights the importance of governments and international bodies in setting safety requirements through laws and standards. They define the hygiene criteria and compliance mechanisms for producers, processors, and retailers, while educating producers, food handlers, and consumers on safe practices. Regulatory agencies often enforce these rules via inspections, certifications, and legal controls. The WHO Global Strategy for Food Safety 2022-2030 also cites "the need for competent authorities to adopt and implement these food safety policies and ensure awareness and shared responsibility amongst all the stakeholders."[5]

Introduction: Approaches to Food Safety

Traditional food safety management systems have been predominantly process-focused, emphasising procedural compliance and technical controls as opposed to modern approaches based on behaviour-based safety management,[6] integrating people-centred organisational culture with science-based food safety principles to create a more comprehensive system. They recognise that effective food safety cannot be achieved through linear cause-and-effect thinking but requires an understanding of complex, interconnected relationships and feedback mechanisms.

Complementing this shift, the emergence of risk-based food safety strategies can be seen as another critical approach, particularly in addressing the complexities of global food markets. Studies on health risk in food markets advocate such strategies to protect public health from "consumption of foods with poor quality and safety", while prioritising resources and interventions based on scientific risk assessment and evidence.[7] The farm-to-fork approach further recognises that food safety vulnerabilities can emerge at any stage of production, processing, distribution, or consumption.[8] Together, these approaches highlight diverse strategies for ensuring food safety throughout the food lifecycle and underscore the role of stakeholders in the process.

The need for robust food safety systems is evident from the substantial global burden of foodborne diseases. According to WHO (World Health Organization), one in every 10 people worldwide fall ill each year after consuming contaminated food—about 600 million cases annually—resulting in 33 million disability-adjusted life years (DALYs) and 420,000 deaths.[9] These figures highlight the severe human health impact of inadequate food safety.

The productivity lost from premature death and disability, as well as the costs of treating foodborne illness, go as high as US$110 billion a year in low- and middle-income countries.[10] Table 1 lists some of the foodborne hazards and their economic implications.

Table 1: Foodborne Hazards and Their Economic Cost

Foodborne Hazards	Common Infectious or Toxic Agents	Incidence of Foodborne Illness	Deaths Due to Foodborne Illness	Total DALYs
Bacteria	Salmonella, Vibrio, E.coli, Shigella, Listeria, Brucella, Campylobacter	359,747,420	272,554	20,188,792
Virus	Noro virus, Hepatitis A	138,513,782	120,814	3,849,845
Protozoa	Entamoeba, Giardia, Crystococcus, Toxoplasma	77,462,734	6,242	1,311,435
Worms	Cestodes (tapeworms), Nematodes (round worms), Trematodes (flatworms), Helminths (parasites)	26,063,664	90,261	11,599,735
Chemicals	Aflatoxins, Cyanogenics, Diaoxins, Heavy Metals	217,632	19,712	908,356

Source: Biomedical Journal[11]

Vulnerable populations face the disproportionate risks of failures in food safety. For instance, children under five years of age bear 40 percent of the global foodborne disease burden, accounting for 125,000 deaths each year and a third of all foodborne illness fatalities.[12,13] The United Nations has highlighted how food safety incidents have a greater impact on children, the elderly, pregnant women, and those with compromised immune systems.[14] As a result, incorporating food safety into long-term sustainability and development goals becomes important. Several SDGs—especially SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), and SDG 8 (Decent Work and Economic Growth)—emphasise poverty reduction, clean water, responsible production, and partnerships that ensure food security and nutrition with food safety as the mainstay. They collectively underscore the need for safe food to fight against hunger and malnutrition.

The globalisation of food systems has fundamentally altered the risk landscape for food safety. Modern food systems span borders, with scope for local contamination to spiral into international crises.[15] Additional cross-border risks include climate change, conflict, and natural disasters, which disrupt supply chains and introduce new threats. For example, climate change-induced flooding can spread pathogens. These factors increasingly nudge all stakeholders to re-evaluate the connection between health and the environment, especially in terms of sanitation, given that many pathogens are zoonotic, i.e., originating in animals.[16] Figure 1 outlines the drivers—environmental challenges, global food systems, and technological advancements—and their implications for food safety.

Figure 1: Drivers of Food Safety

Drivers	Consequence	Food safety implications
Interests and demands for food safety	Increased attention and resources on food safety	• Improved protection of consumers • Reduced risks from unsafe foods • Greater trust and confidence in national food control systems
Global food safety threats	Multinational food safety emergencies	• Improved food safety legislation and control measures
Global changes and their impacts on the food supply chain	Extended and complex global supply chains	• Higher risks of intentional contamination and adulteration of food • More challenges to traceability and recalls
Environmental challenges	Accelerating climate change, increased agricultural waste, and environmental pollution	• Increased likelihood of transmission of certain foodborne pathogens and levels of certain chemical contaminants • Higher risks of environmental pollution into the food chain
Society: changing expectations and behaviour around food	Changes in consumer purchasing patterns, new business models, and communication platforms	• Increased food control challenges associated with new commercial trends • New challenges for risk communication to tackle misinformation on social media platforms
Rise of new technologies and digital transformation	Novel food ingredients, production and analytic methods	• Increased demand for risk assessment on novel foods and the application of new technologies to food production • New solutions for prevention and control of food safety risks
Demographic changes	Population growth, ageing societies, and urbanisation	• Higher proportion of vulnerable groups for food safety risks • More challenges to provide safe and healthy food for a growing population

Source: World Health Organization[17]

Key Challenges to Food Safety

Contemporary food safety faces multifaceted challenges spanning microbiological, chemical, and systemic dimensions. Experts identify three areas of concern that continue to threaten global food systems in the 21st century. These include microbiological safety, chemical safety, and personal and environmental hygiene.[18]

1. Among these, microbiological safety is the most critical challenge. It becomes a widespread problem since the biological nature of food inherently supports microbial growth that can cause foodborne diseases. Some microorganisms are worse than others. While viruses are responsible for a majority of foodborne illnesses, bacterial agents cause the most severe outcomes. For instance, leading bacterial pathogens—Salmonella, Campylobacter, and E. coli—cause over 90 percent of classic food-poisoning cases.[19]

2. Chemical risks pose another challenge, arising from non food-grade additives, including unauthorised colourants and preservatives, as well as pesticide residues and heavy metals (lead, cadmium, arsenic, mercury, and copper) that accumulate through inadequate hygiene practices.[20] Combined with poor personal and environmental hygiene by food handlers, as well as inadequate recycling and waste disposal facilities, contamination, spoilage, pest infestations, and pathogen proliferation are inevitable.[21]

3. Personal and environmental hygiene are critical to food safety. Poor hygiene among food handlers poses direct risks to public health. Food waste and inadequate recycling can cause food spoilage and contamination, and impact environmental hygiene. Equally important are sanitation standards in areas where food is prepared, processed, packed, and stored, as these conditions directly affect safety.

Beyond traditional biological and chemical hazards, food safety is increasingly compromised by traceability gaps, technological limitations, and regulatory fragmentation.[22] The complexity of the global food trade network can be quantified by the total trade volume of the food and agricultural network, amounting to US$1.9 trillion.[23] This fragmentation complicates traceability and accountability, as responsibility is divided among multiple unfamiliar businesses that must coordinate to meet safety standards. Accountability becomes especially difficult across jurisdictions with different standards, which hinders timely responses to contamination events.

Key Challenges to Food Safety

The COVID-19 pandemic further exposed vulnerabilities in food logistics, from labour shortages to concerns over hygiene, packaging, and delivery.[24] Preventing future crises requires investment in technology, cross-border regulatory alignment, and proactive crisis planning.

Several trends are reshaping global food safety and helping build resilience.[25] Pathogens and vectors, such as insects and dust, often carry foodborne microbes that stress crops and reduce disease resistance. Climate change further compounds risks by influencing the spread of foodborne pathogens.[26] Some of its effects, such as rising temperatures and humidity, promote microbial growth, while water and sanitation disruptions increase contamination risks.[27]

Figure 2: Megatrends and Strategies Impacting Food Safety

Source: IFT[28]

Demographic shifts and geopolitical instability are among the megatrends affecting food security. An ageing population and expanding urbanisation create unique vulnerabilities. Older adults are more susceptible to foodborne illnesses due to weaker immune systems and reduced sensory capabilities. This is worsened by aspects of increasing urbanisation, such as risks from wet markets, street food, and inadequately regulated home delivery services.[29] At the same time, urban agriculture faces a disadvantage due to potential contamination issues from pathogens, heavy metals, and pesticide use. Food

adulteration and fraud, along with mislabelling and information failures, also create manifold public health risks.

These practices, often economically motivated, expose weak regulatory enforcement and are exacerbated by complex trade and distribution networks, particularly in developing countries.[30] These countries also suffer from geopolitical and socioeconomic megatrends that disrupt their supply chains, weaken inspection capacity, and complicate international cooperation. There is a visible weaponisation of supply chains in the case of political conflicts, while overly nationalist food policies hinder information sharing and risk mitigation.[31]

In this context, even sustainable and circular economy models present both opportunities and risks for food safety.[32] The transformation to circular agrifood systems introduces risks from micro- and nano-plastics, pathogen survival during valorisation, persistence of natural toxins, food fraud, and the allergenic potential of biopolymers. Technological integration can present new vulnerabilities in food safety systems. For instance, the concentration of agrichemicals and natural toxins in novel foods like plant-based proteins or upcycled foods can increase because of diversified consumer choices for sustainable food products. These also hold the potential to trigger allergenic responses through varied proteins.[33]

Vulnerable populations are particularly at risk as they are forced to shift to unhealthy diets and consume unsafe foods, ultimately leading to increased healthcare expenditure.[34] The lack of food safety, therefore, bears massive societal costs: lost productivity, increased healthcare expenses, trade disruptions, and the erosion of public trust in food systems. Preventing these outcomes requires examining the interplay between traditional hazards and emerging threats, alongside proactive risk management to reduce illness, disability, and death among consumers.

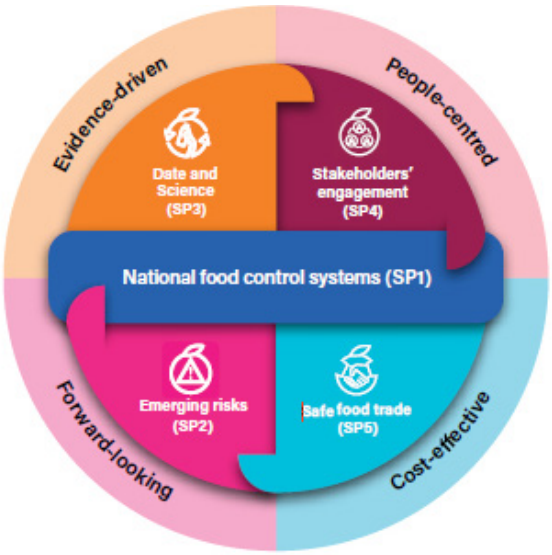
Strategic Responses and Solutions

Resilient food systems are essential for food safety preparedness amid evolving global challenges and emerging risks. Strategies must be comprehensive, integrating risk management, resilience building, and proactive intervention.[35] To be effective, food safety systems must shift from traditional reactive models to proactive approaches that utilise anticipatory frameworks to identify, evaluate, and address risks before they escalate into public health crises.[36]

Resilience-based food safety strategies focus on the capacity of supply chains to recover and adapt to shocks, ensuring the delivery of safe food within reasonable time frames.[37] They emphasise the dynamic nature of food safety strategies, moving beyond static prevention to encompass adaptive capacity and system-wide resilience. It is to be noted that all strategies to ensure food safety emphasise different but interconnected components of food governance. While some exclusively focus on discrete drivers such as climate change or globalisation, others, like the above-mentioned resilience theory, supply chain risk management, stakeholder collaboration, and organisational adaptation, are more holistic. These approaches underline the need for collaboration among government agencies, research institutions, and international entities to generate reliable data and support evidence-based decision-making. Frameworks such as climate-smart agriculture (CSA) and sustainable food systems strengthen food security through enhanced surveillance,[38] while data-driven models using climate and food safety indicators support predictive risk assessment.[39,40]

The WHO Global Strategic Framework for Food Safety Systems has provided the most comprehensive international response framework for food safety in a globalised world (Figure 3).

Figure 3: The Global Strategy for Food Safety: Five Priorities



Source: World Health Organization[41]

Another strand of strategic responses lies in technology-centred frameworks, which emphasise the role of innovation in addressing food safety challenges across global supply chains. For them, technology is a pillar for integrated systems, with multiple technologies needed for comprehensive food safety management.[42] It plays a crucial role in increasing food quality and safety monitoring by enhancing traceability, lowering contamination, and supporting proactive oversight, giving it transformative potential. By enabling transparent, responsive, and predictive systems, technology strengthens the recovery and adaptation capacity of supply chains, ensuring safe food delivery within reasonable timeframes.[43] This framework also proposes a three-step methodology: resilience context specification, resilience measurement, and resilience improvement—acknowledging that growing threats to food safety demand a more adaptive and resilient food supply system.

Strategic Responses and Solutions

The Integrated Six Ts Framework categorises strategic factors for food safety planning into three categories: robustness factors (traceability and transparency), enabling factors (trust and training), and complicating factors (testability and time).[44] The evolved framework adds two new dimensions: target (geographical presence and regulatory environment) and tactics (structural planning and operational strategies), under social and emerging factors. These additions highlight behavioural issues, chain structures, and public-private standards. It recognises that food safety strategies must address both technical and relational dimensions of supply chain management.

Food safety preparedness has also taken a multidisciplinary approach through the EMPRES, or emergency prevention system framework, which is structured around three interconnected pillars: early warning, emergency prevention, and rapid response.[45] The approach stresses international, regional, and national partnerships in preventing, mitigating, and managing food safety threats. It works through three pillars, defining eight major strategic elements, such as early warning activities through INFOSAN and horizon scanning, prevention via timely escalation and threat prioritisation, and rapid response mechanisms to address emergencies effectively.[46] The framework emphasises that all activities are conducted within the broader scope of the Food and Agriculture Organization (FAO)-stipulated initiatives, including capacity building and scientific advice, and recognises that effective food safety preparedness requires both technical capabilities and institutional coordination mechanisms operating across multiple levels of governance.

The highlighted food safety challenges demand comprehensive strategic responses that address both traditional risks and emerging threats of the 21st century. Several interconnected technological innovations, regulatory frameworks, stakeholder engagement measures, and adaptive management approaches offer solutions across the food supply chain.

The evolving landscape of food safety challenges demands comprehensive strategic responses that address both traditional risks and emerging threats. Interconnected solutions—ranging from technological innovations and regulatory frameworks to stakeholder engagement and adaptive management—offer pathways to strengthen safety across the food supply chain.

Strategic Responses and Solutions

A strong technological foundation enables the rapid identification of contamination sources and supports efficient recall during emergencies. The deployment of Internet of Things (IoT) devices and smart sensors allows continuous monitoring to prevent food safety incidents. Artificial intelligence (AI) and machine learning (ML) amplify these capabilities, predicting safety risks and identifying contamination patterns that might escape human detection. Beyond large-scale risk identification, these technologies help in the daily monitoring of temperature deviations, humidity changes, and other environmental factors that could compromise food safety.

Regulatory harmonisation and international cooperation are fundamental to global food safety, as recognised by the WHO. Key initiatives include coordination through geographical indications, uniform labelling systems, and information-sharing protocols, which enhance consumer empowerment and strengthen supply chain coordination. Effective governance requires institutional linkages and active coordination to promote adaptability across the supply chain.

Innovation in early warning systems is key to strengthening food safety mechanisms. These systems rely on surveillance networks, risk assessment tools, extensive communication protocols, and response mechanisms that utilise statistical techniques, ML, and computational simulations to forecast illness outbreaks based on environmental and epidemiological factors. Its strategic value lies not just in detection but also in enabling coordinated responses that involve food producers, processors, regulators, and consumers, translating early warning into actionable measures.

Stakeholder engagement and capacity-building are essential for coordinated action among government agencies, food businesses, and consumers. These strategies must account for diverse knowledge bases, incentive structures, and capacity limitations. Consumer-facing initiatives include awareness and education programmes that empower households to practise food safety. Capacity building also encompasses organisational development and system strengthening, ensuring institutional capacity at every stage rather than focusing solely on knowledge transfer.

Conclusion

This brief sought to illustrate how food safety strategies transcend traditional boundaries between sectors, disciplines, and geographic regions. Solutions, therefore, require integrated approaches across the domains of technology, regulation, and stakeholder engagement to build adaptive capacity across supply chains. The interconnected nature of these strategies reflects the complex, global, and evolving challenges of the 21st century, which demand not only reactive but also preventive and safe-by-design management approaches.

Food safety considerations can no longer be treated as a rudimentary exercise; they must be embedded in the design of food systems, technologies, and practices. Ultimately, preparing for the unexpected requires unprecedented collaboration, sustained investment in technological and institutional capacity, and data-led decision-making that prioritises public health through food safety and security.

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