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Review Article

Safety and public health concerns associated with animal-origin food

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Abstract

Animal-derived foods (meat, milk, eggs, and fish) play a key role in human diets worldwide, providing high-quality protein and essential micronutrients. At the same time, their production and consumption are increasingly linked with safety concerns that affect both public health and consumer confidence. Biological hazards such as *Salmonella* spp., *Campylobacter* spp., and *Listeria* spp. continue to drive a major share of foodborne disease globally, while chemical contaminants, veterinary drug residues, and environmental pollutants add long-term risks. Natural toxins and sporadic physical hazards further complicate the landscape. Antimicrobial resistance has now emerged as a critical cross-cutting challenge, reinforcing the interdependence of human, animal, and environmental health. This review brings together evidence on the spectrum of hazards in animal-origin foods and examines advances in detection technologies, predictive modelling, and early warning systems. By framing food safety within a One Health perspective, it argues for coordinated action across disciplines and sectors to ensure that animal-source foods remain both nutritious and safe for future generations.

Keywords: Consumer protection, Foodborne illness burden, Livestock production systems, Surveillance systems, Zoonotic hazards;

Highlights

- Comprehensive analysis reveals multi-hazard risks across animal-origin foods
- Global data confirm antimicrobial resistance as an urgent, escalating threat
- Evidence supports advanced detection and One Health strategies for prevention

INTRODUCTION

Animal-origin foods such as milk, meat, eggs, and fish are indispensable to global nutrition and food security. They supply high-quality proteins with a favourable amino acid balance and provide bioavailable micronutrients such as iron, zinc, vitamin B12, and long-chain omega-3 fatty acids that are difficult to obtain in adequate amounts from plant sources (Sheffield et al. 2024). Livestock and aquaculture also underpin rural livelihoods, support millions of smallholders, and generate substantial economic value through local markets and international trade. The same scale and complexity that make these foods vital also make their safety a pressing public health concern.

Worldwide, unsafe food causes an estimated 600 million illnesses and 420,000 deaths each year, which corresponds to roughly 33 million disability adjusted life years (DALYs) lost annually, with children under five accounting for about 40 per cent of this burden and about 125,000 deaths (World Health Organization [WHO], 2024). Low- and middle-income countries bear the greatest impact, with annual productivity and medical losses estimated at 95 to 110 billion US dollars. Animal-origin foods are a major driver of this burden. A global source attribution analysis indicates that meat, dairy, eggs, and fish together account for a large share of foodborne disease, with six key pathogens including *Salmonella*, *Campylobacter*, and *Taenia solium* responsible for nearly 86 per cent of the DALYs linked to animal source foods (Hoffmann, 2020). As per US-CDC report, beef, game, pork, and poultry were linked to 29 percent of deaths caused due to foodborne illnesses and out of which poultry accounted for 19 per cent (Centers for Disease Control and Prevention [CDC], 2025). Region-specific assessments echo these patterns. In Rwanda, for example, dairy products are implicated in 23 pe rcent

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of foodborne disease cases, 48 per cent of deaths, and 44 percent of total DALYs attributable to foodborne illness (Sapp et al., 2023). In India, analysis of Integrated Disease Surveillance Programme records for 2009–2018 documented 2,688 foodborne-disease outbreaks, 153,745 reported illnesses, and 572 deaths, indicating a persistent national burden (Bisht et al., 2021). Although cereals and mixed dishes were frequently implicated, several outbreaks and a notable proportion of deaths were associated with milk, meat, poultry, egg preparations and fish products, reflecting the risks linked to animal-origin foods.

The hazards embedded in animal-origin foods span microbiological, chemical, and physical categories. Microbiological threats remain the most significant. The 2017 to 2018 *Listeria monocytogenes* outbreak in South Africa linked to ready-to-eat meats caused 1060 cases and 216 deaths (National Institute for Communicable Diseases [NICD], 2018), while the European Union consistently reports Campylobacteriosis and Salmonellosis as leading zoonoses and *L. monocytogenes* as the cause of the highest hospitalization and fatality rates (European Food Safety Authority [EFSA], & European Centre for Disease Prevention and Control [ECDC], 2023). Chemical contaminants add another layer of risk. Per and polyfluoroalkyl substances have been detected in eggs and milk at levels producing dietary hazard quotients above unity in some regions (Bonato et al., 2025), and residues of veterinary drugs, heavy metals, and persistent organic pollutants continue to challenge regulators. Physical hazards, although less common, remain a concern. Consumer complaint surveillance in Brazil documented foreign materials such as bone fragments, plastics, insects, and metals in a range of processed meats despite established Hazard Analysis and Critical Control Point (HACCP) and Good Manufacturing Practice (GMP) programs (Cavalheiro et al., 2020).

These threats are amplified by antimicrobial resistance, which the World Health Organization lists among the top global health challenges. Indiscriminate use of antibiotics in livestock production and human medicine accelerates the emergence of multidrug resistant pathogens. Resistant strains of *Staphylococcus aureus*, *Escherichia coli*, and *Salmonella* are frequently isolated from meat and dairy products, complicating treatment and driving longer hospital stays and higher healthcare costs (Dafale et al., 2020; Elbehiry et al., 2025). The persistence and spread of resistance determinants across animals, humans, and the environment illustrate why food safety cannot be addressed in isolation.

In Indian context, animal sourced foods raise several safety and public health concerns. These include the risk of infections from bacteria and viruses such as *Salmonella* and *E. coli*, as well as zoonotic viral threats like Avian Influenza (Mahindroo et al., 2024). Chemical residues from antibiotics and pesticides also pose a major risk (Vijay et al., 2022). Overuse of antibiotics in agriculture and animal farming is contributing significantly to antimicrobial resistance (AMR) across India (Taneja & Sharma, 2019; Rajagopal et al., 2021). With rising demand for animal sourced foods growth of intensive farm animal production systems, and the prevalence of informal markets with poor regulation and hygiene, these risks are further amplified. Addressing them requires adopting a One Health framework that bridges animal, human, and environmental health, and ensures food safety throughout the farm to consumer chain (Kumar et al., 2025; Chakraborty et al., 2024).

Ensuring the safety of animal origin foods therefore requires a One Health approach that integrates human, animal, and environmental health. Pathogens and chemical hazards can originate on farms, in feed and water, during slaughter and processing, or along cold chains and retail systems. Many survive in soil and water, requiring coordinated surveillance and risk management strategies that cut across sectors and geographic boundaries (Pal et al., 2015). Fig. 1 illustrates this integrated One Health framework, showing how multidisciplinary collaboration, risk-assessment tools, and timely detection and mitigation converge to protect public health. This review

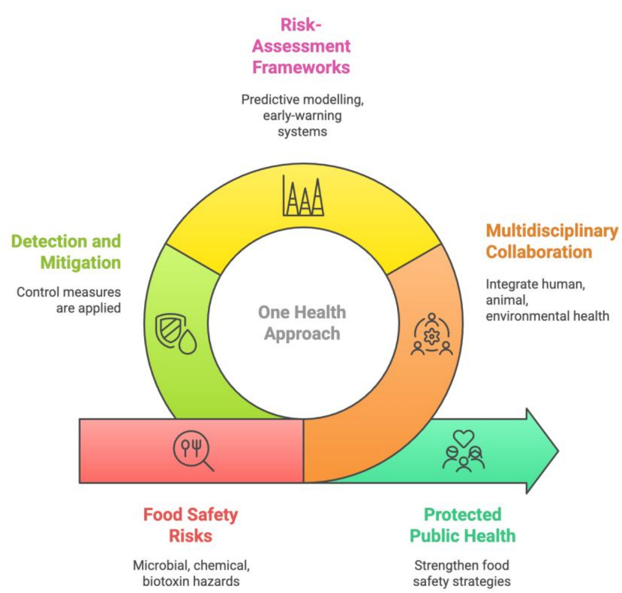

Fig. 1. Possible strategies to ensure food safety

synthesizes current knowledge of microbial, chemical, and biotoxin hazards in animal-origin foods, examines the public health consequences of antimicrobial resistance, and evaluates detection technologies, predictive models, and policy frameworks. By framing food safety within a One Health perspective, it highlights practical strategies to reduce disease burden, strengthen consumer confidence, and safeguard both human and planetary health.

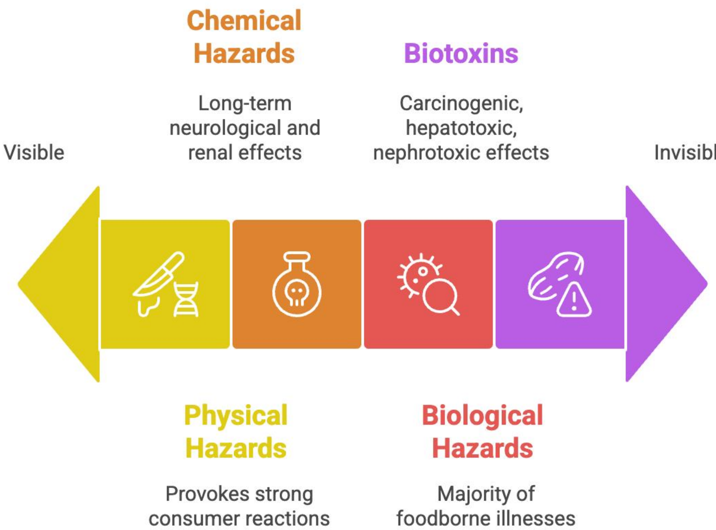

Fig. 3. Continuum of food safety hazards in animal-origin foods from visible physical risks to invisible microbial, chemical, and biotoxin threats

Safety hazards in animal-origin foods

While the importance of animal-origin foods to human diets is well established, less attention is often given to the diversity of risks they entail. These risks are not uniform; they arise from very different sources and manifest in distinct ways, ranging from visible foreign objects that immediately alarm consumers to invisible chemical residues and microbial pathogens that quietly drive much of the global foodborne disease burden. Understanding these hazards in their individual forms is essential, not only because they vary in severity and frequency, but also because they require very different approaches to detection, regulation, and control. These hazards are grouped into four categories-physical, chemical, biological, and biotoxins, each contributing differently to consumer complaints, health risks, foodborne illnesses, and management challenges, collectively leading to erosion of consumer trust (Fig. 2). Fig. 3 illustrates this continuum of risks from visible to invisible, highlighting how consumer perception often differs from actual public health impact, with microbial and chemical hazards posing the most significant yet least immediately perceptible threats (Food and Agriculture Organization of the United Nations & World Health Organization, 2016).

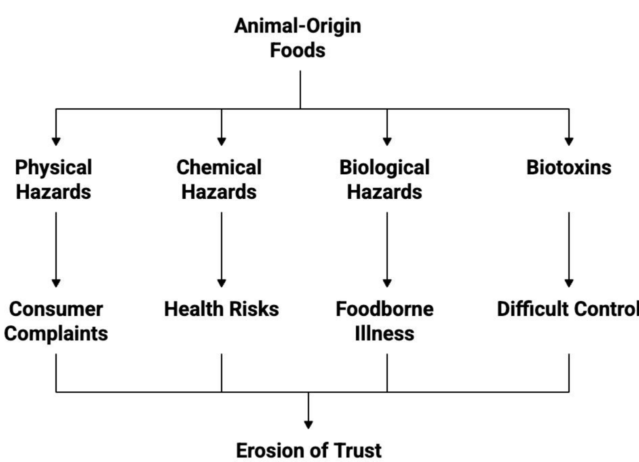

Fig. 2. Classification of food safety hazards in animal-origin foods

Physical hazards

Physical hazards are among the most visible safety failures and often provoke strong consumer reactions. They arise when slaughtering, processing, or packaging systems break down, allowing foreign materials such as bone fragments, glass, plastic, wood splinters, or metal shavings to enter finished products. Although they rarely cause outbreaks, they can result in choking, dental injury, or gastrointestinal perforation. Between 2016 and 2018, Brazilian consumer complaints documented 408 cases of physical contaminants in meat products, particularly in sausages (33.3%), hamburgers (17.9%), and chicken meat (12.3%). Bone fragments (27%) and plastic pieces (25%) were the most common hazards (Cavalheiro et al., 2020). These data reveal that even in systems guided by HACCP and GMP principles, equipment malfunction and inadequate monitoring allow lapses with direct public health and reputational consequences.

Chemical hazards

Chemical hazards pose more chronic and less perceptible risks. Veterinary drug residues, especially antimicrobials and antiparasitic agents, are widely reported when withdrawal periods are disregarded. Their persistence in food exposes consumers to toxic effects and fosters resistance selection in the gut microbiota. Heavy metals including lead, cadmium, and mercury enter meat, milk, and fish through contaminated feed, soil, and water, accumulating in tissues and causing long-term neurological and renal effects. Persistent organic pollutants such as dioxins and PCBs accumulate in fatty tissues of ruminants and aquaculture species, remaining in circulation for decades. Increasing attention is also directed at emerging pollutants like per- and polyfluoroalkyl substances (PFAS). A recent review documented PFAS in eggs and milk across several regions, with hazard quotients exceeding 1 in some cases, indicating risks of immune and endocrine disruption (Bonato et al., 2025). Beyond these, systematic reviews highlight that approximately 66.2% of global dairy products are contaminated with aflatoxin M1, with mean concentrations near 57.2 ng/kg-levels of concern given its carcinogenic and immunotoxic potential (Jahromi et al., 2025). These examples highlight that chemical hazards are not merely a farm-level issue but are increasingly tied to environmental and industrial contamination.

Biological hazards

Biological hazards remain the dominant drivers of global foodborne disease burden. Pathogens such as *Salmonella enterica*, *Campylobacter* spp., *Listeria monocytogenes*, and Shiga toxin-producing *Escherichia coli* account for the majority of foodborne DALYs linked to animal-origin foods (WHO, 2015; EFSA & ECDC, 2023). *Listeria monocytogenes* exemplifies the risk of persistent environmental pathogens: the 2017–2018 outbreak in South Africa, traced to ready-to-eat meat, caused 1,060 confirmed cases and 216 deaths (NICD, 2018; Smith et al., 2019). Campylobacteriosis and salmonellosis continue to dominate notifications in the European Union, while parasitic hazards such as *Taenia solium* in pork drive neurocysticercosis in endemic regions. Viruses including Hepatitis E and Norovirus further add to the burden, particularly where hygiene lapses compromise meat or shellfish supply chains. A unifying dimension across these hazards is antimicrobial resistance (AMR). Resistant strains of *E. coli*, *Staphylococcus aureus*, and *Salmonella* have been isolated from retail meat and dairy worldwide (Dafale et al., 2020; Elbehiry et al., 2025). The World Health Organization (WHO) recognizes AMR as one of the top ten threats to global health, with resistant infections already linked to nearly 5 million deaths annually. The economic burden is equally striking: in the United States, the annual cost of foodborne illness is estimated at US$75 billion, with non-typhoidal *Salmonella* (US$17.1 billion) and *Campylobacter* (US$11.3 billion) contributing the largest shares (Hoffmann et al., 2025). Within food systems, misuse of antimicrobials in animals accelerates the emergence and spread of resistance genes that traverse human, animal, and environmental reservoirs.

Biotoxins

Biotoxins complete the hazard spectrum, adding risks that are difficult to control once contamination occurs. Mycotoxins such as aflatoxin B1, fumonisins, and ochratoxin A arise in feed grains and carry through into animal products, where they exert carcinogenic, hepatotoxic, or nephrotoxic effects (Neng et al., 2020). In aquatic food systems, harmful algal blooms generate marine biotoxins including saxitoxins, domoic acid, and ciguatoxins. These compounds resist cooking and processing, leading to paralytic, amnesic, and ciguatera fish poisoning in consumers (Wang et al., 2024). Bacterial toxins such as *Clostridium botulinum* neurotoxins and *Staphylococcus aureus* enterotoxins are particularly dangerous because they can develop post-processing if cold chains or hygiene are inadequate. Unlike bacterial cells, most toxins are heat-stable, making their prevention far more critical than downstream control.

The above overview showed that animal-origin foods are vulnerable to acute, chronic, and emerging risks. Physical contaminants erode consumer trust, chemical residues and pollutants drive long-term health concerns, biological agents remain the leading cause of global foodborne illness, and biotoxins present difficult-to-manage natural risks. Their overlapping nature demonstrates why food safety cannot be managed in silos but must instead account for multiple pathways of entry and persistence across the entire food chain.

Detection and mitigation of food-safety hazards

This section focuses on how hazards in animal-origin foods are found and how they are controlled in practice-moving from tools that detect problems quickly and reliably to interventions that reduce risk at the source, during processing, and along distribution. Emphasis is placed on methods that are validated in the literature and scalable in regulatory and commercial settings and has been summarized in Fig. 4. Table 1 provides a consolidated overview of key food safety hazards associated with animal-derived foods. It summarizes the major types of hazards along with their primary public-health concerns, typical validated

Table 1. Major food safety hazards in animal-derived foods: public-health concerns, detection methods, and mitigation strategies

Type of hazard	Public-health concern	Detection (validated examples)	Mitigation / Control	Key References
Physical - foreign bodies in processed meats	Acute injuries (choking, dental/GI damage); 408 incidents in Brazilian meats 2016-2018	In-line metal detectors; X-ray imaging; hyperspectral imaging + ML	HACCP prerequisite programs, equipment maintenance, sieves/magnets, packaging control; CCP verification and rapid complaint investigation	Cavalheiro et al., 2020
Chemical - veterinary drug residues (milk/meat)	Toxic exposure; resistance selection in gut microbiota	QuEChERS-UPLC-MS/MS (LOD ~0.7 µg/L, recoveries 73-112 %); ELISA/ LFIA screening	Adherence to withdrawal periods & MRLs; supplier verification; validated cleaning to prevent carry-over	Zhu et al., 2025
Chemical - heavy metals & persistent organic pollutants (POPs)	Chronic neurological, renal and endocrine effects from Pb, Cd, Hg; dioxins/PCBs in animal fat	HR-ICP-MS or AAS for metals; GC-MS/ MS for POPs	Feed & water quality assurance; sourcing from low-contamination areas; monitoring & traceability	
Chemical - per- and polyfluoroalkyl substances (PFAS)	Hazard quotients >1 in some regions; immune & endocrine disruption	Targeted LC-MS/MS; high-resolution MS for non-target screening	Source control in feed/water; risk-based surveillance and recalls	Bonato et al., 2025
Chemical - aflatoxin M1 in dairy	~66 % global dairy contamination; carcinogenic & immunotoxic	LC-MS/MS quantitation; ELISA/LFIA screening	Good Agricultural Practices (feed drying, aeration); supply-chain traceability & market recalls	Jahromi et al., 2025
Chemical - multi-mycotoxin contamination in animal feed	High co-occurrence of aflatoxin B1, deoxynivalenol, zearalenone (China 2021–24); risk of carry-over to milk/ meat/eggs	Large-scale feed sampling; HPLC and LC-MS/MS	Multi-mycotoxin monitoring; improved drying/storage; certified binders	Liu et al., 2025
Chemical - aflatoxin B1 in foods/feeds (global)	Potent carcinogen and hepatotoxin	Chromatography (HPLC, LC-MS/MS); immunoassays; electrochemical biosensors	GAP; biological control of *Aspergillus*; detoxification (binders, probiotics, intelligent packaging)	Kêpka-Borkowska et al., 2025

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Type of hazard	Public-health concern	Detection (validated examples)	Mitigation / Control	Key References
Chemical - mycotoxins in ready-to-eat foods	Ochratoxin A, fumonisins etc.; nephrotoxic, carcinogenic	LC-MS/MS, rapid immunoassays, AI-assisted spectral analysis	Improved post-harvest storage, updated regulatory limits, consumer awareness	Di Salvo et al., 2025
Chemical - veterinary drug residues via manure recycling	Antibiotic residues in manure-fertilized soils entering crops/ animal feeds; AMR selection	LC-MS/MS quantification of residues in manure, soil, foods	Stricter manure-use regulation; composting treatments; monitoring high-risk drugs	Khalifa et al., 2024
Chemical/ Biological - mycotoxin exposure in poultry	Immunosuppression, reduced vaccine efficacy, growth depression; residues in meat & eggs	Feed LC-MS/MS; histopathology; serology for immune impact	Toxin-binding feed additives; probiotics; strict feed hygiene & storage	Olariu et al., 2025
Chemical - dietary exposure to diverse mycotoxins in foods	Significant global dietary risk from cereals, nuts, animal products	National monitoring surveys; LC-MS/MS; risk-assessment modelling	Global surveillance; harmonized regulatory limits; improved storage & processing	Li et al., 2025
Biological - *Salmonella* / *Campylobacter* in meat & poultry	Major DALYs & economic burden worldwide	Culture & serotyping; PCR/real-time PCR; WGS for cluster detection	On-farm biosecurity; vaccination (e.g., poultry); HACCP process control	EFSA & ECDC, 2023
Biological - *Listeria monocytogenes* in RTE meats	High fatality rates; South Africa 2017-18 outbreak (1,060 cases, 216 deaths)	Culture confirmation; whole-genome sequencing	Validated kill steps (e.g., HPP with product-specific validation); routine environmental monitoring; hygienic plant design	NICD, 2018; Smith et al., 2019
Biological - AMR across foodborne pathogens	~5 M deaths in 2019; projected 10 M annually by 2050	Phenotypic AST; WGS/AMR-gene profiling; integrated food-clinical-environment surveillance	Prudent veterinary antimicrobial use; AMR stewardship; vaccines; phage/ probiotic alternatives	WHO, 2023; Rhouma et al., 2022
Biological - antimicrobial-resistant pathogens in retail meat	High prevalence of resistant *E. coli* and other pathogens in Chinese retail meat	Culture & phenotypic antimicrobial-susceptibility testing; molecular typing	Stronger slaughter/ processing hygiene; national AMR surveillance; antibiotic-use reduction	Ren et al., 2024
Biological - *Vibrio* spp. (climate-driven	Expansion into Baltic & North Seas with warming	Seafood monitoring; WGS; risk-modelling of sea-surface	Climate-informed surveillance and early warning;	Riedinger et al., 2024; Gyraitė et al., 2024;

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Type of hazard	Public-health concern	Detection (validated examples)	Mitigation / Control	Key References
expansion)	waters; rising seafood -borne illness risk	temperature	harvest-area closures; strict cold -chain handling	Schets et al., 2025
Biological - *Vibrio parahaemolyticus* AMR in seafood	High ampicillin resistance; frequent multidrug resistance in ready-to-eat seafood	Culture + AST; genomic ARG profiling	AMR stewardship in aquaculture; hygiene & temperature control	Zin et al., 2025; Beshiru & Igbinosa, 2023
Biotoxins - marine toxins (saxitoxins, domoic acid, ciguatoxins)	Severe paralytic, amnesic & ciguatera poisoning; heat-stable toxins	LC-MS/MS multi-toxins (regulatory standard)	Monitoring harmful algal blooms; conditional harvesting; rapid chilling	Wang et al., 2024; Ahuja et al., 2023
Biotoxins - mycotoxins (aflatoxin B1, ochratoxin A, fumonisins)	Carcinogenic, hepatotoxic, nephrotoxic; feed carry-over into animal products	LC-MS/MS; rapid immunoassays	Good Agricultural Practices (drying, storage, aeration); feed adsorption/ binders	Neng et al., 2020

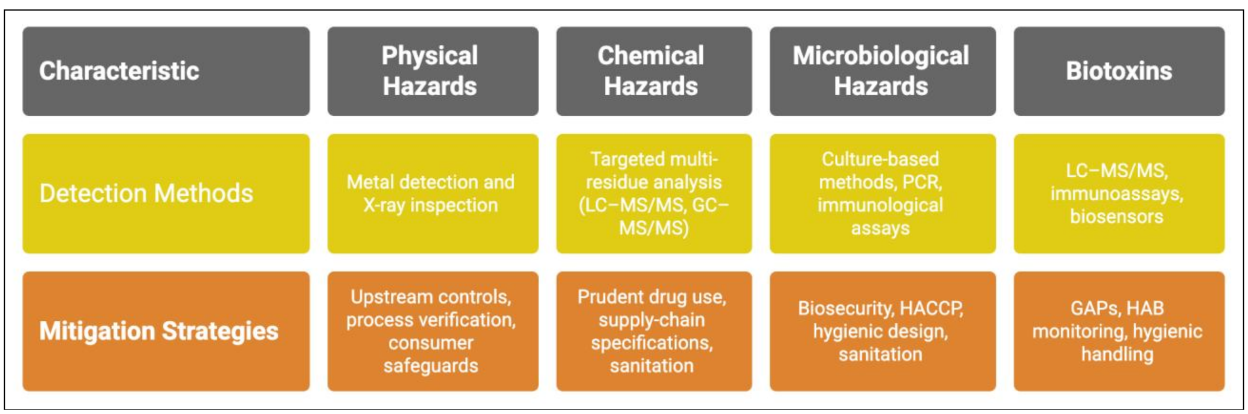

Fig. 4. Overview of detection methods and mitigation strategies in animal-origin foods

detection approaches, and core mitigation or control strategies. This text-based summary offers a clear reference point for understanding how diverse hazards are identified and managed across the food chain without including specific citations.

Detection and mitigation of physical hazards

Because foreign-body incidents erode trust and can cause acute injury, processors combine prevention programs with in-line detection. Metal detection and X-ray inspection are used where, metal detector detect ferrous/non-ferrous metals and X-ray detects a broader density range (e.g., bone, some plastics/glass) depending on energy and matrix thickness. Non-destructive imaging such as hyperspectral imaging (HIS**),** supports automated visual inspection in specific lines, particularly when paired with machine learning (Soni et al., 2022). Research continues to extend coverage to challenging matrices (e.g., poultry bone in deboned products) using imaging/signal-processing approaches; nonetheless, foreign-body programs still rely on layered controls that begin upstream (Cavalheiro et al., 2020; Soni et al., 2022).

Mitigation involves upstream controls, wherein prerequisite programs under HACCP equipment maintenance and calibration, raw-material specifications, sieves/filters/magnets where appropriate, tool accountability, and controlled packaging supplies reduce introduction points. Further, process verification including critical-control-point placement of detection devices, routine performance checks (test pieces), and documented corrective actions ensures sustained interception effectiveness. Additionally, consumer-facing safeguards like traceable lots and rapid complaint investigation loop events back into root-cause analysis and engineering fixes (Cavalheiro et al., 2020).

Detection and mitigation of chemical hazards

The detection of chemical hazards in animal-origin foods depends heavily on advanced instrumentation supported by robust sample preparation techniques. Targeted multi-residue analysis remains the gold standard, with QuEChERS extraction followed by LC-MS/MS or GC–MS/MS serving as the workhorse for detecting pesticides, veterinary drug residues, and process contaminants in complex food matrices. For example, Zhu et al. (2025) present a modified QuEChERS-UPLC-MS/MS method that enables simultaneous detection of 20 pesticide and veterinary drug residues in buffalo and cow milk with high sensitivity (LOD as low as 0.7 μg/L) and recoveries between 73.1–111.6%. The validated approach, offering precision, eco-friendliness, and robustness, provides a reliable tool for ensuring milk safety in food monitoring systems. For rapid, low-cost screening, immunoassays such as ELISA and lateral flow immunoassays (LFIA) are widely employed, particularly for monitoring classes of antimicrobials like sulfonamides and â-lactams in milk, although positive samples require confirmatory testing via chromatographic methods (Hua et al., 2018). More advanced approaches have expanded the scope of detection, with high-resolution mass spectrometry (HRMS) enabling both suspect and non-target screening, particularly useful in food safety incident investigations (Gavage et al., 2021). In parallel, surface-enhanced Raman spectroscopy (SERS) offers potential for portable, sub-ppm detection of specific contaminants and adulterants, provided that careful calibration is ensured (Neng et al., 2020). Nevertheless, for toxin confirmation and precise quantitation, mass spectrometry continues to be the definitive analytical platform (Ahuja et al., 2023).

Mitigation of these chemical hazards in animal-origin foods requires interventions spanning the entire farm-to-fork continuum. At the source, risk reduction hinges on prudent veterinary drug use with strict adherence to withdrawal periods and compliance with maximum residue limits (MRLs), alongside implementation of feed and water quality assurance programs to minimize ingress of heavy metals and mycotoxins. Supply-chain specifications, coupled with supplier verification, further strengthen upstream preventive control (Rose, 2012; Vignesh et al., 2024). Within processing environments, hazard control emphasizes segregation of high-risk raw materials, careful selection of equipment and contact materials to reduce chemical migration, and optimization of smoking and thermal processes to limit the formation of polycyclic aromatic hydrocarbons (PAHs) and nitrosamines. Additionally, validated cleaning and sanitation protocols are critical to preventing inadvertent chemical carry-over (Vignesh et al., 2024). Beyond production, robust market surveillance and traceability systems provide a final safeguard, enabling risk-based monitoring, targeted recalls, and rapid containment of contaminated products. The development of interoperable traceability platforms further facilitates timely corrective actions across international food supply chains (Abid et al., 2024; Liberty et al., 2025).

Detection and mitigation of microbiological hazards

Culture-based methods remain the cornerstone of legal and diagnostic frameworks in food safety testing because they provide viable isolates essential for confirmation, serotyping, and subtyping. However, their inherent slowness limits their usefulness in supporting modern process control and rapid decision-making. To address this gap, laboratories have increasingly adopted integrated approaches that combine classical enrichment with rapid, high-throughput techniques offering specific advantages in speed, sensitivity, or resolution. Nucleic-acid–based assays, including conventional and real-time PCR, multiplex PCR, isothermal amplification platforms such as LAMP (loop-mediated isothermal amplification) and NASBA (nucleic acid sequence-based amplification, and microarray technologies, enable rapid detection of species- or virulence-specific sequences, thus accelerating screening and confirmatory testing (Aladhadh, 2023; Law et al., 2015). Immunological assays such as ELISA and lateral-flow devices are widely employed for inexpensive, field-deployable, and high-throughput screening; nonetheless, they still require culture confirmation due to occasional cross-reactivity (Law et al., 2015). Biosensor technologies, both optical and electrochemical, are advancing process monitoring by significantly reducing time-to-result, while hyperspectral imaging coupled with machine learning can non-destructively identify surface contamination and hygiene lapses on meat and fish products, providing valuable complementarity to swab-based methods (Soni et al., 2022). At the forefront, whole-genome sequencing (WGS) and metagenomics have revolutionised foodborne disease surveillance and source attribution. WGS offers unparalleled resolution for outbreak reconstruction, antimicrobial resistance (AMR) gene profiling, and cross-jurisdictional cluster detection (Brown et al., 2019; Nadon et al., 2017). Today, routine WGS of food, clinical, and environmental isolates forms the backbone of national and international networks, allowing field detections to be directly linked to timely control and intervention measures (Nadon et al., 2017). Effective food safety management requires layered control measures applied across the entire farm-to-fork continuum. At the pre-harvest stage, in both animal and aquaculture systems, strict biosecurity, water and feed hygiene, targeted vaccination programs (such as *Salmonella* vaccines in poultry), and reduced antimicrobial use under stewardship initiatives are essential to lowering pathogen pressure before slaughter or harvest (Heredia & García, 2018). During processing and product design, HACCP-based frameworks remain the backbone of safety, supported by validated kill steps and the application of multiple "hurdles," including pH adjustment, water activity reduction, and use of preservatives. Advanced non-thermal technologies, such as high-pressure processing (HPP), are increasingly applied to ready-to-eat foods to inactivate *Listeria monocytogenes* without compromising product quality; however, EFSA Panel on Biological Hazards (EFSA Panel on Biological Hazards (BIOHAZ), 2022) emphasizes that HPP conditions must be carefully validated for each product matrix to ensure efficacy and safety. In the post-processing and environmental phase, robust hygienic design, validated sanitation protocols - including routine *Listeria* environmental monitoring along with allergen and line segregation and strict cold-chain maintenance are indispensable. In addition, emerging interventions such as bacteriophages and protective microbial cultures can help mitigate recontamination risks, provided they are validated and integrated into HACCP systems in compliance with regulatory standards (Urban-Chmiel et al., 2025).

Detection and mitigation of Biotoxins

The detection of chemical and biological toxins in animal-origin foods increasingly relies on advanced analytical tools that combine sensitivity, specificity, and regulatory acceptance. For marine biotoxins, LC-MS/MS-based multi-toxin methods have now largely replaced traditional mouse bioassays in many jurisdictions, offering precise quantification of compounds such as saxitoxins, domoic acid, okadaic acid group toxins, brevetoxins, and ciguatoxins in shellfish and fish (Wang et al., 2024; Ahuja et al., 2023). Bacterial and fungal toxins continue to require targeted immunoassays, with confirmatory mass spectrometry applied where available, particularly for enterotoxins from *Staphylococcus aureus* and neurotoxins produced by *Clostridium botulinum*. Mycotoxins that accumulate in milk, meat, and eggs through feed carry-over are routinely quantified by LC-MS/MS, while rapid immunoassays are widely used for preliminary screening in both feed and food matrices (Ahuja et al., 2023). In addition, portable and field-deployable options such as immuno-lateral flow devices and biosensors are gaining prominence for triage in seafood and feed supply chains, enabling quick on-site decisions; however, laboratory confirmation remains necessary for enforcement and regulatory actions (Neng et al., 2020; Hua et al., 2018).

Mitigation strategies for mycotoxins and marine toxins span both primary production and post-harvest interventions. At the primary production stage, good agricultural practices (GAPs) such as proper crop drying, moisture and temperature control, aeration, and crop rotation are essential to minimize fungal growth and subsequent mycotoxin formation, thereby limiting carry-over into the food chain. In aquaculture and wild-harvest fisheries, monitoring of harmful algal blooms (HABs) combined with area closures and conditional harvesting remains the most effective public health measure for preventing marine biotoxin contamination (Wang et al., 2024). Post-harvest controls further complement these measures through hygienic handling, rapid chilling, and the application of validated heat steps to reduce the growth of toxin-producing organisms. However, because many toxins are heat-stable, preventive measures are more effective than attempts at removal. Emerging approaches such as selective adsorption in animal feed and biocontrol or fermentation-based detoxification strategies also show considerable promise, though their efficacy requires careful validation for specific toxins and matrices (Ahuja et al., 2023; Vignesh et al., 2024).

Emerging zoonoses and antimicrobial resistance in terrestrial and aquatic food systems: public health implications

Antimicrobial resistance (AMR) is the ability of microorganisms to survive or grow despite exposure to drugs intended to inhibit or kill them. This makes standard treatments ineffective and contributes to prolonged illness, increased mortality, and significant economic losses (Food and Agriculture Organization [FAO], 2025). In agriculture, AMR reduces productivity, threatens livelihoods, compromises food safety, and endangers global food security. Resistant microbes can spread across humans, animals, plants, and the environment, thereby contaminating the food chain (Uzair et al., 2023). The World Health Organization has identified AMR as one of the top ten global health threats, and its rise is closely linked with zoonoses, which account for more than 60% of emerging infectious diseases worldwide (Jones et al., 2008; Dafale et al., 2020). Zoonoses are caused by viruses, bacteria, fungi, parasites, or prions and include nearly 200 recognized diseases (WHO, 2020) transmitted through food, water, air, or direct animal contact, such as anthrax, brucellosis, rabies, bovine tuberculosis, and Q fever (Said et al., 2023).

The spread of zoonoses and AMR is shaped by complex biological, ecological, and environmental drivers, exacerbated by antimicrobial misuse, climate change, and poor biosecurity. Livestock and aquaculture, while critical for food and income, also act as reservoirs of resistant pathogens, creating a dual challenge that establishes the need for a One Health approach integrating human, animal, and environmental health (Uzair et al., 2023).

Zoonotic pathogens in terrestrial food systems remain important contributors to the global burden of foodborne disease. *Escherichia coli* O157:H7, *Salmonella enterica*, *Campylobacter* spp., and *Listeria monocytogenes* are frequently implicated through contaminated meat, milk, and ready-to-eat foods (EFSA & ECDC, 2023). Other significant zoonotic hazards include *Brucella* spp., a bacterial pathogen responsible for brucellosis in humans and animals (Qureshi et al., 2024), and the parasitic nematode *Trichinella spiralis*, which continues to cause foodborne trichinellosis linked to pork consumption (Bai et al., 2022). Among viral zoonoses, both Nipah virus, associated with severe outbreaks in South and Southeast Asia (Mehnaz et al., 2024), and highly pathogenic avian influenza (HPAI H5N1), which poses pandemic risks due to its high mortality in poultry and humans (CDC, 2024; Simancas-Racines et al., 2025), remain of critical concern. There is also growing recognition of pathogen interactions, whereby influenza virus infections predispose poultry flocks to secondary bacterial infections, leading to increased antimicrobial use and complicating control measures (Joseph et al., 2013; Manohar et al., 2020).

Aquatic food systems present distinct but equally concerning risks. Bacterial pathogens such as *Vibrio* spp., *Aeromonas* spp., *Mycobacterium marinum*, and *Streptococcus iniae* are associated with seafood-borne illness, while parasites including fish-borne trematodes (*Opisthorchis*, *Clonorchis*), *Anisakis* roundworms, and *Diphyllobothrium* tapeworms, are transmitted through raw or undercooked fish. Viral threats such as norovirus and hepatitis A are commonly linked to sewage-contaminated shellfish (European Food Safety Authority (EFSA) BIOHAZ Panel et al., 2024; Ziarati et al., 2022). Climate change is amplifying these risks, with warming seas expanding the range of pathogenic *Vibrio* into previously temperate waters such as the Baltic and North Seas (Riedinger et al., 2024; Gyraitë et al., 2024; Trinanes & Martinez-Urtaza, 2021).

The widespread use of antimicrobials in terrestrial and aquatic production systems is a major driver of AMR) In cattle and poultry, antibiotics are routinely administered not only for treatment but also for prophylaxis and growth promotion, practices that have accelerated the emergence of multidrug-resistant bacteria. Notably, resistant strains of *Escherichia coli*, *Salmonella enterica*, *Staphylococcus aureus*, and *Klebsiella pneumoniae* have been increasingly associated with livestock production environments (Azabo et al., 2022; Mak et al., 2022; Rhouma et al., 2022). Many isolates harbour resistance genes such as extended-spectrum â-lactamases, which can transfer between microorganisms. Meat, milk, and eggs may contain resistant pathogens and antibiotic residues, while animal waste spreads resistance genes into soil and water (Elbehiry et al., 2025). In aquaculture, excessive and inappropriate use of antimicrobials has promoted resistant *Vibrio* and *Aeromonas*, which not only endanger seafood safety but also serve as reservoirs of resistance genes within aquatic microbial communities (European Food Safety Authority (EFSA) BIOHAZ Panel et al., 2024). Table 2 summarizes representative zoonotic pathogens and recent AMR trends documented in terrestrial and aquatic food systems, illustrating their resistance patterns and implications for food safety and public health. The scale of the problem is reflected in estimates that AMR was associated with nearly five million deaths in 2019 and could cause up to 10 million annually by 2050 if unchecked. Economic losses could exceed USD 3.4 trillion in global GDP within a decade, with an additional 24 million people pushed into extreme poverty, particularly in countries with weak regulatory systems (WHO, 2023; United Nations Environment Programme, 2023).

Table 2. Representative zoonotic pathogens and antimicrobial resistance trends in terrestrial and aquatic food systems

System	Pathogen(s)	Key findings on AMR / zoonoses	References
Terrestrial (cattle, poultry, pigs)	*Escherichia coli*, *Salmonella enterica*, *Campylobacter spp.*	EU surveillance (2022–2023) shows high resistance of isolates from food animals and meat to ampicillin, tetracycline, and sulfonamides; increasing ciprofloxacin resistance in poultry-associated *Salmonella* and *Campylobacter*.	EFSA & ECDC, 2023
Terrestrial (poultry meat, Bangladesh)`	*E. coli*	*E. coli* isolated from retail chicken meat: 100% resistant to ampicillin, 87.6% to erythromycin, >80% to third-generation cephalosporins; ESBL production in 41.7% of isolates.	Bhowmik et al., 2025
Terrestrial (broiler farms, Bangladesh)	*E. coli* (fecal & environmental isolates)	Up to 98% ciprofloxacin resistance in fecal isolates; 89% in environmental isolates; widespread MDR confirmed.	Hasan et al., 2023
Terrestrial (global zoonoses)	*Listeria monocytogenes*, *Brucella* spp., *Trichinella spiralis*, HPAI (H5N1)	Major zoonotic threats through ready-to-eat meats, unpasteurized dairy, pork, and poultry; influenza outbreaks increase secondary bacterial infections '! greater antimicro bial use.	EFSA & ECDC, 2023; Qureshi et al., 2024; Bai et al., 2022; CDC, 2024; Simancas-Racines et al., 2025
Aquatic (seafood, Korea)	*Vibrio parahaemolyticus*	58.8% of isolates resistant to ampicillin; phenotypic resistance also observed to tetracycline and chloramphenicol; genomic evidence of ARG carriage.	Zin et al., 2024
Aquatic (climate-driven expansion)	*Vibrio spp.* (*V. vulnificus*, *V. parahaemolyticus*)	Warming seas expanding *Vibrio* into the Baltic and North Seas; climate projections show illness risk increases ~1.5× per 1 °C water temperature rise.	Riedinger et al., 2024; Gyraitė et al., 2024; Schets et al., 2025
Aquatic (parasites & viruses)	*Anisakis*, *Opisthorchis/ Clonorchis*, *Diphyllobothrium*; Norovirus, Hepatitis A	Zoonotic parasites and enteric viruses linked to raw/undercooked fish and sewage-contaminated shellfish remain significant seafood safety concerns.	(EFSA) BIOHAZ Panel et al., 2024; Ziarati et al., 2022

The convergence of these zoonotic threats with escalating antimicrobial resistance emphasizes the urgency of integrated One Health approaches, including strengthened surveillance, stewardship, and climate-informed monitoring systems. At farm and aquaculture levels, vaccination, biosecurity, and good husbandry reduce the need for antimicrobials. Prudent use, guided by diagnostics and stewardship programs, helps preserve drug efficacy. Whole genome sequencing is increasingly applied for outbreak tracing and resistance profiling, while climate-informed surveillance systems now provide early warnings for seafood-related risks such as *Vibrio* proliferation (European Food Safety Authority (EFSA) BIOHAZ Panel et al., 2024; Riedinger et al., 2024). Public awareness, farmer and veterinarian training, and consumer demand for antibiotic-free products provide additional incentives for responsible practices. At the policy level, strengthened regulation, investment in alternatives such as vaccines, probiotics, and phage therapy, and international collaboration through WHO, FAO, WOAH, and UNEP are critical. Emerging zoonoses and AMR in terrestrial and aquatic food systems thus represent converging threats driven by ecological change, intensification of production, and global trade. Their intertwined nature requires integrated prevention, stewardship, and surveillance to protect food safety, safeguard public health, and ensure the sustainability of animal-origin foods.

Recent global evaluations continue to demonstrate that zoonotic infections and antimicrobial resistance remain major challenges across food systems. World Health Organization (2025) highlights persistent resistance trends in priority human pathogens and notes substantial gaps in antimicrobial use and resistance reporting, particularly in low-resource regions. Complementing this, the World Organisation for Animal Health (2024) documents wide variation in antimicrobial use in animals among member countries and emphasizes that reporting capacity and data completeness remain uneven across regions. Environmental pathways are also increasingly recognized as critical components of the AMR cycle, with the United Nations Environment Programme (2023) specifying the role of wastewater, effluents, and agricultural runoff in the maintenance and spread of resistance determinants. These observations align closely with One Health Joint Plan of Action (2022–2026) given by the Food and Agriculture Organization of the United Nations, United Nations Environment Programme, World Health Organization, and World Organisation for Animal Health (2022) which reaffirms the necessity of integrated One Health strategies while acknowledging that implementation is constrained by disparities in laboratory infrastructure, surveillance capability, and regulatory coordination across sectors. Collectively, these up-to-date assessments confirm the relevance of One Health recommendations and highlight the need for strengthened surveillance architecture, harmonized reporting mechanisms, and targeted investments in institutional capacity to effectively mitigate AMR and zoonotic risks in terrestrial and aquatic food systems.

Risk assessment frameworks, predictive modelling, and early warning systems for food safety

Risk assessment framework: Food safety and risk assessment are fundamental pillars in the protection of public health. Food safety refers to the extent to which foods comply with established requirements to minimize risks of illness, while risk assessment is defined as the scientific evaluation of known or potential adverse health effects resulting from human exposure to food borne hazards (Benefo et al., 2022). Food safety and risk assessment encompass all stages of the food chain, from primary production to consumption, with the overarching objective of preventing foodborne diseases and promoting human health (European Food Safety Authority [EFSA], 2010; WHO, 2015).

Risk assessment in food safety consists of four key steps:

Hazard identification – Recognizing potential biological hazards (e.g., *Salmonella* in poultry, *Vibrio parahaemolyticus* in seafood, *Clostridium botulinum* in canned foods) that may cause illness.

Dose–response assessment – Establishing the relationship between the level of exposure and the likelihood/severity of adverse health effects, while accounting for differences in consumer susceptibility.

Exposure assessment – Estimating the extent of human exposure to hazards under various conditions (e.g., type of food, season, harvesting location) and considering how control measures alter exposure.

Risk characterization – Integrating the above steps into a quantitative estimate of the probability and impact of adverse effects in a population, while acknowledging uncertainties and data limitations, as well as potential economic and social implications (FAO, 2024; Foegeding, 1997).

Risk assessment and HACCP are often discussed together but serve different purposes. Risk assessment provides the scientific basis for risk management and communication, integrating science with public policy to evaluate product safety at the consumer end. In contrast, HACCP is a preventive, process-based system designed to identify and control hazards during food production and handling.

Although both begin with hazard identification, risk assessment focuses on estimating overall product risk, while HACCP ensures day-to-day process control. Risk assessment steps can inform HACCP criteria (e.g., allowable levels of microorganisms), but limiting risk assessment to this function overlooks its broader role. In practice, both approaches overlap within the wider framework of risk analysis, where HACCP is one management strategy and risk assessment evaluates the product under that strategy (Foegeding,1997).

Predictive modelling and smart technologies

Predictive modelling is a crucial tool in the food industry for assessing microbial behaviour and ensuring food safety throughout production. Microorganisms can contaminate food, leading to spoilage and health risks. Predictive microbiology studies microbial behaviour under various environmental conditions and mathematical models help evaluate shifts in microbial populations from harvesting to consumption. Tools such as Growth Predictor, DMfit, Seafood Spoilage Predictor, SOPHY, and GroPIN are used for predictive model for microbial growth, spoilage, and shelf life. Mathematical approaches include kinetic, probabilistic, empirical, and mechanistic models, supported by software like ComBase and PMP (Stavropoulou & Bezirtzoglou, 2019).

Emerging smart technologies further strengthen food safety. AI and machine learning enhance hazard prediction and quality assessment, IoT sensors enable real-time monitoring of storage and transport conditions, blockchain ensures transparent traceability, and big data analytics forecast risks using vast datasets (Abid et al., 2024). Digital twins optimize processes and predictive maintenance, reducing waste and extending shelf life.

Despite challenges-high costs, technical complexity, regulatory gaps, and environmental concerns these technologies improve transparency, efficiency, and consumer trust, offering transformative potential for safer and more sustainable food systems (Liberty et al., 2025).

Early warning system

Early warning (EW) systems are composed of mechanisms, processes, and networks that detect and validate potential signals, analyse related data, and deliver timely alerts to stakeholders to support informed risk management and decision-making. Their primary goal is to prevent and mitigate serious food safety emergencies across the entire food chain. To achieve this, countries must strengthen national EW capacities while linking them with regional and global alert networks.

Traditionally, EW systems have been reactive, identifying hazards only after contamination or illness occurs. However, there is a growing shift toward building predictive capacity, where broader signals and drivers of emerging risks are monitored to anticipate threats before they escalate. Effective EW systems therefore combine both predictive and reactive approaches to enhance preparedness, prevention, and strategic decision-making (FAO, 2015).

Modern EW systems leverage risk assessment, predictive models, and real-time data to identify emerging food safety threats. They integrate diverse data sources-including inspections, sensors, consumer complaints, and online platforms-and use AI-driven analysis to detect anomalies. Tools such as FSRvis support risk visualization, helping regulators quickly identify high-risk products and factors. Automated alerts enable rapid response when thresholds are exceeded, while systems like the EU's Rapid Alert System for Food and Feed (RASFF) facilitate swift cross-border communication (Sari et al., 2025). Additionally, advanced EW systems offer traceability and targeted control measures, allowing authorities to trace hazards to their source, prioritize surveillance, and reduce supervisory costs (Chen et al., 2023).

To function effectively at the national level, EW systems can be conceptualized around three sequential pillars (Fig. 5). Pillar 1 – Detection: Surveillance, inspections, horizon scanning, and intelligence tools to identify signals of food safety threats, supported by data-sharing platforms and databases. Pillar 2 – Verification: Validation of signals through trace-backs,

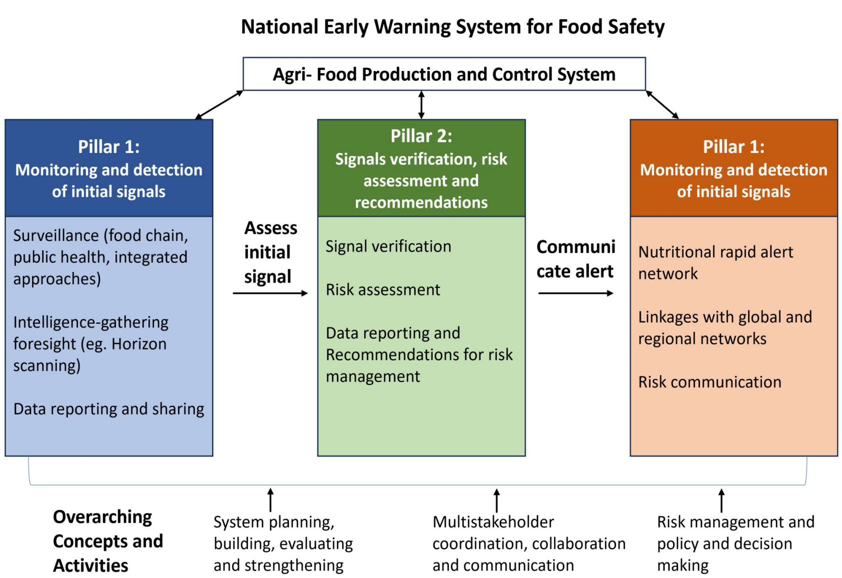

Fig. 5. Processes and functions of a national EW system for food safety

trace-forwards, and epidemiological investigations, combined with rapid risk assessment and management options. Pillar 3 – Communication: National rapid alert networks that coordinate EW activities and ensure timely dissemination of verified alerts to all stakeholders.

This integrated framework ensures that EW systems not only anticipate risks proactively but also respond effectively, strengthening national, regional, and global food safety preparedness (FAO, 2015).

Recent work from 2024-2025 shows that the usefulness of digital and predictive early-warning tools is determined largely by the quality, completeness, and consistency of the underlying data. Many current systems struggle with uneven data reporting, limited metadata, and fragmented information flows, which makes it difficult to validate models and limits their acceptance by regulators (Garcia-Vozmediano et al., 2024). For these tools to be trusted within national food-safety frameworks, they must be supported by transparent validation procedures, harmonised data standards, and laboratory verification mechanisms. Without such foundations, even advanced models face scepticism from regulators and risk managers (Elbehiry et al., 2025). Strengthening data governance and intersectoral coordination is therefore essential for digital and predictive approaches to function as reliable components of early-warning systems.

Factors contributing to risk

Growing demand: Rapid growth in consumption of animal-source foods driven by income gains, urbanization, and dietary change-has expanded animal inventories and accelerated shifts toward more intensive production systems. The OECD–FAO Outlook projects that emerging economies will drive most of the global increase in meat, dairy, and egg consumption to 2034, with total meat demand and animal herds rising in parallel; India is a major contributor to this trajectory. Such scale-up concentrates animals, movement, and waste, elevating opportunities for pathogen amplification and spillover (Organisation for Economic Co-operation and Development/Food and Agriculture Organization [OECD/FAO], 2025).

Informal markets: India's informal food economy remains critical for access and livelihoods, yet it often operates with weak infrastructure, limited cold-chain, and uneven regulatory oversight-conditions that heighten consumer exposure to microbiological and chemical hazards. Evidence from global LMIC assessments and India-focused analyses highlights that micro and small enterprises face capacity and incentive gaps for systematic food safety management, making hazards more likely to reach households through fresh meat, milk, and ready-to-eat foods (Jaffee & Henson, 2024).

Lack of regulation/oversight in IFAP: In South Asia, rapid expansion of intensive farm animal production (IFAP) has frequently outpaced regulatory capacity, with gaps in waste management, biosecurity, and surveillance linked to elevated zoonotic risks. Reviews and agency reports note that poorly regulated intensive systems can contaminate air and water with pathogens and residues, and that risk scales with high animal densities and movement unless countered by robust standards and enforcement (WellBeing International, 2013).

Mitigation strategies

Mitigating public-health risks from animal-origin foods in India demands a One Health operating model, hard regulatory controls, improved farming practices, etc. as detailed below:

One Health approach: Adopt an integrated One Health model that links human, animal and environmental health functions for joint risk assessment, shared data streams, and coordinated response to zoonoses and AMR. In India, the National One Health Mission (Office of the Principal Scientific Adviser/ICMR) and the NCDC Centre for One Health provide the institutional scaffolding, while the National Action Plan on AMR (2017–2021) operationalizes surveillance, stewardship, and intersectoral action across the farm-to-food continuum (Government of India & World Health Organization, 2017; Indian Council of Agricultural Research [ICAR], 2025; Indian Council of Medical Research [ICMR], 2025; Office of the Principal Scientific Adviser, Government of India, 2025).

Regulation and monitoring: Reduce chemical and microbiological hazards by enforcing residue limits and verified testing. Food Safety and Standards (Contaminants, Toxins and Residues) Regulations specify MRLs for pesticides and pharmacologically active substances, including default LOQ provisions, and are supported by notified analytical manuals for pesticide-residue testing (GC-MS/LC-MS, QuEChERS). These instruments enable risk-based market surveillance, compliance audits, and corrective action (Food Safety and Standards Authority of India [FSSAI], 2011).

Improving farming practices: Cut pathogen spread at source by tightening biosecurity and waste/effluent control in animal agriculture and processing. CPCB's *Environmental Guidelines for Poultry Farms* set siting, housekeeping, carcass/manure handling, and wastewater measures; sector compendia and directions for slaughterhouses/meat & seafood prescribe effluent standards and ETP operation (BOD/COD/TSS), reducing environmental contamination and cross-transmission along poultry and meat chains (Central Pollution Control Board, 2022).

Consumer awareness: Leverage demand-side programs that make safety visible and nudge better practices. FSSAI's Eat Right India platform (including the Hygiene Rating Scheme and Clean Street Food Hub guidance) uses public grading, certification, and toolkits for vendors and campuses, empowering consumers to choose safer outlets and incentivizing businesses to sustain hygiene, traceability, and FSMS compliance (FSSAI, 2020).

Conclusion

Animal-origin foods are consumed worldwide, yet the very systems that bring them to our plates also carry risks that cannot be ignored. Pathogens, chemical residues, resistant microbes, and natural toxins remind us that food safety is fragile and must be actively protected at every stage. The lesson from recent outbreaks and surveillance data is clear: hazards rarely act in isolation, and their impacts ripple across health, trade, and livelihoods. Addressing them requires more than laboratory tests or regulations alone, and it calls for practical changes on farms, careful stewardship of antibiotics, transparent supply chains, and the intelligent use of new tools such as genome sequencing and digital monitoring. Building capacity where it is most needed, sharing knowledge across borders, and engaging both producers and consumers will be essential. Ensuring safe animal-derived foods is ultimately about safeguarding trust in what we eat and securing the resilience of our food systems for the future. This also demands stronger institutional frameworks that can link veterinary services, public health agencies, and food-control systems in a coordinated manner. Clear policy commitments and sustained investment in these structures will determine how effectively countries can anticipate risks and protect consumers in the years ahead.

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