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GLOBAL FOODS - INNOVATIONS AND FUTURE PERSPECTIVES

Editor

Dr. Muhammad Imran

Associate Professor, Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan

Dr. Muhammad Kamran Khan

Associate Professor, Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan

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FOODBORNE ZOONOSES AND FOOD SAFETY SYSTEM AS PREVENTIVE STRATEGY

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REVIEW BASED BOOK CHAPTER

FOODBORNE ZOONOSES AND FOOD SAFETY SYSTEM AS PREVENTIVE STRATEGY

Georgeta Stefan[1]

[1]*Department of Infectious Diseases and Preventive Medicine, University of Agronomic Sciences and Veterinary Medicine, Faculty of Veterinary Medicine, Splaiul Independentei 105, Bucharest, Romania 050097 EU*

For Correspondence
georgeta.stefan@fmvb.usamv.ro

Abstract

Foodborne zoonoses constitute a significant public health concern worldwide, as they account for a substantial proportion of emerging and re-emerging infectious diseases. These diseases are predominantly result of transmission from animals to humans via the consumption of food products of both animal and non-animal origin that have been contaminated with pathogenic agents at different stages of the food production chain, including primary production, slaughtering, processing, and distribution. The implementation of a comprehensive food safety system is a mandatory requirement across all stages of the food production chain. Ensuring food safety relies predominantly on preventive, science-based methodologies that prioritize the application of good hygiene practices and the systematic integration of procedures based on the principles of Hazard Analysis and Critical Control Point (HACCP).

Keywords
Foodborne Diseases, Food Safety System, Hazard Analysis and Critical Control Point (HACCP), One Health

1. Introduction

1.1 Overview of foodborne zoonoses

The term "zoonosis" was introduced into scientific literature by Rudolf Virchow in 1880 to refer to diseases that affect both humans and animals. The World Health Organization (WHO) later provided an official definition in 1959, describing zoonoses as "those diseases and infections which are naturally transmitted between vertebrate animals and humans". Recent progress in human and veterinary medicine has revealed that many diseases previously thought to be species-specific possess zoonotic potential, meaning they can infect humans. Similarly, it has been shown that certain diseases that were traditionally thought to be unique to humans may have animal reservoirs, whether domestic or wild, that plays a vital role in maintaining and disseminating infectious agents within ecosystems.

Foodborne zoonoses represent a major public health concern worldwide, as they are responsible for a substantial proportion of foodborne illnesses and related morbidity and mortality. These are transmitted from animals to humans primarily through ingesting foodstuffs (animal or non-animal origin) that are contaminated by pathogenic microorganisms at various stages of the food production chain, such as farming, slaughtering, processing, distribution, domestic handling, etc. The etiology of foodborne zoonoses includes a broad spectrum of pathogens, notably bacterial agents such as *Salmonella spp*., *Campylobacter spp*., *Listeria monocytogenes*, *Escherichia coli O157:H7*; viruses such as *noroviruses*, *hepatitis E virus*; parasites including *Toxoplasma gondii*, *Trichinella spiralis* and prion agents responsible for transmissible spongiform encephalopathies (TSEs), namely the agent of bovine spongiform encephalopathy (BSE) in cattle and its zoonotic counterpart, variant Creutzfeldt–Jakob disease (vCJD) in humans.

The global burden of foodborne zoonotic diseases is exacerbated by the increasing globalization of the food trade, changes in production and consumption patterns, and the emergence of antimicrobial-resistant strains. Effective prevention and control therefore require a multidisciplinary "One Health" approach, integrating human, animal and environmental health perspectives to ensure food safety throughout the entire food chain [1, 2].

These diseases are highly relevant to public health due to their significant impact on population health, their often-severe course, multiple complications, and potential for fatal outcomes.

Given the significant socio-economic impact they can have on human society, the economic importance of zoonotic diseases should not be underestimated. At the same time, compromised animal health can lead to considerable economic losses due to reduced productivity.

It is estimated that 600 million people worldwide suffer from foodborne diseases each year, resulting in around 420,000 deaths. Children under 5 years old account for almost a third of these deaths [3]. Zoonotic pathogens are responsible for a significant proportion of these cases, posing an ongoing challenge to public health and food systems. The growing globalization of food supply chains, the intensification of livestock production and climate change further increase the risks associated with foodborne zoonoses [4, 5].

1.2. One Health approach in prevention and control of foodborne zoonoses

These diseases have many causes, so effective prevention strategies must be based on a food safety system that looks at all the risks. This system must include human, animal and environmental health sectors and be based on the One Health approach [6]. This approach emphasizes that human health is intimately connected to the health of animals and ecosystems. Since many foodborne zoonoses originate at the animal–environment interface, prevention requires coordinated surveillance, risk management, and communication across sectors [7].

The One Health concept is reflected in the statement of William Karesh, which highlights the intrinsic interdependence between human health, animal health and the health of ecosystems. According to this approach, health cannot be understood or managed in isolation because biological and social systems are interconnected through interconnected factors such as globalization, environmental decline and climate change [8]. In a world that is becoming increasingly interconnected, with people, animals and wildlife all interacting more closely, One Health approach has become crucial for prevention and control of emerging and re-emerging diseases, particularly zoonoses. International organizations such as the World Health Organization (WHO), the World Organization for Animal Health (WOAH, formerly the OIE) and the Food and Agriculture Organization of the United Nations (FAO) jointly promote this integrated approach as a key strategy for strengthening global health security, food safety and environmental sustainability [9].

Veterinary public health has faced significant challenges in recent decades due to a marked increase in the risk of infection affecting both human and animal populations. Numerous factors can be identified as determinants in epidemiology of foodborne zoonoses, shaping the complex dynamics of pathogen–host interactions. Among these, ecological and climatic changes, increased mobility of human and animal populations, the intensification of international trade, and uncontrolled urbanization play particularly significant roles [8, 10]. Moreover, alterations in agricultural and food production practices, coupled with an insufficient epidemiological surveillance system, further contribute to the persistence and dissemination of zoonotic pathogens. Furthermore, ecological balances have been disrupted by human-induced environmental changes, such as deforestation, habitat fragmentation and agricultural expansion, thereby facilitating closer interactions between wildlife, domestic animals and human populations [11].

The evolution of contemporary society, marked by globalization, rapid urbanization, and profound changes in consumption behavior, has led to a significant increase in the risk of foodstuffs contamination and foodborne infections. Transformations in food production, processing, and distribution, together with the expansion of international trade, have facilitated both the emergence and the rapid spread of foodborne pathogens on a global scale. An analysis of recent cases and outbreaks indicates that the main vulnerabilities within the food chain are associated with inadequate hygiene during food processing, improper storage temperatures, incorrect handling practices, and insufficient consumer awareness regarding safe food practices.

Foodborne pathogens such as *Listeria monocytogenes*, *Salmonella spp.*, *Escherichia coli*, and *Campylobacter spp.* continue to pose serious threats to public health, with significant repercussions not only for human populations but also for the livestock and agri-food sectors.

Over the past two decades, numerous foodborne outbreaks have been reported worldwide, caused by the contamination of foodstuffs (animal- and non-animal origin) with various pathogenic agents. These public health incidents highlight the persistent vulnerabilities within the food chain and emphasize the critical importance of strict compliance with hygiene and food safety regulations throughout all stages of production, processing, distribution, and consumption [12, 13]. Foodborne pathogens such as *L. monocytogenes*, *Salmonella spp.*, *Escherichia coli* O157:H7, and *Campylobacter spp.* continue to represent major threats to public health in Europe and globally.

Infections caused by *Salmonella* spp., especially serovars *S. typhimurium*, *S. enteritidis*, *S. infantum*, remain among the most frequent causes of foodborne illness worldwide [14]. The incident occurred in 2022 when several European countries, including Finland, reported outbreaks of *S. enterica* serovar *typhimurium* associated to chocolate products manufactured in Belgium. Epidemiological investigations confirmed that contamination occurred during production flow [15].

Listeriosis outbreaks caused by *L. monocytogenes* are a major concern, given that this foodborne agent can multiply in refrigerated products at low temperatures. In 2018, Europe confronted a significant listeriosis outbreak associated with the consumption of frozen corn manufactured in Hungary. This outbreak impacted several EU Member States and resulted in the removal of a substantial quantity of products from the market [16, 17]. The risks associated with microbiological contamination in globalised food production chains were illustrated by this incident, which also emphasised the need for effective control measures during processing and distribution.

Campylobacter spp., another major foodborne agent, is responsible for campylobacteriosis, the most reported zoonosis in the European Union. Transmission typically occurs through the consumption of undercooked poultry meat or contaminated water [18].

Outbreaks associated with *Shiga toxin–producing Escherichia coli (STEC) O157:H7* have often been linked to the consumption of undercooked minced meat, raw milk, or contaminated vegetables during handling. These infections can result in severe complications such as hemolytic uremic syndrome, particularly affecting children and the elderly.

The analysis of recent outbreaks demonstrates the necessity of strengthening official control systems, ensuring continuous monitoring of the food chain, and promoting effective collaboration among national and international competent authorities. The prevention of future outbreaks requires comprehensive food safety systems, continuous surveillance, and effective international cooperation. Public awareness and education remain indispensable in ensuring that consumers play an active role in maintaining food safety across the entire supply chain.

3. Food Safety system – preventive strategies of foodborne zoonoses

3.1. Overview of food safety system

Food safety represents a fundamental strategic objective of modern society, aiming to protect public health by ensuring the quality and safety of food products.

Ensuring food safety is a strategic and multidimensional objective that requires the coordinated efforts of public authorities, stakeholders in the food production chain and consumers. Grounded in scientific principles, collective responsibility and preventive measures, it aims to protect public health and ensure continuous access to safe, high-quality food. In a global context characterized by population growth, climate change and intensified international trade, ensuring food safety has become a public policy priority with direct implications for economic and social sustainability.

A globally coordinated approach based on cooperation, transparency, and the exchange of information among states is required to deal with contemporary challenges. These include supply chain volatility, the emergence of new pathogens, pressure on natural resources, and rapid technological change in the food industry. Strengthening the resilience of food systems, diversifying supply sources and integrating sustainability principles are therefore essential for ensuring long-term food security and safety.

At the international level, several frameworks and regulatory bodies establish harmonized food safety standards that guide national legislation and industry practices. The Codex Alimentarius Commission, established jointly by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO), provides a globally recognized set of food standards, codes of practice, and guidelines that underpin modern food safety systems. These standards promote consistency in food production and trade while safeguarding consumer health.

In the European Union, food safety is regulated under the General Food Law (Regulation EC No 178/2002), which emphasizes the “farm-to-fork” approach, mandating traceability and preventive controls across the entire supply chain. The food hygiene regulations—such as Regulation (EC) No 852/2004 on the hygiene of foodstuffs—mandate the application of GMP, SSOP, and Hazard Analysis and Critical Control Points (HACCP) systems to ensure the safety and traceability of food products.

The European Food Safety Authority (EFSA) is responsible for providing scientific expertise at the European level. This expertise supports decision-making processes, helps to harmonize standards across Member States and strengthens consumer confidence in the European single market.

In the United States, the Food and Drug Administration (FDA) enforces GMP requirements under 21 CFR Part 117, while the US Department of Agriculture (USDA) oversees SSOP compliance in meat and poultry processing. The Food Safety Modernization Act (FSMA) highlights the preventive controls and risk-based approaches across the supply chain.

Together, these frameworks reflect a globally coordinated effort to enhance food safety governance, promote best practices, and facilitate international trade in safe and high-quality food products.

The food safety framework transcends national barriers and is a global public benefit and a key part of the international governance of health, trade and sustainable development. It reflects the deep interconnection between economic security, environmental protection and the fundamental human right to have access to safe and adequate food.

A preventive food safety system operates throughout the entire food chain, incorporating proactive measures to identify and control hazards before they reach consumers. According to Regulation (EC) No 178/2002, food safety is based on the principle of "from farm to fork," which implies the application of rigorous and coherent control throughout the entire food chain. This guarantees the full traceability of agri-food products and ensures that biological, chemical and technological hazards are systematically monitored.

Food safety regulations are designed to ensure that food products reaching consumers are safe, wholesome, and of consistent quality. Within this regulatory framework, Good Agricultural and Animal Husbandry Practices (GAP), Good Manufacturing Practices (GMP), Sanitation Standard Operating Procedures (SSOP), Hazard Analysis and Critical Control Points (HACCP) serve as critical components for achieving and maintaining compliance.

At the primary production level, applying GAP alongside comprehensive biosecurity measures is essential for ensuring animal health and maintaining food safety. The aim of these measures is to prevent the introduction, establishment and dissemination of pathogenic agents within food-producing animal populations. Effective risk mitigation is achieved through stringent feed management, the provision of clean and potable water, proper waste handling and disposal, and the systematic control of vectors and environmental reservoirs. These actions reduce the likelihood of contamination and help to produce safe, high-quality animal origin food products [19]. Prudent and responsible use of antimicrobials in food-producing animals is essential to minimize the emergence and spread of antimicrobial resistance in zoonotic bacterial pathogen. The inappropriate use of antimicrobials in livestock production can lead to the development of resistant bacterial strains that can be transmitted to humans through direct contact, the food chain or the environment. Therefore, implementing antimicrobial usage monitoring programs and adhering to veterinary prescription guidelines are critical components of sustainable food animal production and public health protection [20].

During food processing, storage and handling stages, GMP and SSOP ensure hygienic conditions during slaughtering, processing, etc. GMP provides the general principles and operational guidelines necessary to control environmental conditions, personnel hygiene, and equipment maintenance in food production facilities. Complementing this, SSOP outlines detailed sanitation procedures that must be routinely followed to prevent contamination during slaughtering, processing, packaging, storage, distribution. The integration of GMP and SSOP minimizes the risk of cross-contamination, supports microbial control, and upholds product integrity throughout the production chain. Moreover, these practices facilitate effective traceability systems, enabling swift identification and withdrawal of contaminated products when necessary. Overall, adherence to GMP and SSOP not only fulfills legal and regulatory obligations but also strengthens consumer confidence and promotes public health protection [21].

The Hazard Analysis and Critical Control Points (HACCP) system is a preventive approach to food safety system. It identifies, assesses and controls hazards throughout the food production process, ensuring food safety and preventing foodborne zoonoses. The nature of preventive system shifts the focus from end-product testing to systematic hazard control [22]. The food safety system is based on seven fundamental principles: conducting hazard analysis; identifying critical control points (CCPs); setting critical limits; establishing monitoring procedures; defining corrective actions; verifying the system's effectiveness; and maintaining detailed records [23].

The HACCP principles guide food producers in identifying points in the production process where hazards — biological, chemical, or physical — are most likely to occur and where control measures can effectively prevent or reduce them.

The foundation of food safety system is to integrate the GMP and SSOP with the HACCP system. GMP and SSOP provide the fundamental conditions for maintaining a hygienic production environment, but HACCP introduces a systematic, science-based methodology for identifying, evaluating, and controlling specific hazards that pose risks to food safety. GMP and SSOP serve as prerequisite programs on which the HACCP plan is built, ensuring that baseline sanitary and operational conditions are met before critical control points are established [24].This integrated approach enhances the effectiveness of hazard prevention, supports continuous monitoring and ensures compliance with national and international regulatory requirements. Overall, the combined implementation of GMP, SSOP and HACCP establishes a thorough food safety assurance framework that protects public health and encourages sustainable practices within the food industry.

HACCP system provides a comprehensive and proactive approach to protect public health by preventing foodborne zoonoses. Through the identification and control of critical points in food production and handling, HACCP ensures that foods of animal origin are safe for consumption. Its preventive, science-based nature makes it an indispensable tool in modern food safety system and an essential strategy in the global effort to reduce the burden of zoonotic diseases.

Zoonotic foodborne pathogens such as *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, *E. coli* O157, *Brucella* spp. can be found in raw or undercooked meat, poultry, dairy products and ready-to-eat foods. Improper handling, insufficient heat treatment, post-heat treatment contamination and improper refrigeration or storage facilitates their survival and transmission through human consumption. Implementing HACCP not only reduces the incidence of foodborne zoonoses but also enhances consumer confidence, supports regulatory compliance, and facilitates international trade. Regulatory frameworks, such as the European Union Regulation (EC) No 852/2004 on the hygiene of foodstuffs, require food businesses to apply HACCP-based systems.

Efficient food safety system, based on HACCP principles, must be implemented throughout the entire food chain to control foodborne zoonoses and ensure public health protection and requires rigorous regulatory monitoring and international collaboration. It is imperative that a sustained commitment to surveillance, education, and international collaboration is maintained to mitigate the risks associated with zoonotic pathogens. At the European level, the responsibility for surveillance, risk assessment, monitoring trends and investigating outbreaks lies with the European Food Safety Authority (EFSA) and its national counterparts.

As food systems continue to evolve on a global scale, a preventive, integrated approach to food safety system is key to protecting both human and animal health.

3.2. Preventive strategies against *Salmonella* spp. infection

Salmonella spp., as foodborne pathogen, is a major concern among the biological hazards controlled through HACCP due to its association with foodborne illness, specifically salmonellosis. The HACCP system shall be designed to prevent or eliminate contamination by *Salmonella* spp. at critical points in the food production process. A systematic evaluation of the production process is used to identify potential sources of Salmonella contamination. Common hazards include handling raw poultry, cross-contamination during processing, cooking temperatures that are too low and storing food at the wrong temperature.

Human salmonellosis, one of the most prevalent foodborne diseases worldwide, is commonly transmitted through the consumption of contaminated food products, such as raw or undercooked eggs, poultry, meat, unpasteurized dairy products, and contaminated foodstuffs (as results as cross-contamination, usually) [25]. The typical clinical presentation includes symptoms such as diarrhea, fever and abdominal cramps, which emerge within 6–72 hours of infection) [26]. Severe cases can lead to dehydration and invasive infections, especially in young children, the elderly and immunocompromised individuals.

Animal health monitoring, biosecurity and feed hygiene are some of the preventive measures in place at the primary production level to limit contamination by *Salmonella* spp.

At food industry level, implementing a food safety system based on HACCP principles is essential for preventing salmonellosis, as it controls *Salmonella* spp. contamination throughout the food supply chain. The critical control points, such as proper heat treatments (cooking, pasteurization), GHP, temperature monitoring during cooling, refrigeration storage, distribution, are key in mitigating the risk of infection. For instance, achieving an internal cooking temperature of at least 75°C for poultry meat has been proven effective in eliminating *Salmonella* spp. [27]. The effectiveness of preventive measures is ensured by monitoring and verification processes, combined with thorough record-keeping.

The effective implementation of HACCP in food industries, especially in the processing of poultry and dairy, has been shown to lead to a significant decrease in the prevalence of Salmonella and the number of salmonellosis outbreaks.

Reducing the incidence of salmonellosis requires public education and consumer awareness about safe food handling at home. Educating consumers about proper hygiene, cooking temperatures and food storage practices can help prevent bacterial contamination and growth at the household level. The importance of avoiding high-risk behaviors, such as consuming raw or undercooked animal products, can be reinforced by awareness campaigns and community outreach programs, and adherence to food safety guidelines can be encouraged. The encouragement of informed choice-making and responsible food handling at home is a significant means of interrupting the transmission chain of *Salmonella* spp. and reducing the overall public health burden of foodborne diseases.

3.3. Preventive strategies against *Campylobacter* spp. infection

Campylobacteriosis, an infection caused by Campylobacter spp., is a globally distributed zoonosis with significant public health implications and a considerable socio-economic impact. Infections caused by *Campylobacter* spp., particularly the *C. jejuni* and *C. coli* species, are among the most common bacterial causes of gastroenteritis in humans. They remain a significant public health concern worldwide and are closely linked to food hygiene practices and sanitary and veterinary control systems within the food industry.

Campylobacteriosis is typically associated with the consumption of contaminated poultry, unpasteurized milk, and untreated water. Asymptomatic carriers of these bacteria, chickens are the main natural reservoir. Food contamination usually occurs during the slaughtering and processing of poultry meat, when the bacteria can be transferred from the gut surface to the carcass. At the European level, chickens and poultry meat were identified as the primary source of infection in 20-30% of human campylobacteriosis cases reported.

The presence of *Campylobacter* spp. in various foodstuffs, particularly poultry meat and meat products, can be reduced by implementing preventive and control measures throughout the food processing chain. Early detection of *Campylobacter* spp. in chicken flocks and carcasses is facilitated by regular monitoring and testing. The Member States of the European Union mandate routine *Campylobacter* spp. monitoring in broiler flocks to track contamination levels [28].

An integrated, multi-sectoral approach is required to reduce the global burden of campylobacteriosis. Effective preventive strategies begin with strict biosecurity measures on farms, continue with hygienic food processing and require significant consumer education and public health regulation. The most effective way to mitigate the risk of *Campylobacter* spp. infection and ensure safer food systems worldwide is through a coordinated effort across the agricultural, food safety and health sectors, supported by surveillance and One Health approach.

At farm level, biosecurity measures are essential for preventing and controlling *Campylobacter* spp., particularly in poultry. The implementation of rigorous biosecurity programs on farms can prove to be an effective strategy for the substantial reduction of bacterial introduction and dissemination. Effective measures that can be taken at farm level include restricting access to poultry houses, wearing protective clothing, controlling the access of vehicles and equipment, supplying clean, uncontaminated water and feed, applying the all-in/all-out principle, cleaning regularly and preventing contact between poultry and wild birds [28, 29]. Research into biological therapy, such as probiotics, bacteriophages and vaccination, is currently ongoing. Although these methods show potential in decreasing the presence of *Campylobacter* spp. in the intestines of poultry, their large-scale application is restricted due to their inconsistent effectiveness [30]. However, the most effective way to minimize bacterial introduction into the food chain is to combine these approaches with strict farm hygiene.

In accordance with HACCP principles, potential sources of contamination must be identified and controlled at the slaughtering and processing stages. To mitigate the proliferation of Campylobacter spp., rigorous cleaning and sanitation procedures must be implemented, strict physical segregation must be maintained between clean and dirty zones, and carcasses must be chilled rapidly to temperatures below 4 °C [31].

Preventive measures in foodstuffs handling and consumption at home are important to reduce household transmission of *Campylobacter* spp. that are most often linked to inadequate storage and preparation of poultry products. *C. jejuni* and *C. coli* are effectively eliminated at an internal temperature of at least 74 °C in poultry meat, provided that adequate time–temperature exposure is achieved to ensure uniform heat distribution throughout the product [32]. Public education campaigns that highlight the importance of safe food handling practices have been shown to significantly reduce the risk of *Campylobacter* spp. being transmitted through consumption.

3.4. Preventive strategies against *Listeria monocytogenes* infection

Listeriosis is a zoonosis that has shown a significant increase in prevalence over the past two decades, which coincides with global socio-economic development and changes in food production and consumption patterns. The human infection is most associated with consumption of contaminated food products, particularly ready-to-eat foods.

L. monocytogenes is currently recognized as a major zoonotic pathogen primarily transmitted through the consumption of contaminated food products. It poses a significant threat to food safety and public health due to its ability to cause listeriosis, a severe invasive infection, particularly in vulnerable populations such as pregnant women, newborns, and the elderly and immunocompromised individuals.

Outbreaks of listeriosis have often been linked to various ready-to-eat foods, such as dairy products, meat, seafood and fresh produce. This highlights the widespread occurrence of the pathogen and its ability to persist in food processing environments.

Unlike most foodborne pathogens, *L. monocytogenes* due to its psychrotrophic nature and capacity to survive under refrigeration conditions, in high salt concentrations, in moderate acidity pH and adhere to food contact surfaces , is particularly challenging to control in food processing environments [33, 34]. Effective prevention requires a systematic food safety system focused on risk assessment and control throughout the food chain

Its persistence in food-processing facilities often results in recurring contamination and product recalls, requiring the implementation of strict microbiological criteria and monitoring procedures.

L. monocytogenes, being considered a high-risk microbiological hazard, the regulatory bodies - the European Food Safety Authority, U.S. Food and Drug Administration have established specific microbiological criteria and regular surveillance and testing of ready-to-eat (RTE) foods to ensure compliance with food safety standards and to mitigate public health risks. At the level of EU Member States, Regulation (EC) No 2073/2005 sets out specific limits for L. monocytogenes in ready-to-eat foods. International organizations, such as the World Health Organization and the Codex Alimentarius Commission, emphasize a risk-based approach to controlling it. Ensuring compliance with these standards requires the integration of hazard analysis, preventive controls, and continuous environmental monitoring within food safety systems, reinforcing *L. monocytogenes* as one of the most critical pathogens addressed in modern food safety regulation.

A thorough understanding of ecology, virulence mechanisms, and resistance to environmental stress is essential to develop effective monitoring and mitigation strategies that ensure food safety and protect public health.

Preventive strategies against Listeria monocytogenes infection focus primarily on strict food safety and hygiene measures throughout the entire production process. GMP and HACCP are essential to reduce risk of *L. monocytogenes* contamination in the food industry. Key measures include maintaining hygienic processing environments, controlling temperature (below 4 °C), preventing cross-contamination and regularly cleaning and disinfecting equipment and surfaces [35]. The continuous monitoring of the environment for Listeria in processing facilities, combined with the use of pasteurized ingredients and formulation controls such as adjusting the pH level and water activity, helps to limit bacterial growth [36].

At the consumer level, prevention involves practicing safe food handling, ensuring proper refrigeration and avoiding high-risk foods, such as unpasteurized dairy products and ready-to-eat refrigerated meats. Particular care should be taken by vulnerable groups, such as pregnant women, the elderly and immunocompromised individuals [37].

Reducing the incidence of *L. monocytogenes* infections and protecting public health requires a comprehensive, multi-level approach integrating HACCP principles, GMPs, and rigorous environmental and regulatory controls. Ongoing verification, staff training, and consumer awareness remain vital to sustaining food safety and protecting public health.

3.5. Preventive strategies against *Escherichia coli* O157 infection

Escherichia coli O157 infections represent a significant public health concern as a major cause of foodborne illness worldwide. This pathogen belongs to the group of Shiga toxin–producing *E. coli* (STEC) strains and is characterized by its ability to produce potent cytotoxins known as Shiga toxins (Stx1 and Stx2). It's one of the most serious forms of *E. coli* infection and can lead to severe gastrointestinal disease and life-threatening complications (hemolytic uremic syndrome). Although the incidence of infection is low compared to other enteric pathogens, such as *Campylobacter* spp., *Salmonella* spp., *E.coli* O157 illnesses tend to be more severe and have a higher mortality rate.

Transmission occurs primarily through the ingestion of contaminated food or water. Due to its low infectious dose and potential for severe outcomes, *E. coli* O157 continues to represent a major priority for food safety monitoring and public health interventions.

The intestinal tract of healthy cattle is populated by *E.coli* O157, with particular colonization in the recto-anal junction. Contamination of meat, dairy products and the external environment occur during slaughtering, milking and manure handling.

The prevention of *E. coli* O157 infection depends on the integration of food safety, environmental control, personal hygiene, and public health interventions. Sustained public health efforts and intersectoral collaboration between the food industry, environmental agencies, and healthcare systems are essential to mitigate infection risk and reduce the incidence of severe complications.

In livestock segment, with its focus on cattle, implementation of safe management of animal manure, prevention of fecal contamination of water sources can minimize the risk of contamination. The study by Matthews et al. highlights the usefulness of vaccinating cattle and using probiotic feed additives in reducing bacterial shedding [38].

Outbreaks are particularly prevalent in rural and developing regions due to contamination of water sources through pollution or inadequate sanitation. Access to a microbiologically safe source of drinking water is one of the fundamental measures to prevent the transmission of this infection to humans. This source must be available for both humans and animals. Regular microbiological monitoring of public water systems, alongside the proper management of livestock waste, can help to reduce the risk of contamination [39].

The undercooked ground beef and beef meat products represent potential sources of *E. coli* O157 responsible for human infections. GHP and GMP are fundamental to preventing the contamination of carcasses and meat products during the slaughtering and processing stages, respectively. The effective heat treatment of meat to an internal temperature of at least 70°C ensures the inactivation of bacteria [40].

The consumption of unpasteurized milk, cheese and various fruit juices is associated with a significant risk of *E. coli* O157 infection. The pasteurization process and cold-chain management procedures are compulsory in order to prevent outbreaks.

Contaminated irrigation water or contacts with animal manure are potential contamination sources of fresh fruits and vegetables. Avoiding untreated manure as fertilizer and maintaining hygienic harvesting and packaging conditions are recommended as preventive measures [41].

Public education and awareness are essential for preventing E. coli infections. This involves emphasizing the importance of safe food handling and avoiding the consumption of products of animal origin that are not cooked.

3.6. Preventive strategies against *Brucella* spp. infection

Brucellosis is an infectious and contagious zoonotic disease affecting humans and a wide range of domestic and wild animal species. It is caused by various species of the genus Brucella, Gram-negative, non-motile, aerobic, non-spore-forming bacteria with a marked tropism for the reticuloendothelial system and the reproductive organs.

Human brucellosis is principally attributed by four species of the genus Brucella, which have distinct host specificities, geographic distributions and pathogenic potentials. The main causative agents are *B. abortus*, which predominantly infects cattle; *B. melitensis*, which is commonly found in sheep and goats; *B. suis*, which is primarily present in pigs; and *B. canis*, which infects dogs [42, 43]. Of these species, *B. melitensis* is considered the most virulent and is the main cause of human brucellosis worldwide, particularly in regions where small ruminant husbandry is practiced [44]. The four *Brucella* species pose a significant threat to public and animal health worldwide.

Human infection occurs through direct contact with infected animals or their secretions, the ingestion of unpasteurized dairy products or the inhalation of contaminated aerosols [45]. The clinical manifestations of the disease can vary from acute febrile illness to chronic multisystem infection, as result of intracellular persistence of *Brucella* spp. and its capacity to evade host immune responses.

Despite being recognized since ancient times and first described by Hippocrates around 450 BC, brucellosis continues to pose a significant global public health challenge [46]. In many regions, human brucellosis remains classified as an emerging or re-emerging zoonotic disease, reflecting its persistent prevalence and the ongoing difficulties in its control and eradication. Over the past decade, the epidemiology of human brucellosis — the most common zoonotic infection worldwide — has changed significantly due to sanitary, socio-economic and political factors, as well as the increasing frequency of international travel, as reported by the World Health Organization. The highest prevalence of human brucellosis is currently reported in Africa, Asia, Latin America and the Middle East. In contrast, the incidence has markedly decreased in developed countries as a result of effective veterinary control programmes and the widespread pasteurization of dairy products [47].

The World Health Organization has identified it as one of seven neglected zoonotic diseases. The endemic nature of this infection poses significant challenges to the effective implementation of prevention and control measures, particularly in low-income and developing countries. The associated costs of epidemiological surveillance, diagnostic testing and treatment are often too high for these interventions to be feasible in countries with limited resources [48-50]. The main factors hindering the implementation of effective prevention and control measures are inadequate veterinary and public health infrastructure, ineffective regulation of livestock trade and dairy production, and a low level of health awareness among livestock farming communities [51]. A large proportion of cases therefore remain undiagnosed, reported incidence rates are underestimated, and preventive strategies fail to have a meaningful impact on socioeconomically disadvantaged populations. The long-term endemicity of the disease in low- and middle-income countries is due to factors such as raw-milk consumption, ineffective slaughter practices, extensive animal husbandry, and budgetary limitations [48].

To achieve a sustainable reduction in the burden of brucellosis, a multisectoral strategy is required that integrates animal health programmes (e.g. vaccination, slaughter of infected animals, movement control), human health surveillance and diagnostics, community education (especially regarding the consumption of raw milk), and financial mechanisms to support farmers (e.g. compensation for livestock culled due to the disease). Studies have emphasized the importance of the One Health approach in enabling effective control in endemic areas but implementing it in contexts with limited resources remains challenging [48, 52, 53]. Effective preventive measures include animal health and food safety system, public health surveillance and awareness of the human population [47].

The fundamental principle underlying the prevention of *Brucellosis* is the implementation of infection control measures in the animals that act as reservoirs for the disease. Prevention measures such as immunoprofilactic programmes against *B. abortus* (strains 19 and RB51) infection in cattle and *B. melitensis* (strain Rev1) infection in small ruminants can significantly reduce the spread of *Brucella* spp. infection in susceptible animal populations and the risk of transmission to humans [45]. Surveillance of animal health measures, such as regular serological examinations (e.g. agglutination tests) of susceptible species, rigorous identification and control of animals, and the culling of infected animals, contribute to preventing the spread of infection and reducing its prevalence in a herd. Implementing measures for the proper disposal and destruction of placentas, aborted foetuses, and uterine secretions from females undergoing abortion, as well as materials used in obstetric manoeuvres, is a highly effective way of reducing the transmission of infection [54].

The consumption of raw milk and cheeses made from unpasteurized milk poses a considerable epidemiological risk to human health. Many outbreaks of human brucellosis in the Mediterranean Basin region occur as a result of consuming artisanal or traditional cheeses made from raw goat or sheep milk [55]. According to the European Food Safety Authority, consumption of raw dairy products is one of the main ways that Brucella is transmitted to humans in endemic regions [56]. To minimize the risk of human infection via contaminated food sources, milk from cows, goats, and sheep should undergo pasteurization prior to consumption. In endemic areas, the exclusive use of pasteurized milk for cheese production is public health goal, to prevent the transmission of *Brucella* species through food. The milk pasteurization performed at 63 °C for 30 minutes or 72 °C for 15 seconds, in accordance with Codex Alimentarius recommendation, has am efficient bactericidal action and has been proven to destroy *Brucella* spp. in contaminated milk [57, 58].

Routine pasteurization of milk and regular animal health monitoring by veterinarians are two of the most important components of integrated strategies to prevent human brucellosis, as both are useful in breaking the cycle of *Brucella* transmission from animals to humans.

To achieve sustainable control and eventual eradication, coordinated efforts between veterinary and public health authorities within the One Health framework are essential.

4. Surveillance and monitoring of foodborne zoonoses

Foodborne zoonoses pose a significant threat to global public health and require surveillance and monitoring programmes to enable early detection, source tracing and control measures. The study of the occurrence and spread of foodborne zoonoses is complicated by the fact that there are multiple potential sources of infection, including livestock and wildlife. Contamination can also occur along the food chain, and environmental and human behavioral factors can also play a significant role [59].

There are currently multiple challenges at an international level that require a new approach to the surveillance of these foodborne zoonoses, with a particular focus on integrated One Health strategies. The integrated surveillance of food borne pathogens in humans, animals and foodstuffs enables early detection and rapid response to outbreaks of zoonoses. Technological advancements such as whole-genome sequencing have enhanced the ability to attribute sources and investigate outbreaks [60]. The predictive capacity of national surveillance systems is strengthened by using data from different sectors together under the One Health initiative [61].

The surveillance of foodborne zoonotic diseases is a critical component of food safety and public health programmes. The surveillance and monitoring systems ensure understanding the evolving epidemiology of these diseases and improve the capacity of response to outbreaks and provide information for prevention strategies.

The purpose of surveillance is to detect emerging and re-emerging zoonotic foodborne pathogens at an early stage, enabling prompt intervention to prevent their widespread transmission.

Monitoring trends in the incidence and prevalence of zoonotic foodborne agents and antimicrobial resistance patterns provides valuable epidemiological data on foodborne zoonoses [62]. Identifying sources and transmission pathways is facilitated by surveillance data. Based on this, the identification of animal reservoirs and critical control points throughout the food chain can be improved, allowing specific mitigation measures to be applied. Furthermore, surveillance systems are useful in risk assessment based on evidence of pathogen occurrence, exposure levels and disease burden.

A variety of interconnected sectors and authorities need to work together to effectively monitor foodborne zoonoses.

World Health Organization supports the surveillance of foodborne zoonoses through Global Foodborne Infections Network (GFN) and the International Food Safety Authorities Network (INFOSAN). These networks strengthen laboratory capacity, enhance data sharing, and facilitate timely communication during foodborne disease outbreaks. Through collaborative international efforts, they promote standardized surveillance and rapid response coordination across countries [63]. The focus of human health surveillance is monitoring of foodborne zoonoses outbreaks through clinical laboratories, hospital data and national notification systems.

World Organization for Animal Health (WOAH/formerly OIE) collects and manages global animal health information and requires the reporting of zoonotic diseases in animals. The monitoring of zoonotic foodborne pathogens in farm animals, wildlife and pets is the responsibility of veterinary services as part of animal health surveillance.

In Europe, the European Food Safety Authority (EFSA) and the European Centre for Disease Prevention and Control (ECDC) release annual "One Health Zoonoses" reports, in which data on zoonotic agents in humans, animals and food is covered. For instance, *campylobacteriosis* and *salmonellosis* were the most frequently reported zoonoses in humans in 2023.

As part of the food industry, the monitoring of the food chain involves the regular sampling of foodstuffs (of animal and non-animal origin) for the detection of foodborne zoonotic pathogens, in accordance with regulatory provisions and food safety programmes.

Monitoring antimicrobial resistance effectively as part of animal and public health surveillance is essential to understanding how antimicrobial use in animal production affects the spread of resistant zoonotic bacteria. Potential transmission routes are identified through environmental surveillance, which involves examining the processing environment, as well as the water, feed and surfaces for contamination.

The WHO Global Strategy for Food Safety (2022–2030) sets out a risk-based approach to national food control systems, prioritizing prevention, inclusive practices, and sustainability [64, 65].

Enhanced surveillance will enable earlier detection and intervention; support the development of effective preventive strategies and contributing to effective food safety systems and healthier animal and human populations.

5. Conclusions

Foodborne zoonoses continue to pose a significant threat to global health, food security and economic stability. It is crucial to establish a preventive, science-based food safety system anchored in the One Health approach to minimize these risks. Surveillance, biosecurity and food safety systems integrated with effective governance mechanisms enable early intervention and food pathogen risk control across the food chain. The long-term resilience of these systems depends on political commitment, collaboration across different sectors, and ongoing capacity building.

Several challenges to food safety system are still present even though there have been significant advancements in this area. The increase in the global food trade poses a greater risk of the transboundary transmission of zoonotic agents. Implementing a preventive food safety system can be challenging, especially in low- and middle-income countries, and small-scale food producers due to financial or technical constraints.

The emergence of antimicrobial resistance in foodborne pathogens poses an additional threat, complicating treatment and control efforts.

Furthermore, climate change is affecting the survival and distribution of pathogens, presenting new challenges to food safety authorities.

An effective food safety system is essential to reduce the incidence and impact of foodborne zoonoses. The HACCP principle, along with good agricultural, good animal welfare, farm biosecurity, good hygienic and good manufacturing practices, provides the basis for effective food safety management, highlighting risk assessment, foodborne hazards prevention and continuous monitoring across the entire food chain.

Conflicts of interest

The authors declare no conflict of interest.

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