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# Mitigating Foodborne Diseases in Developing Countries: Integrating Farm-to-Fork Strategies, Climate Adaptation, and Community Interventions for Enhanced Public Health

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## ABSTRACT

Foodborne diseases remain a significant public health concern in developing countries, including Nigeria, where infrastructural limitations, weak regulatory enforcement, and climatic variability exacerbate risks. This review focuses on integrating farm-to-fork strategies, climate adaptation, and community interventions to mitigate foodborne diseases. Principal approaches include adopting Good Agricultural Practices (GAP), Good Manufacturing Practices (GMP), and Hazard Analysis and Critical Control Points (HACCP), which collectively reduce contamination from production to consumption. Strong policy frameworks, regulatory enforcement, and international collaboration are highlighted as essential for sustainable food safety governance. Community engagement, capacity building, and behavioral change communication are identified as critical for promoting safe food-handling practices among households, market traders, and street food vendors. Additionally, the study stresses the influence of climate variability, including elevated temperatures, flooding, and droughts, on pathogen survival, proliferation, and transmission, and the importance of sustainable environmental management in mitigating these risks. The findings emphasize a multifaceted, proactive approach that integrates scientific, regulatory, behavioral, and environmental interventions to enhance food safety, safeguard public health, and ensure resilient food systems. The study advocates for future research and policies that strengthen capacity, infrastructure, and climate-adaptive strategies, thereby promoting safe and sustainable food production in Nigeria and similar developing contexts.

**Keywords:** Foodborne diseases, public health, climate adaptation, community interventions, Good Agricultural Practices, Hazard Analysis and Critical Control Points, sustainable food systems.

## 1. INTRODUCTION

The increasing prevalence of foodborne pathogens and microbial contamination poses a significant public health threat, which necessitates urgent attention and intervention. Globally, foodborne diseases account for an estimated 600 million illnesses and approximately 420,000 deaths each year, stressing that 1 in 10 individuals falls ill from unsafe food (Havelaar et al., 2015; Oladunjoye & Awani-Aguma, 2023). The World Health Organization (WHO) highlights that the burden of foodborne illness is comparable to other major communicable diseases, such as HIV/AIDS and malaria, indicating a critical public health challenge that cannot be overlooked (Havelaar et al., 2015; Devleeschauwer et al., 2018; Cook & Phuc, 2019; Kuchenmüller et al., 2009). The economic ramifications of foodborne illnesses compound this issue, with direct healthcare costs and lost productivity resulting in significant societal losses across nations. This is particularly evident in developing countries, where public health infrastructure may be lacking (Abdullahi et al., 2025).

Microbial safety in food production is paramount for mitigating the public health risks posed by foodborne pathogens (Odubo et al., 2024; Izah et al., 2024; Ogwu et al., 2024). Factors contributing to this contamination can range from preharvest agricultural practices to post-harvest processing and distribution (Odubo et al., 2024). Studies indicate that pathogens like *Salmonella* and *Listeria* species can persist and proliferate in various environments, including contaminated water and soil (Kutter et al., 2006; Larsen et al., 2014). As such, ensuring microbiological safety becomes integral not only for public health but also for the protection and enhancement of nutrition, thus linking food safety to the Sustainable Development Goals (SDGs), particularly SDG 3 regarding good health and well-being, and SDG 2 aiming for zero hunger (Tomasello et al., 2024; Quinto et al., 2019).

The relationship between food safety and nutrition is bidirectionally beneficial. On the one hand, enhancing food safety practices is vital to ensure that food contributes positively to health outcomes; on the other hand, the availability of safe, nutritious food is crucial for achieving food security and promoting health (Alegbeleye et al., 2018; Uyttendaele et al., 2015). As the global population continues to grow and urbanize, the interdependencies of food production, safety practices, and health outcomes become increasingly pronounced. Sustainable agricultural practices must encompass comprehensive risk assessments and interventions to minimize pathogen exposure from farm to fork (Yang et al., 2016; Johnson, 2019). For instance, implementing rigorous food control protocols and educating consumers about safe food handling practices can significantly reduce the incidence of foodborne diseases (Nganje et al., 2010).

This review focuses on the burden of foodborne pathogens and microbial contamination throughout the food chain, from production to consumption, and emphasizes their public health significance. It examines major bacterial, viral, and parasitic foodborne pathogens and their routes of transmission in diverse food systems. The paper critically reviews trends in antimicrobial resistance among foodborne microorganisms. The review further aligns food safety challenges with relevant Sustainable Development Goals to highlight their role in sustainable public health outcomes.

The study provides a consolidated understanding of foodborne microbial hazards for researchers, public health professionals, and policymakers. It supports evidence-based decision-making for improving food safety regulations and surveillance systems. The review highlights gaps in current knowledge and practice, guiding future research priorities. It promotes awareness of the link between food safety, antimicrobial resistance, and sustainable development. The study also contributes to strategies to reduce foodborne diseases and improve population health, especially in developing countries.

## 2, Common Foodborne Pathogens of Public Health Importance

Common foodborne pathogens of public health importance include a wide range of bacterial, viral, and parasitic agents that significantly contribute to foodborne diseases worldwide. Bacterial pathogens such as *Salmonella* spp., *Escherichia coli*, *Listeria monocytogenes*, and *Campylobacter* spp. are frequently associated with contaminated foods of animal and plant origin. They are significant causes of morbidity and mortality. Viral pathogens, particularly Norovirus and hepatitis A virus, are highly infectious and often transmitted through contaminated food, water, or poor hygiene during food handling. In addition, parasitic pathogens like *Giardia*, *Cryptosporidium*, and *Taenia* spp., as well as emerging and re-emerging foodborne microorganisms, pose increasing public health challenges due to changes in food systems, globalization, and environmental factors.

### 2.1 Bacterial Pathogens

#### *Salmonella* spp.

*Salmonella* is prevalent in Nigeria and other developing countries, primarily due to poor food-handling practices, inadequate refrigeration, and rampant informal food vending. This pathogen is commonly associated with the consumption of poultry, eggs, meat, fish, and fresh vegetables sold in open markets. The ability of *Salmonella* to cause salmonellosis significantly contributes to the burden of diarrheal diseases, particularly affecting children under five years of age (Jibril et al., 2020; Odo et al., 2021). The high prevalence of *Salmonella* in these food sources highlights the urgent need for improved food safety practices within the country's agricultural and retail sectors (Okafor, 2024).

Research indicates that commercial poultry farms exhibit a concerning prevalence of *Salmonella* infections, with figures reported at approximately 47.9% in various regions of Nigeria (Jibril et al., 2020). These findings highlight the critical link between animal husbandry practices and the potential

transmission of foodborne pathogens to humans. Furthermore, poor sanitation in both domestic and commercial sectors exacerbates the risk, making Salmonella a significant public health concern (Okafor, 2024; Ibrahim et al., 2021)

*Escherichia coli* (Especially Pathogenic Strains)

Pathogenic strains of *E. coli*, particularly *E. coli* O157:H7, are frequently linked to outbreaks related to contaminated water, poorly washed vegetables, undercooked meat, and street foods in Nigeria. Poor sanitation and unsafe water supply in many Nigerian communities heighten the likelihood of transmission, leading to severe diarrhea, bloody stools, and potential kidney complications (Odo et al., 2021; Okafor, 2024). The economic implications of these infections are profound, as they place additional pressure on the country's limited healthcare resources, often resulting in increased hospital visits among vulnerable populations, particularly children (Okafor, 2024).

Reports indicate that *E. coli* can be isolated from various fresh produce and ready-to-eat foods (Izah et al., 2022; Kigigha et al., 2017a,b, 2016, 2015a,b; Izah et al., 2015) sold in markets, highlighting the interconnected nature of agricultural practices and public health (Ajiboye et al., 2023). This necessitates implementing stringent food safety protocols and conducting educational campaigns to address the growing public health threat posed by this pathogen (Okafor, 2024).

*Listeria monocytogenes*

*Listeria monocytogenes* has been found in locally processed and ready-to-eat foods, including unpasteurized milk and soft cheeses, contributing to foodborne illness outbreaks in Nigeria. The weak regulatory oversight and limited cold chain infrastructure enhance the risk of contamination with *Listeria*, a pathogen known for its particularly severe consequences in pregnant women, neonates, and immunocompromised individuals (Odeyemi, 2015). The presence of *Listeria* in food products adds another layer of complexity to the country's food safety landscape. It necessitates focused attention on the risks associated with traditional food processing methods, where hygiene standards are often inadequate (Odeyemi, 2015).

*Campylobacter* spp.

*Campylobacter* spp. Represents another significant bacterial pathogen commonly transmitted through undercooked poultry, raw milk, and contaminated water sources. The high prevalence of *Campylobacter* is closely associated with backyard poultry production, wherein inadequate slaughterhouse hygiene practices further complicate the problem (Ibrahim et al., 2021). Acute gastroenteritis attributed to *Campylobacter* infections is a major contributor to gastrointestinal illnesses in Nigeria, underscoring the need to improve hygiene practices on poultry farms and in processing facilities (Okafor, 2024). This highlights a critical public health challenge that requires immediate intervention.

## 2.2 Viral Pathogens

Norovirus

Norovirus is a formidable viral pathogen that spreads rapidly through contaminated foods, water, and infected food handlers, especially in densely populated urban areas of Nigeria. Outbreaks are often reported in schools, markets, and communal living environments, stressed by poor hand hygiene and limited access to clean water (Okafor, 2024). The fecal-oral transmission route of Norovirus elevates the importance of sanitation and hygiene practices in public health measures to prevent foodborne illnesses (Okafor, 2024).

Hepatitis A virus transmission can occur through the consumption of contaminated food and water, particularly during flooding and rainy seasons when sanitation infrastructure is compromised. The outbreaks disproportionately affect low-income communities, which often lack access to safe drinking water and proper sanitation (Odo et al., 2021). Thus, addressing Hepatitis A involves not only improving healthcare responses but also implementing robust community outreach programs focused on sanitation and hygiene education (Okafor, 2024).

## 2.3 Parasitic Pathogens

*Giardia lamblia*

*Giardia lamblia* is prevalent in fruits and vegetables sold in major markets in Ilorin, Nigeria (Ojo 2023) and Boyo Division Health District, North- West Region of Cameroon (Yufanyi & Ifemeje, 2019), where untreated surface water is commonly utilized for drinking and food preparation. This pathogen is a leading cause of chronic diarrhea, malnutrition, and impaired growth in affected

children (Kinyua et al., 2016). The implications of Giardia infections extend beyond immediate health effects, highlighting the urgent need for access to safe drinking water and improved sanitation facilities (Okafor, 2024).

*Cryptosporidium* spp.

*Cryptosporidium* spp. is frequently detected in contaminated water sources and fresh produce irrigated with wastewater, posing a significant risk as it can resist conventional water treatment methods in developing settings. The pathogen is particularly dangerous for immunocompromised individuals, who may experience severe and prolonged illness (Olopade et al., 2023). The persistence of *Cryptosporidium* in the environment, coupled with inadequate public health infrastructure, stresses the need for comprehensive strategies focused on pathogen monitoring and improving water quality (Okafor, 2024).

*Taenia* spp.

*Taenia* spp. infections linked to the consumption of poorly cooked beef and pork from informal slaughter facilities pose an ongoing challenge due to weak meat inspection systems in some developing countries (Opara et al., 2006). The implications of *T. solium* infections are particularly severe, as they can lead to neurocysticercosis, a preventable cause of epilepsy. Enhancing meat inspection protocols and improving public awareness of proper cooking methods are critical to controlling *Taenia* transmission in the country (Okafor, 2024).

#### 2.4 Emerging and Re-emerging Foodborne Microorganisms

The increasing prevalence of foodborne pathogens in developing countries could be driven by rapid urbanization, population growth, and climate change-related flooding, which contaminate water sources and food systems. Additionally, the misuse of antibiotics in both human health and animal production contributes to the emergence of antibiotic-resistant strains of pathogens, posing a significant threat to public health (Izah et al., 2025; Cudjoe et al., 2022).

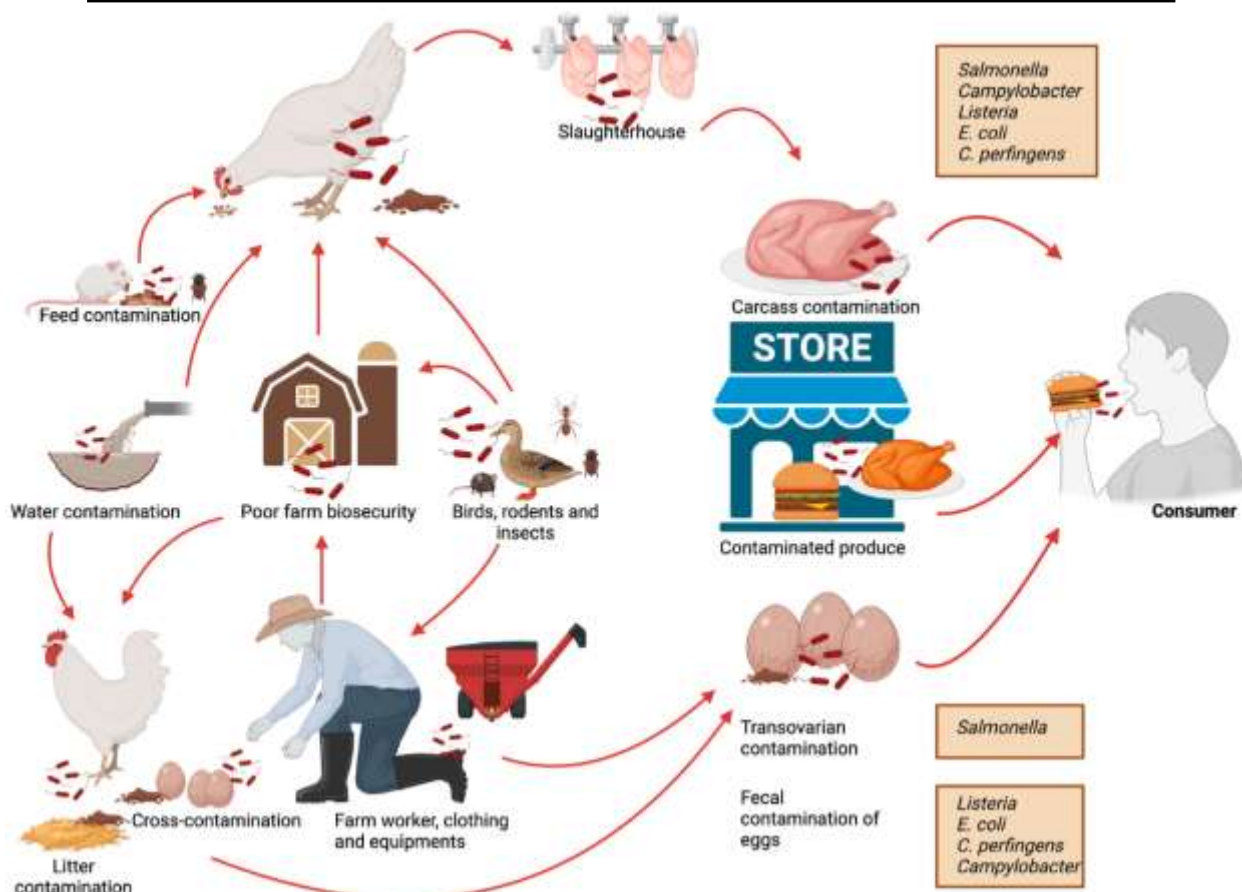
The re-emergence of pathogens such as drug-resistant *Salmonella* species stresses the need for improved laboratory capacity and surveillance systems to facilitate early detection and response to potential outbreaks (Okafor, 2024). Furthermore, addressing these public health challenges aligns with the Sustainable Development Goals (SDGs) by emphasizing the need for enhanced health interventions to reduce foodborne infections and thereby improve overall health outcomes.

#### 2.5 Relevance to Sustainable Development Goals (SDGs)

Reducing foodborne infections is essential to lowering preventable illness and death rates in Nigeria, thereby contributing to SDG 3: Good Health and Well-being. Strengthening food safety, water, sanitation, and hygiene (WASH) systems plays a vital role in improving population health while promoting child survival, maternal health, and overall socio-economic development in developing nations (Okafor, 2024). The persistence of foodborne pathogens necessitates a coordinated response that includes policies to strengthen food safety regulations, community education, and improved healthcare access to mitigate their impacts on public health.

### 3. Sources and Routes of Microbial Contamination along the Food Chain

Microbial contamination of food is an intricate issue that occurs at multiple points throughout the food chain, commonly referenced as “from farm to fork” (Figure 1). This contamination is influenced by factors such as interactions with contaminated environments, insufficient hygiene practices, inadequate infrastructure, and unsafe handling methods. Table 1 summarises the sources and routes of microbial contamination along the food chain. While these routes are universal, they are extremely pronounced in developing countries, where limited regulatory oversight, weak infrastructure, and the prevalence of informal food systems exacerbate the risks associated with microbial contamination (Eromo et al., 2016; Birgen et al., 2020; Amare et al., 2019).



**Figure 1.** Farm-to-fork transmission pathways of different microbial particularly bacterial foodborne pathogens. Source: Sharma et al. (2025)

Table 1: Sources and routes of microbial contamination along the food chain

Stage	Sources of Contamination	Routes / Contributing Factors
Primary Production	<ul style="list-style-type: none"> <li>- Soil (pathogens, spores)</li> <li>- Irrigation water (contaminated rivers, ponds)</li> <li>- Manure and organic fertilizers - Animal reservoirs (livestock, poultry)</li> </ul>	<ul style="list-style-type: none"> <li>- Contaminated soil, water, and tools</li> <li>- Use of untreated manure</li> <li>- Poor irrigation methods</li> <li>- Zoonotic pathogen transmission</li> </ul>
Food Processing & Handling	<ul style="list-style-type: none"> <li>- Poor personal hygiene</li> <li>- Unsanitary surfaces and equipment</li> <li>- Cross-contamination</li> </ul>	<ul style="list-style-type: none"> <li>- Handling raw and cooked foods with same utensils</li> <li>- Inadequate cooking, cleaning, or preservation</li> <li>- Street-vended and informal food processing</li> </ul>
Distribution & Storage	<ul style="list-style-type: none"> <li>- Temperature abuse</li> <li>- Poor transport and storage infrastructure</li> <li>- Pest infestation</li> </ul>	<ul style="list-style-type: none"> <li>- Lack of cold chain</li> <li>- Open or contaminated transport containers</li> <li>- Overcrowded, unventilated storage facilities</li> </ul>
Consumption / Household Level	<ul style="list-style-type: none"> <li>- Unsafe water</li> <li>- Poor hygiene in food prep</li> <li>- Cultural/behavioral practices</li> </ul>	<ul style="list-style-type: none"> <li>- Improper thawing or reheating of leftovers</li> <li>- Handling food with unwashed hands</li> <li>- Consumption of undercooked foods</li> </ul>

### 3.1 Primary Production

The primary production stage represents a critical entry point for foodborne pathogens into the food supply, as agricultural environments provide multiple opportunities for microbial introduction and persistence. Interactions among crops, soil, water, animals, and farm workers create complex pathways for contamination, particularly in settings with limited environmental management and regulatory oversight.

Pathogenic microorganisms such as *Clostridium* spp., *Salmonella* spp., and *Escherichia coli* occur naturally in soil and pose direct risks during cultivation and harvesting activities. Contaminated soils often originate from refuse dumpsites, poorly managed farmlands, or flood-prone areas where pathogens accumulate and persist over time if appropriate control measures are absent (Birgen et al., 2020; Amare et al., 2019). The ability of microbial spores and parasitic forms to survive for prolonged periods further enhances the potential for recurrent contamination, allowing soil to act as a long-term reservoir for foodborne pathogens that may re-enter the food chain repeatedly (Mwove et al., 2024).

Water used for irrigation constitutes another major source of microbial contamination at the primary production level. Untreated or inadequately treated surface water from rivers, streams, and ponds frequently harbors pathogenic microorganisms, thereby increasing the microbial load of irrigated crops (Kariuki et al., 2017). Pollution arising from sewage discharge, industrial effluents, and agricultural runoff intensifies contamination risks, particularly when such water sources are applied directly to crops through irrigation systems (Amare et al., 2019; Hussein et al., 2020). Flooding events further exacerbate this challenge by spreading pathogens across farmlands, significantly increasing contamination of agricultural produce in affected regions (Ekhatior et al., 2017).

Organic fertilizers and animal manure also serve as essential vehicles for microbial transmission during crop production. The use of untreated or inadequately composted manure introduces enteric pathogens such as *E. coli* O157:H7, *Salmonella*, and *Listeria monocytogenes* into the soil-plant interface, where they may survive long enough to contaminate edible portions of crops (Amare et al., 2019; Birgen et al., 2019). Such practices remain common in low-resource agricultural systems, increasing the likelihood of microbial persistence and transfer to consumers.

Animal reservoirs represent an additional pathway for contamination at the farm level. Livestock and poultry frequently harbor zoonotic pathogens that are shed through feces onto pasturelands and cultivated fields. Direct contact between animals and crops, or indirect contamination through runoff and soil contact, facilitates the transfer of microorganisms to edible plants, thereby increasing the risk of foodborne infections (Birgen et al., 2020; Mwove et al., 2024).

Agricultural practices play a significant role in determining the extent of microbial contamination during primary production. Inappropriate irrigation techniques, especially overhead irrigation systems, promote direct contact between contaminated water and the edible parts of crops, creating favorable conditions for pathogen attachment and survival. The absence of routine water quality monitoring allows microbial contamination to remain undetected and uncontrolled (Amare et al., 2019; Birgen et al., 2019). Additionally, the use of contaminated harvesting tools and poor hand hygiene among farm workers contribute to the transfer of pathogens from environmental sources to harvested produce (Birgen et al., 2020).

### 3.2 Food Processing and Handling

Microbial contamination is significantly increased during food processing and handling, particularly in settings where hygiene standards are poorly enforced and regulatory oversight is limited. These stages often serve as critical amplification points for foodborne pathogens, as foods are repeatedly exposed to human handling, contaminated surfaces, and suboptimal environmental conditions, thereby increasing the likelihood of microbial survival and proliferation.

Poor personal hygiene remains a major contributor to food contamination during processing and handling. Inconsistent handwashing practices, especially after using the toilet, significantly increase the risk of transferring pathogenic microorganisms to food through unclean hands, fingernails, or infected wounds (Mwove et al., 2024). Food handlers, including vendors and household food preparers, may unknowingly act as vectors for pathogens when basic hygiene practices are neglected. Such behaviors create direct crossover points for microbial transmission into foods, particularly in high-contact preparation processes (Oladipo-Adekeye & Tabit, 2021; Kariuki et al., 2017).

Unsanitary processing environments further exacerbate the risk of microbial contamination. The frequent presence of dirty food-contact surfaces, utensils, and processing equipment creates favorable conditions for the persistence and spread of pathogenic microorganisms. Limited access to potable water in many food processing settings undermines effective cleaning and sanitation, leading to inadequate washing of raw materials, utensils, and preparation surfaces. These conditions significantly compromise food safety and facilitate repeated contamination events (MAO et al., 2019; Birgen et al., 2019).

Cross-contamination represents a persistent and widespread challenge in food processing and handling systems. Shared preparation spaces for raw and cooked foods increase the probability of transferring pathogens from contaminated raw materials to ready-to-eat products. This issue is particularly pronounced among street food vendors, where the same knives, cutting boards, and preparation surfaces are often used for multiple food items without proper cleaning or sanitization between uses. Such practices enable the efficient transfer of microorganisms from contaminated surfaces to consumable foods, posing serious public health risks (Nawawee et al., 2019; Sabbithi et al., 2014).

Inadequate processing controls further undermine food safety during handling and preparation. Insufficient thermal processing, including cooking foods at temperatures that fail to inactivate pathogenic microorganisms, allows pathogens to survive and persist in finished products. Improper preservation methods, such as poorly controlled drying, fermentation, or salting processes, also promote microbial growth and spoilage. These shortcomings highlight the importance of structured food safety management systems, including strict adherence to Hazard Analysis and Critical Control Points (HACCP), to minimize contamination risks and ensure food safety throughout processing stages (MAO et al., 2019; Mahon et al., 1999).

The informal food processing sector presents additional complexities for food safety management. Unregistered food processors frequently operate without formal training in food hygiene and safety, increasing the likelihood of unsafe practices that threaten consumer health. Street-vended foods are particularly vulnerable to contamination from environmental hazards such as dust, flies, refuse, and wastewater. Extended holding of cooked foods at unsafe ambient temperatures further elevates the risk of microbial growth and toxin production (Birgen et al., 2020; Oladipo-Adekeye & Tabit, 2021). Economic constraints often compel vendors to reuse cooking oil and water beyond safe limits, compounding contamination risks and further compromising the microbiological quality of foods offered to consumers (Ekhaton et al., 2017; Amare et al., 2019).

### 3.3 Distribution, Storage, and Consumption

Post-processing handling plays a decisive role in determining the microbiological safety of food before it reaches consumers. Temperature abuse remains a significant concern, particularly in contexts where cold chain systems are absent or unreliable, as such conditions create favorable environments for the survival and rapid multiplication of foodborne pathogens (Tawfik et al., 2023; Nawawee et al., 2019). In many developing settings, inadequate transportation infrastructure further compounds this problem, leading to prolonged transit times and repeated exposure of food products to unsuitable environmental conditions, such as high ambient temperatures and poor sanitation. These challenges significantly increase the likelihood of microbial contamination and deterioration of food quality during distribution (Oladipo-Adekeye & Tabit, 2021; Mordechay et al., 2024).

Storage conditions pose additional, persistent challenges to food safety throughout the food chain. The lack of functional refrigeration or cold storage facilities limits the ability to maintain perishable products at temperatures that inhibit microbial growth. This situation is often exacerbated by overcrowded, poorly ventilated storage environments, which promote moisture accumulation and microbial proliferation. Pest infestations, particularly involving rodents and insects, also pose serious threats during storage, as these vectors can introduce or spread pathogenic microorganisms through direct contact with food or food-contact surfaces (Nawawee et al., 2019; Mao et al., 2019). Collectively, these storage-related factors significantly elevate the risk of foodborne disease transmission.

Food safety risks persist at the household level, where everyday practices strongly influence the safety of the foods consumed. Inadequate food-handling behaviors, including poor personal hygiene during food preparation and unsafe thawing or reheating, frequently lead to microbial contamination. The use

of contaminated water for cooking, washing utensils, and cleaning food-contact surfaces further increases exposure to foodborne pathogens, particularly in areas with limited access to potable water (Birgen et al., 2020; Sabbithi et al., 2014). Cultural practices, such as the consumption of undercooked or improperly prepared foods, also contribute to the sustained prevalence of foodborne illnesses within communities (Ekhatior et al., 2017; Nawawee et al., 2019).

#### 3.4 Linkage to Sustainable Development Goals (SDGs)

Microbial contamination of food has wide-ranging consequences that directly threaten the achievement of global sustainable development targets. Food safety failures undermine health, productivity, and economic stability, thereby weakening progress across multiple Sustainable Development Goals.

Unsafe food represents a significant barrier to achieving SDG 2 (Zero Hunger), as foodborne illnesses contribute to malnutrition, impaired nutrient absorption, and stunted growth, particularly among vulnerable populations such as children and the elderly. Significant post-harvest losses from microbial spoilage further reduce food availability and accessibility, underscoring the importance of adequate food safety measures to support food security and nutritional adequacy (Amare et al., 2019; Birgen et al., 2019).

The attainment of SDG 6 (Clean Water and Sanitation) is closely linked to food safety outcomes. Contaminated water used in agricultural production, food processing, and domestic food preparation substantially increases the burden of foodborne diseases. Improved access to clean water and enhanced sanitation infrastructure reduce environmental contamination with pathogenic microorganisms and form a foundational component of effective food safety systems, thereby advancing broader public health goals (Nawawee et al., 2019; Eromo et al., 2016; El-Shenawy et al., 2011).

Progress toward SDG 12 (Responsible Consumption and Production) also depends heavily on promoting safe, hygienic, and sustainable food production and handling practices. Microbial spoilage contributes significantly to food waste, placing additional strain on environmental and economic resources. Strengthened food safety regulations, alongside increased consumer awareness and education, are essential for reducing waste, improving food quality, and ensuring that food systems operate in a manner that is both health-conscious and environmentally sustainable (Oladipo-Adekeye & Tabit, 2021; Amare

#### 4. Antimicrobial Resistance in Foodborne Pathogens

Antimicrobial resistance (AMR) in foodborne pathogens poses a significant threat to public health globally, particularly exacerbated by the misuse and overuse of antibiotics in agricultural and livestock production (Izah et al., 2025). The factors contributing to AMR are multifaceted, including the therapeutic, prophylactic, and growth-promoting use of antibiotics, as well as practices in aquaculture and the overarching regulatory frameworks, or the lack thereof, that govern these practices.

##### 4.1 Use of Antibiotics in Agriculture and Livestock Production

The therapeutic use of antibiotics in agriculture primarily aims to treat bacterial infections in food-producing animals, such as poultry, cattle, and pigs, as well as in aquaculture species (Table 2). This practice plays a vital role in reducing morbidity and mortality, maintaining animal welfare, and sustaining livestock productivity. Despite these benefits, therapeutic antibiotic use is frequently poorly regulated in many developing countries. Weak enforcement of veterinary drug policies, limited diagnostic capacity, and reliance on empirical treatment often result in inappropriate drug selection, incorrect dosing, and prolonged treatment durations. In settings such as Nigeria, these challenges contribute significantly to the emergence and persistence of antimicrobial-resistant bacteria within livestock populations, with potential spillover effects on human health (Esiovwa et al., 2022; Woolhouse et al., 2015).

**Table 2: Use of Antibiotics in Agriculture and Livestock Production**

Issue	Outcomes
Therapeutic Use in Animals	Antibiotics used to treat sick animals can drive AMR when overused or misused (FAO, 2023).
Growth Promotion	Use of antibiotics for growth promotion in livestock contributes to resistant bacteria that may spread to humans (WHO, 2023).
Prophylactic Use	Routine preventive antibiotic use in healthy animals accelerates resistance development (FAO, 2023).
Environmental Antibiotic Exposure	Antibiotics in animal waste, water, and soil create conditions that select for resistant bacteria (CDC, 2023).
Horizontal Gene Transfer	Resistance genes can spread between bacteria in animal guts or environments, enhancing multidrug resistance (Fahim et al., 2025; Michaelis & Grohmann, 2023)
Impact on Food Chain	Resistant microorganisms from agriculture can enter food systems and be transmitted through animal products (FAO, 2023).

Prophylactic use of antibiotics involves administering antimicrobial agents to healthy animals to prevent the onset of disease, particularly in intensive farming systems characterized by overcrowding, poor hygiene, and inadequate biosecurity. This preventive strategy is commonly adopted as a substitute for improved farm management and sanitation. Continuous exposure of bacterial populations to low doses of antibiotics under such conditions creates intense selective pressure that favors the survival and proliferation of resistant strains. Over time, this practice accelerates the development and dissemination of antimicrobial resistance within animal populations and the surrounding environment, contributing to the growing global burden of resistant infections (Founou et al., 2016; Woolhouse et al., 2015).

The use of antibiotics as growth promoters represents another major driver of antimicrobial resistance in agricultural systems. Sub-therapeutic doses of antibiotics are routinely incorporated into animal feed to enhance feed conversion efficiency and promote rapid weight gain. Persistent exposure to these low antibiotic concentrations provides ideal conditions for the selection of resistant bacteria within the gut microbiota of animals. Resistant strains arising from this practice can contaminate meat, milk, and other animal products, facilitating their entry into the human food chain. The public health implications of this practice are considerable, particularly in regions where regulatory controls are weak or poorly enforced (Founou et al., 2016; Kazim et al., 2024).

Antibiotic use in aquaculture poses unique challenges due to direct interactions between antimicrobial agents and the aquatic environment. Antibiotics are often added directly to water or feed to control bacterial infections in fish and shellfish. This practice leads to the accumulation of antibiotic residues in water bodies and sediments, creating reservoirs of resistance among aquatic microorganisms. Resistant aquatic bacteria can transfer resistance genes to human pathogens through ecological interactions, thereby compromising food safety and public health. Poor management practices, including excessive stocking densities and inadequate water quality control, further exacerbate the spread of antimicrobial resistance in aquaculture systems (Founou et al., 2016; Woolhouse et al., 2015).

Inadequate veterinary oversight significantly intensifies the misuse of antibiotics in agricultural settings. Limited access to qualified veterinary professionals and weak regulatory enforcement allow antibiotics to be purchased and administered without prescriptions. Farmers often rely on personal experience or informal advice when selecting and dosing antibiotics, leading to inappropriate use. Such practices not only increase the risk of resistance development but also contribute to environmental contamination through improper disposal of unused drugs and medicated waste. These challenges are particularly pronounced in developing countries, where veterinary infrastructure and surveillance systems remain underdeveloped (Esiowwa et al., 2022; Founou et al., 2016).

Environmental dissemination of antibiotics and resistant bacteria occurs through the excretion of unmetabolized antimicrobial compounds in animal waste. Manure containing antibiotic residues and resistant microorganisms is frequently applied to agricultural land as fertilizer, facilitating contamination of soil, surface water, and crops. Runoff from farms can further spread resistant bacteria into surrounding ecosystems, increasing the likelihood of human exposure through food, water, and direct contact. This environmental pathway represents a critical link between agricultural

antibiotic use and the broader spread of antimicrobial resistance across ecological and human health systems (Founou et al., 2016; Meier et al., 2022).

Horizontal gene transfer plays a central role in the amplification and spread of antimicrobial resistance originating from livestock production systems. Resistant bacteria harbored by food-producing animals can exchange resistance genes through mechanisms such as plasmid transfer, transposons, and integrons. These genetic exchanges can occur between commensal and pathogenic bacteria, enabling resistance traits to spread rapidly across species barriers. The transfer of resistance genes from animal-associated bacteria to human pathogens raises serious concerns regarding the increasing difficulty of treating infections in human populations and highlights the interconnected nature of antimicrobial resistance across human, animal, and environmental health domains (Founou et al., 2016; Woolhouse et al., 2015).

#### **4.2 Transmission of Resistant Bacteria Through Food**

The transmission of antimicrobial-resistant bacteria through food is a well-documented and significant public health pathway that contributes to the global burden of antimicrobial resistance (Table 3). Food serves as an effective vehicle for the movement of resistant bacteria from animals and the environment to humans, facilitating widespread exposure across populations and increasing the risk of treatment failure in infectious diseases (Founou et al., 2020; Bokhary et al., 2021).

**Table 3: Transmission Through Food and Public Health Consequences**

Category	Outcome
Contaminated Animal-derived Foods	Resistant bacteria can contaminate meat, dairy, and eggs during slaughter and processing (CDC, 2023).
Plant/Fruit & Vegetable Contamination	Produce can be contaminated via soil or water containing resistant bacteria from animal waste (CDC, 2023).
Cross-contamination and Handling Risks	Poor food handling at markets or kitchens allows resistant bacteria to spread (Maroney, 2023).
Inadequate Food Processing	Undercooking or improper processing allows resistant bacteria to survive and infect consumers (CDC, 2023).
Colonization and Infection	Consumption of contaminated food may introduce resistant bacteria into humans, colonizing the gut and transferring resistance genes (CDC, 2023).
Treatment Failure	Resistant foodborne infections are harder to treat, often requiring stronger drugs or resulting in treatment failure (WHO, 2023).
Increased Disease Severity	Resistant infections may lead to longer illness, complications, and increased risk of hospitalization or death (WHO, 2023).
Healthcare & Economic Impact	Severe resistant infections result in higher healthcare costs and economic strain (FAO, 2023).

Animal-derived food products are a significant source of antimicrobial-resistant bacteria, particularly during slaughter, processing, and distribution stages, where contamination can readily occur. Meat, poultry, milk, and other animal products may harbor drug-resistant pathogens, including *Salmonella* spp., *Escherichia coli*, *Campylobacter* spp., and *Listeria monocytogenes*. These pathogens have been frequently implicated in foodborne disease outbreaks associated with antimicrobial resistance, reflecting the impact of antibiotic use in animal production systems and inadequate hygiene controls along the food chain (Founou et al., 2020; Bokhary et al., 2021).

Fresh produce also constitutes an essential route for the transmission of resistant bacteria to humans. Contamination may occur when crops are irrigated with water polluted by sewage or animal waste, or when untreated manure from livestock exposed to antibiotics is applied as fertilizer. This situation highlights the close interconnection between agricultural practices, environmental contamination, and public health risks associated with antimicrobial resistance, particularly in settings where regulation of water quality and waste management is limited (Founou et al., 2016; Kazim et al., 2024).

Food-handling practices also contribute to the spread of resistant bacteria through cross-contamination. Poor hygiene during food preparation can enable the transfer of resistant organisms from raw foods to cooked or ready-to-eat products. Contamination at multiple points along the food

supply chain highlights the complex, multisectoral nature of food safety challenges and the need for coordinated interventions across agriculture, food processing, and public health sectors (Likotrafiti et al., 2018; Founou et al., 2016).

Inadequate food processing represents another critical factor in the persistence of resistant bacteria in foods intended for consumption. Insufficient cooking temperatures, improper processing methods, and pasteurization failures can allow resistant bacteria to survive and remain viable in ready-to-eat foods. Such lapses increase the likelihood of human exposure and permit resistant strains to persist even after food preparation, thereby amplifying the public health impact of antimicrobial resistance (Kazim et al., 2024; Woolhouse et al., 2015).

Food distribution and storage conditions play a significant role in shaping the risks associated with antimicrobial-resistant bacteria. Poor cold chain management, prolonged storage at inappropriate temperatures, and inadequate transportation infrastructure can encourage bacterial survival and proliferation. These challenges are particularly evident in informal food systems operating with limited regulatory oversight, especially in low-resource settings where enforcement of food safety standards is weak (Founou et al., 2016; Grépin et al., 2023).

Human colonization occurs after consuming food contaminated with resistant bacteria, which then establish in the gastrointestinal tract. Once present, resistant bacteria may persist and facilitate the horizontal transfer of resistance genes to commensal gut microbiota or pathogenic bacteria. This process complicates clinical treatment options and intensifies public health challenges as resistant infections become increasingly common and complex to manage (Kazim et al., 2024; Woolhouse et al., 2015).

#### 4.3 Public Health Consequences of Antimicrobial-Resistant Foodborne Infections

The growing prevalence of antimicrobial resistance (AMR) among foodborne pathogens poses a serious, multifaceted threat to public health, with profound implications for disease management, patient outcomes, and health system sustainability. As resistance spreads across commonly implicated foodborne bacteria, the effectiveness of standard treatment regimens is increasingly compromised, leading to cascading clinical, economic, and societal consequences.

Treatment failure has become one of the most immediate and concerning outcomes of AMR in foodborne infections. The rising incidence of resistant strains reduces the effectiveness of first-line antibiotics used to manage gastrointestinal and systemic diseases. As a result, clinicians are often forced to resort to second- or third-line antimicrobials that are more expensive, less accessible, and frequently associated with greater toxicity. This challenge disproportionately affects low- and middle-income countries, where limited access to advanced antibiotics and diagnostic tools exacerbates health inequities and undermines timely and effective care (Woolhouse et al., 2015; Founou et al., 2016).

Increased disease severity is another significant consequence associated with antimicrobial-resistant foodborne pathogens. Infections caused by resistant organisms are often more challenging to control, leading to prolonged clinical courses, higher complication rates, and increased mortality. The emergence of multidrug-resistant (MDR) and extensively drug-resistant (XDR) strains has further intensified the severity of outbreaks, as these pathogens can evade multiple therapeutic options and spread rapidly within communities (Kazim et al., 2024; Woolhouse et al., 2015).

Longer duration of infection is frequently observed in individuals infected with resistant foodborne pathogens. Resistance delays effective treatment, allowing pathogens to persist longer in the host and prolonging symptom duration. Prolonged infection also leads to protracted bacterial shedding, which heightens the risk of onward transmission to household contacts and the wider community. This sustained circulation of resistant organisms places additional strain on already overburdened healthcare systems and amplifies public health risks (Kazim et al., 2024; Founou et al., 2016).

Higher healthcare costs represent a significant downstream impact of AMR-related foodborne infections. Increased hospital admissions, extended lengths of stay, repeated diagnostic testing, and the need for more costly antimicrobial therapies collectively drive up healthcare expenditures. These financial pressures threaten the sustainability of health systems, particularly in low- and middle-income countries where resources are limited and health budgets are already stretched (Kazim et al., 2024; Founou et al., 2016).

Limited treatment options have emerged as a defining challenge in the era of AMR. The spread of MDR and XDR foodborne pathogens substantially narrows the range of effective antibiotics,

complicating clinical decision-making and infection control strategies. Infections that were once easily treated now pose serious therapeutic challenges, stressing the urgent need for coordinated policies to promote antimicrobial stewardship, surveillance, and resistance containment (Kazim et al., 2024; Founou et al., 2016).

Threats to vulnerable populations are particularly pronounced in the context of antimicrobial-resistant foodborne infections. Children, older adults, pregnant women, and immunocompromised individuals are at heightened risk of severe disease outcomes due to reduced immune defenses and limited physiological resilience. In these groups, resistant infections can progress rapidly and lead to serious complications, underscoring the need for targeted prevention, early diagnosis, and tailored treatment strategies (Kazim et al., 2024; Woolhouse et al., 2015).

The economic and social burden associated with AMR extends beyond healthcare systems to households and communities. Illness caused by resistant foodborne pathogens leads to lost productivity, increased out-of-pocket healthcare spending, and reduced household income. At a broader level, declining consumer confidence in food safety can disrupt agricultural markets, reduce trade opportunities, and undermine economic stability, particularly in food-dependent economies (Kazim et al., 2024; Woolhouse et al., 2015).

AMR in foodborne pathogens also constitutes a significant global health security risk. Resistant organisms do not respect national boundaries and can spread rapidly through international trade, human travel, and migration. This transboundary nature of AMR undermines global disease control efforts and increases the likelihood of widespread outbreaks that challenge existing public health preparedness frameworks (Baloch et al., 2020; Woolhouse et al., 2015).

The feedback loop between human health and the environment further complicates the AMR challenge. Infected individuals excrete resistant bacteria and resistance genes and enter the environment through wastewater, agricultural runoff, and improper waste disposal. These resistant organisms can then re-contaminate food, water, and ecosystems, perpetuating a continuous cycle of resistance amplification. Addressing this interconnected cycle requires comprehensive, multisectoral interventions that integrate human, animal, and environmental health perspectives (Woolhouse et al., 2015; Founou et al., 2016).

#### 4.4 Linkage to Sustainable Development Goals (SDGs)

Efforts to address antimicrobial resistance closely align with achieving several Sustainable Development Goals, particularly those focused on health, sustainability, and responsible resource use. AMR poses a direct threat to global development by undermining progress in disease control, food security, and economic stability.

Advancing actions against AMR directly supports SDG 3, which aims to ensure good health and well-being for all. Reducing the burden of antimicrobial-resistant foodborne infections can significantly lower morbidity and mortality rates, improve treatment outcomes, and strengthen health systems by reducing the pressure associated with prolonged, complex diseases. Enhanced surveillance, effective antimicrobial stewardship, and improved infection prevention measures contribute to better health outcomes and reinforce the core objectives of SDG 3 (Kazim et al., 2024; Woolhouse et al., 2015).

Alignment with SDG 12, which emphasizes responsible consumption and production, is also evident in efforts to combat AMR. Prudent use of antibiotics in food production systems, alongside sustainable agricultural practices and improved food safety measures, plays a critical role in reducing the emergence and spread of resistance. Strengthening regulatory frameworks, enhancing monitoring and surveillance, and increasing consumer awareness of antibiotic use and food safety are essential steps toward achieving sustainable and resilient food and health systems that align with the goals of SDG 12 (Kazim et al., 2024; Founou et al., 2016).

### 5. Detection, Surveillance, and Monitoring of Foodborne Pathogens

The detection, surveillance, and monitoring of foodborne pathogens are integral components of food safety and public health. This process is accomplished through various methodologies, primarily categorized into conventional microbiological methods and rapid molecular detection techniques. These approaches are essential in identifying pathogens, conducting outbreak investigations, and ensuring food safety at every level of the food supply chain.

#### 5.1. Conventional Microbiological Methods

##### Culture-based Techniques

Conventional microbiological methods serve as a foundation for identifying foodborne pathogens. Table 4 summarises the advantages and limitations of culture based techniques. These methods often begin with culture-based techniques that utilize selective and differential media, such as MacConkey agar, XLD agar, and TCBS agar, to isolate common foodborne pathogens, including *Salmonella* spp., *Escherichia coli*, *Vibrio* spp., and *Shigella* spp. (Mieta 2017; Neyaz et al., 2024). Selective media promote the growth of target organisms while inhibiting non-target species, enhancing the efficiency of microbial load enumeration. Techniques such as total viable counts, coliform counts, and fecal indicator organism assessments are used to evaluate food hygiene and safety, providing crucial information on potential microbial load.

Table 4: Detection of Foodborne Pathogens (Conventional and Rapid/Molecular Methods)

Category	Methods/Techniques	Advantages	Limitations/Challenges
Conventional Microbiological	<ul style="list-style-type: none"> <li>- Culture on selective/differential media</li> <li>- Biochemical tests</li> <li>- Serological/serotyping</li> </ul>	<ul style="list-style-type: none"> <li>- Low cost</li> <li>- Widely accepted (gold standard)</li> </ul>	<ul style="list-style-type: none"> <li>- Time-consuming (2–7 days)</li> <li>- Labor-intensive</li> <li>- May miss VBNC organisms</li> </ul>
Rapid & Molecular	<ul style="list-style-type: none"> <li>- PCR (conventional, qPCR, multiplex)</li> <li>- Next-Generation Sequencing (WGS)</li> <li>- ELISA &amp; lateral flow assays</li> <li>- Biosensors &amp; microfluidics</li> </ul>	<ul style="list-style-type: none"> <li>- Fast results (hours)</li> <li>- High sensitivity &amp; specificity</li> <li>- Detect multiple pathogens simultaneously</li> </ul>	<ul style="list-style-type: none"> <li>- High cost</li> <li>- Requires skilled personnel</li> <li>- Maintenance/logistics challenges in low-resource settings</li> </ul>

The incubation process under specific temperature and atmospheric conditions (aerobic, anaerobic, and microaerophilic) is essential for the recovery of pathogens, ensuring optimal growth conditions for each target species (Lagier et al., 2015). While these culture-based methods are well-established and relatively low-cost, they are often criticized for being time-consuming, with results taking several days. Furthermore, they can be labor-intensive and require skilled personnel to interpret results, posing challenges, particularly in low- and middle-income countries where resources are limited.

#### Biochemical Identification

Following isolation, biochemical identification methods are utilized to characterize the pathogens. Standard tests, such as catalase, oxidase, urease, indole, and citrate utilization tests, allow for differentiation between closely related species. Resource-equipped laboratories may use commercial biochemical identification systems, such as API strips, to facilitate this process. While biochemical tests are critical for identifying specific strains, they can also contribute to lengthy analysis times.

#### Serological Methods

Serological methods complement microbiological techniques by enabling the identification of specific strains through serotyping techniques, such as agglutination tests. These methods are beneficial for outbreak investigations and epidemiological case linking, as they can discern variations within a pathogenic species, such as different *Salmonella* serovars. The advantages of conventional methods include their cost-effectiveness and widely accepted status as reference techniques in many laboratories. However, their limitations, such as the failure to detect viable but non-culturable (VBNC) organisms, necessitate the integration of more rapid detection methodologies.

### 5.2. Rapid and Molecular Detection Techniques

#### Polymerase Chain Reaction (PCR)-based Methods

Recent advancements in rapid and molecular detection techniques, particularly those utilizing polymerase chain reaction (PCR), have revolutionized foodborne pathogen surveillance. Table 4 also shows the merits and demerits of molecular detection techniques. Conventional PCR allows for specific gene detection (such as *invA* for *Salmonella* spp. and *stx* for shiga toxin-producing *E. coli*) enhancing the specificity and sensitivity of pathogen identification in complex food matrices (Delgado 2022; Costa-Ribeiro et al., 2025). Real-time PCR (qPCR) can further improve detection speed and quantification, with multiplex PCR enabling simultaneous detection of multiple pathogens in a single assay, such as *Escherichia coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes*.

Next-Generation Sequencing (NGS) technologies enable comprehensive pathogen characterization, antimicrobial resistance profiling, and outbreak source tracing through Whole Genome Sequencing (WGS), ultimately improving epidemiological surveillance and **food safety** (Tigrero et al., 2025; Vashisht et al., 2023). Enhanced sensitivity achieved through these molecular techniques significantly reduces false negatives, particularly for pathogens that may be present at low levels in food **samples**.

#### Immunological Rapid Tests

Immunological rapid testing methods, such as enzyme-linked immunosorbent assays (ELISA), provide on-site detection of pathogens by identifying specific antigens or toxins, facilitating prompt decision-making in food processing environments (Ngasha et al., 2022). Lateral flow assays further simplify on-site testing, allowing for rapid screening without the need for sophisticated laboratory setups (Zhang et al., 2022).

Emerging technologies, including biosensors and nanotechnology, have shown promise in enhancing pathogen detection capabilities. For example, nanotechnology-based biosensors can provide rapid, real-time results, while microfluidics integrated with smartphone diagnostics facilitate field-level testing (Yadav & Yadav 2025); however, these rapid methods also face challenges in terms of cost and technical expertise, particularly in developing countries.

### 5.3. Foodborne Disease Surveillance and Reporting Systems

#### Routine Surveillance

Effective surveillance systems are vital for understanding and controlling foodborne illnesses (Table 5). Continuous collection and analysis of laboratory-confirmed foodborne illness data from hospitals and clinics allows for monitoring the incidence and geographic distribution of foodborne diseases. Routine surveillance is integral in ensuring a timely response to outbreaks and identifying emerging foodborne threats.

Integrated disease surveillance frameworks, such as Integrated Disease Surveillance and Response (IDSR) (Sesay et al., 2025), highlight the need to incorporate foodborne disease monitoring into broader public health systems, facilitating earlier detection and coordinated responses during outbreaks. Outbreak investigations are critical when rapid epidemiological assessments are executed to identify the source and transmission routes of pathogens, thereby aiding public health officials in managing food safety concerns.

**Table 5: Foodborne Disease Surveillance and Reporting**

Category	Features	Challenges
Routine Surveillance	<ul style="list-style-type: none"> <li>- Continuous lab-confirmed data collection</li> <li>- Monitoring trends &amp; geographic distribution</li> </ul>	<ul style="list-style-type: none"> <li>- Limited healthcare access</li> <li>- Underreporting</li> </ul>
Integrated Surveillance (IDSR)	<ul style="list-style-type: none"> <li>- Early detection of outbreaks</li> <li>- Cross-sector coordination</li> </ul>	<ul style="list-style-type: none"> <li>- Weak coordination between health, agriculture, and veterinary services</li> </ul>
Outbreak Investigation	<ul style="list-style-type: none"> <li>- Epidemiological studies to identify sources</li> <li>- Case-control &amp; cohort studies</li> </ul>	<ul style="list-style-type: none"> <li>- Limited rapid investigation capacity</li> </ul>
Event-Based Surveillance	<ul style="list-style-type: none"> <li>- Media, community alerts, digital platforms</li> </ul>	<ul style="list-style-type: none"> <li>- Data reliability</li> <li>- Limited digital coverage</li> </ul>
Laboratory Capacity & Data Sharing	<ul style="list-style-type: none"> <li>- Centralized databases</li> <li>- One Health integration</li> <li>- Skilled personnel training</li> </ul>	<ul style="list-style-type: none"> <li>- Insufficient infrastructure</li> <li>- Limited international data sharing</li> </ul>

#### Event-based Surveillance

Event-based surveillance, which incorporates informal reporting sources such as media alerts and community notifications, is becoming an increasingly valuable tool for detecting foodborne outbreaks (Kuehne et al., 2019). The integration of digital health tools and mobile reporting systems enhances the efficiency and reach of surveillance efforts, enabling quicker detection of potential foodborne pathogens.

#### 5.4. Role of Laboratory Capacity and Data Sharing

Strengthening laboratory infrastructure is vital in enhancing the capacity for foodborne pathogen detection and monitoring (Table 5). Establishing well-equipped microbiology laboratories at local, regional, and national levels is essential for achieving international accreditation and compliance with quality standards (Castro & De Ungria, 2022). Training of laboratory personnel in modern diagnostic techniques is critical for sustaining human capacity and facilitating effective laboratory operations.

Data management and sharing among various sectors (health, agriculture, and environmental monitoring) are essential for effective surveillance systems. Centralized databases allow for tracking trends and sharing information quickly could provide necessary data for effective public health responses. The One Health approach, which integrates data from human, animal, and environmental health sectors (Izah et al., 2023; Nabebe et al., 2024), further enhances the tracking of zoonotic pathogens throughout the food supply chain, thereby improving overall food safety governance.

#### 5.5 Linkage to Sustainable Development Goals (SDGs)

The detection and surveillance of foodborne pathogens are intrinsically linked to the United Nations Sustainable Development Goals, particularly SDG 3 (Good Health and Well-being) and SDG 9 (Industry, Innovation and Infrastructure). By enhancing early detection and prevention of foodborne disease outbreaks, these efforts significantly reduce morbidity and mortality associated with contaminated food, thereby strengthening health systems. Furthermore, investments in modern laboratory technologies and diagnostic innovations contribute to resilient food safety systems, bolster consumer confidence, and advance the food industry.

#### 6.0 Prevention and Control Strategies for Foodborne Diseases

Foodborne diseases, a significant public health concern worldwide, require comprehensive prevention and control strategies to reduce their occurrence, transmission, and detrimental impacts across the food system (Table 6). Strategies must integrate scientific research, regulatory frameworks, behavioral interventions, and institutional collaborations spanning agriculture, health, environmental, and educational sectors. This multifaceted approach aims to ensure food safety. It aligns with global efforts to create safe, nutritious, and sustainable food systems, highlighting the transition from reactive disease treatment to proactive risk prevention as a primary focus (Mensah et al., 2012; Ulfat, 2025; Karpov, 2025).

Table 6: Prevention and Control Strategies for Foodborne Diseases across the Food Chain

Strategy	Major Components	Examples
Farm-to-Fork Approach	Good Agricultural Practices (GAP)	Safe farming practices; clean irrigation water; proper manure/fertilizer use; pest management; traceability; farmer hygiene and training
	Good Manufacturing Practices (GMP)	Hygiene of facilities, equipment, and personnel; cleaning and sanitation schedules; cross-contamination prevention; relevant for formal and informal sectors
	Hazard Analysis and Critical Control Points (HACCP)	Preventive system identifying hazards; critical control points; monitoring and corrective actions; documentation; applied in meat, dairy, seafood, and ready-to-eat foods
Policy, Regulation, and Food Safety Governance	National Food Safety Laws and Enforcement	Comprehensive legislation; institutional roles; routine inspection and monitoring; penalties for non-compliance; integration into public health policy
	International Standards (Codex Alimentarius)	Global food safety standards; hygiene, additives, residues, microbiological criteria; harmonization of national laws; facilitates international trade
Community Education and Capacity Building	Food Handler Training and Public Awareness	Personal hygiene; safe food storage and preparation; temperature control; street vendors, market traders, household awareness campaigns
	Behavioral Change Communication (BCC)	Cultural-appropriate messaging; mass media and community outreach; changing risky behaviors; promoting safe cooking and hygiene practices; long-term habit adoption

#### 6.1 The Importance of a Farm-to-Fork Approach

The farm-to-fork (or farm-to-table) strategy is essential for promoting food safety at each stage of food production, processing, and consumption. Central to this method are Good Agricultural Practices (GAP), which involve applying safe farming practices to minimize the risk of contamination during agricultural production. Implementing GAP ensures not only the safety of food for consumers but also

supports environmental sustainability and the health of farmworkers (Parry et al., 2025; Karpov, 2025). Specific practices include proper management of soil, water resources, and fertilizers, as well as the safe handling of animal manure. For instance, ensuring that irrigation water is clean and free from contaminants is crucial, particularly in regions reliant on surface or wastewater irrigation (Fajri & Sihombing, 2025).

Furthermore, GAP encourages traceability systems that allow produce to be tracked from the farm to the market, thereby enhancing accountability across the food supply chain. However, challenges such as inadequate access to training and resources, poor water quality, and weak enforcement of agricultural regulations can hinder efforts in regions such as Nigeria and other developing countries (Parry et al., 2025).

#### 6.2 Good Manufacturing Practices (GMP) and HACCP

At the processing level, Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP) serve as foundational frameworks for ensuring food safety. GMP establishes essential hygiene and operational standards, including maintaining cleanliness in processing environments, ensuring proper facility design, and enforcing hygiene protocols among food handlers. This is crucial for both formal and informal food processing sectors, where the risk of cross-contamination is heightened (Fajri & Sihombing, 2025; Parry et al., 2025; Malik et al., 2021).

Conversely, HACCP is a preventive, science-based food safety system that identifies and mitigates biological, chemical, and physical hazards that pose a threat to food safety. It involves establishing critical control points (CCPs) along the food production chain, implementing monitoring procedures, and allowing corrective actions when necessary. The importance of HACCP is particularly pronounced in sectors such as meat, dairy, seafood, and ready-to-eat foods, where public health stakes are exceptionally high (Fajri & Sihombing, 2025; Parry et al., 2025).

While these practices are vital, developing countries often face barriers such as high implementation costs, limited technical expertise, and inadequate regulatory enforcement, which hinder the comprehensive application of these safety systems (Eruaga, 2024; Stanković & Zrnić-Ćirić, 2021).

#### 6.3 Policy, Regulation, and Food Safety Governance

Strong food safety governance frameworks are integral to the sustainability and effectiveness of food safety measures. Comprehensive national food safety laws must cover all aspects of the food chain, ensuring clear delineation of roles among regulatory agencies, routine inspections, and monitoring activities. Effective enforcement of penalties for non-compliance is essential for maintaining standards and instilling public trust in food safety governance (Mensah et al., 2012; Kyule et al., 2023).

Challenges in this area typically include fragmented regulatory responsibilities, inadequate funding for health and safety initiatives, and limited laboratory capacity for food testing. Strengthening food safety governance can increase consumer confidence, reduce foodborne disease outbreaks, and support economic growth through enhanced safe food trade practices (Mensah et al., 2012).

International collaboration is also critical, as exemplified by the Codex Alimentarius, which sets globally recognized food safety standards and guidelines developed by the FAO and WHO. These standards promote safe food handling and hygiene while enhancing the credibility of national food safety systems, particularly supporting developing nations in accessing international markets and improving regulatory frameworks (Wui et al., 2023; Karpov, 2025; Mrdovc et al., 2023).

#### 6.4 Community Education and Capacity Building

Community engagement is central to effectively enhancing food safety. Education initiatives focused on food handling practices among individuals involved in food preparation are crucial. Training programs should emphasize personal hygiene, safe food storage, food preparation, temperature control, and cross-contamination prevention. Target audiences may include street food vendors, market traders, and households involved in local food preparation (Eruaga, 2024; Mensah et al., 2012).

Public awareness campaigns play a vital role in promoting safe cooking practices and hygiene. Behavioral Change Communication (BCC) can help alter risky food-related behaviors by delivering culturally appropriate messages through platforms such as mass media, community events, and educational institutions. This approach fosters long-term adoption of safe food-handling habits and

strengthens community ownership of food safety initiatives, particularly important in regions with minimal regulatory oversight (Fajri & Sihombing, 2025; Ulfat, 2025; Birke & Zawide, 2019).

The integration of education into food safety strategies also aligns with several Sustainable Development Goals (SDGs), including enhancing food safety education (SDG 4), promoting responsible consumption and production (SDG 12), and strengthening governance and institutional integrity (SDG 16) (Kyule et al., 2023).

## 7. Climate Change, Environment, and Foodborne Pathogens

### 7.1 Effects of Climate Variability on Pathogen Survival and Transmission

Climatic and environmental conditions significantly influence microbial contamination dynamics at the primary production stage, with climate variability increasingly shaping pathogen survival and transmission within food systems. Elevated ambient temperatures and high humidity enhance the survival, growth, and replication of foodborne pathogens such as *Salmonella* spp., *Vibrio* spp., and *Escherichia coli* in food, soil, and water environments (Paruch et al., 2014; Barbieri et al., 2024). Warmer conditions facilitate microbial proliferation in irrigation water, thereby increasing the microbial load on crops before harvest. High humidity combined with heat stress prolongs pathogen viability on crops, food-contact surfaces, and within animal reservoirs, creating more opportunities for human exposure (Altieri et al., 2015). Seasonal rainfall patterns further exacerbate contamination risks, as rainy seasons promote wider dissemination of pathogens through runoff and flooding, particularly in regions with limited infrastructure for environmental control (Amare et al., 2019; Birgen et al., 2019). Alterations in precipitation intensity and frequency increase surface runoff, which efficiently transports pathogens to farmlands, irrigation systems, and water sources used in food processing, thereby increasing pathogen loads in waterways following heavy rainfall events (Tyrrel & Quinton, 2003; Tornevi et al., 2014). These environmental dynamics heighten the risk of foodborne disease outbreaks linked to contaminated water sources and agricultural produce (Xiao et al., 2004). Climate-induced shifts in the geographical distribution of pathogen reservoirs and vectors further increase contamination risks, while climate-related stressors affecting livestock and crops weaken inherent immune defenses, facilitating pathogen entry into the food chain (Miller et al., 2007; Alshannaq & Yu, 2017). Biodiversity loss and ecosystem disruption also enable pathogenic microorganisms to dominate ecological niches by weakening natural regulatory mechanisms, thereby exacerbating food safety and public health risks (Hogan et al., 2012).

### 7.2 Flooding, Droughts, and Food Contamination Risks

Extreme weather events such as flooding and droughts substantially amplify food contamination risks and disrupt food supply chains. Flooding events can overwhelm sewage systems and latrines, resulting in widespread contamination of agricultural soils, drinking water sources, and food storage facilities with microbial pathogens, chemical pollutants, and heavy metals (Altieri et al., 2015; Thurston-Enriquez et al., 2005; Yu & Pedroso, 2023). Excessive moisture following floods creates favorable conditions for mold growth and mycotoxin production in stored grains, particularly under poor drying and storage practices, posing serious health risks upon consumption (Bennett & Klich, 2003; Yu & Pedroso, 2023). Drought conditions present contrasting but equally serious challenges, as water scarcity undermines hygiene and sanitation practices and increases reliance on potentially unsafe water sources for irrigation and food processing (Altieri et al., 2015). Reduced water volumes during droughts can concentrate pathogens, elevating microbial loads and increasing contamination risks during irrigation and food washing (Tyrrel & Quinton, 2003). These conditions often encourage informal and unsafe food-handling practices, especially in settings with limited regulatory oversight, thereby increasing vulnerability to foodborne infections (Yu & Pedroso, 2023; Alshannaq & Yu, 2017).

### 7.3 Environmental Sustainability and Food Safety

Sustainable agricultural and environmental management practices play a critical role in mitigating climate-related risks associated with pathogen proliferation. Strategies such as integrated pest management, safe manure handling, and reduced chemical inputs can minimize environmental contamination and limit the spread of pathogens within food systems (Jongman & Korsten, 2016). Protection of water bodies and watersheds is essential to reduce fecal pollution and ensure safer water for irrigation and food processing (Alshannaq & Yu, 2017). Climate-resilient farming systems that enhance soil health and promote biodiversity contribute to the natural suppression of pathogenic

microorganisms and improve overall food safety outcomes (Altieri et al., 2015; Kandpal & Cho, 2014). Environmentally sound waste management practices further prevent cyclical transmission of pathogens among humans, animals, and the environment, while reductions in food loss and waste decrease ecological pressures that favor microbial persistence (Bilgin & Erbaş, 2022; Jongman & Korsten, 2016). Adoption of renewable energy sources and eco-friendly food processing technologies also supports food safety objectives while reducing the ecological footprint of food production systems (Altieri et al., 2015; Kandpal & Cho, 2014).

#### 7.4 Linkages to Sustainable Development Goals

Addressing climate change and its effects on foodborne pathogens aligns closely with several Sustainable Development Goals (SDGs), highlighting the interconnected nature of environmental sustainability and public health. SDG 13 on Climate Action emphasizes the need to strengthen climate adaptation and mitigation strategies to reduce climate-driven risks to foodborne diseases. Integrating climate risk assessments into national food safety and public health planning is essential for reinforcing existing frameworks against the anticipated impacts of climate variability and extreme weather events (Altieri et al., 2015). SDG 15 on Life on Land and SDG 6 on Clean Water and Sanitation further emphasize the importance of environmental stewardship in safeguarding food safety. Conserving terrestrial ecosystems helps maintain ecological balance and limit pathogen emergence and transmission, while sustainable land-use practices reduce soil contamination and enhance food safety outcomes (Altieri et al., 2015; Kandpal & Cho, 2014). Ensuring equitable access to safe water for agriculture, food processing, and household consumption remains fundamental to preventing foodborne infections, and improvements in sanitation infrastructure significantly reduce the environmental dissemination of pathogens into food systems, thereby strengthening public health protection (Altieri et al., 2015; Kandpal & Cho, 2014).

### 8. Conclusion and Future Directions

Foodborne diseases remain a major public health concern in developing nations, particularly in Nigeria, where infrastructural limitations, weak regulatory enforcement, and climatic variability exacerbate the risk of contamination. This study underscores the urgent need for comprehensive strategies to control the prevalence and impact of foodborne pathogens in locally consumed vegetables. Effective prevention requires an integrated, farm-to-fork approach that addresses food safety at every stage of the supply chain. Adoption of Good Agricultural Practices (GAP), proper irrigation and soil management, safe handling of fertilizers and manure, and traceability systems can significantly reduce contamination risks at the production level. At the processing and distribution stages, adherence to Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP) remains essential, though challenges such as limited technical capacity and high operational costs need to be addressed in developing-country contexts.

Sustaining food safety interventions also demands robust policy and regulatory frameworks, routine inspections, strict enforcement, and alignment with international standards such as Codex Alimentarius. Community engagement through education and Behavioral Change Communication (BCC) programs targeting households, market vendors, and food handlers is critical to promote safe practices. Furthermore, climate change and environmental factors (such as floods, droughts, and elevated temperatures) pose additional risks by enhancing pathogen survival and spread, highlighting the need for climate-resilient agricultural practices. Future directions should focus on capacity building for farmers and regulators, research on climate-sensitive pathogen dynamics, improved infrastructure for sanitation and cold-chain management, and public-private partnerships to implement GAP, GMP, and HACCP cost-effectively. Integrating food safety with environmental sustainability will strengthen resilience, reduce disease burden, and ensure safe, nutritious, and equitable food access across Nigeria.

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