



## Food Safety and Microbial Contamination: Implications for Public Health

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### Abstract

Food safety is still a major global public health concern because microbial contamination frequently occurs throughout the food supply chain, from manufacturing to consumption. Contamination can occur during production, processing, storage, and distribution from a variety of sources, including raw materials, water, environmental exposure, food handlers, and improper storage and transit conditions. Globally, foodborne infections brought on by pathogenic microorganisms such as bacteria, viruses, parasites, and fungi result in significant morbidity, mortality, and financial losses. Common foodborne pathogens like *Salmonella spp.*, *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus* are frequently linked to outbreaks caused by contaminated food and water. Globalization, changing consumer behaviour, and the complexity of food supply chains have all increased the risk of contamination. In developing countries like India, issues including poor sanitation, poor hygiene practices, limited awareness, and inadequate infrastructure exacerbate food safety issues. The development of antibiotic resistance in foodborne pathogens poses a severe challenge to effective illness management. Because of their accuracy and reliability, classic culture-based methods are still the gold standard for pathogen detection despite taking a long time. Rapid detection techniques including polymerase chain reaction (PCR), immunological assays, and biosensors require complex infrastructure and technological know-how even if they provide quicker and more sensitive possibilities. For food safety management to be effective, integrated strategies are required. These tactics include norms upheld by agencies like the Food Safety and Standards Authority of India, ISO/IEC 17025-accredited laboratories, and regulatory frameworks like HACCP and Good Manufacturing Practices (GMP). Increasing awareness, putting cutting-edge technologies into practice, and strengthening surveillance are all necessary to ensure food safety and public health.

**Keywords:** HACCP; Foodborne Diseases; Food Safety Regulations; Rapid Detection Techniques; Antimicrobial Resistance

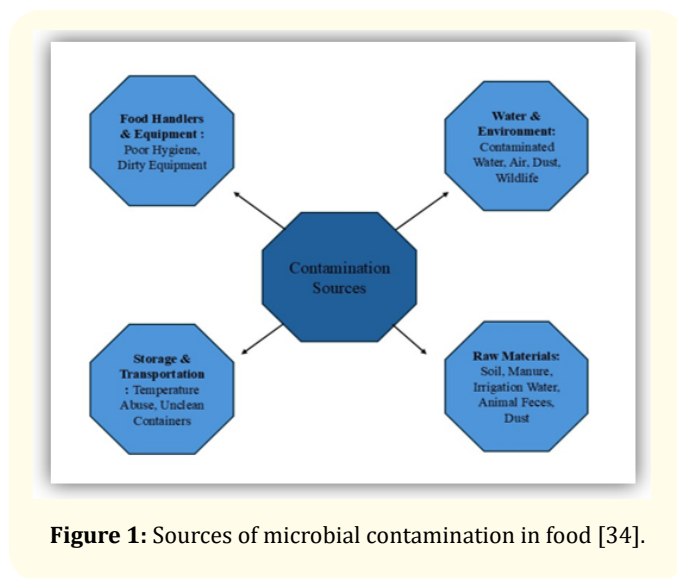
### Introduction

Because microbial contamination regularly occurs across the food supply chain, from production to consumption, food safety continues to be a significant global public health concern [1]. Food must be handled, cooked, and stored correctly to avoid infection and guarantee that it is safe for human consumption [51]. Raw materials, tainted water, exposure to the environment,

food handlers, and inappropriate storage conditions throughout various phases of production, processing, storage, transit, retail, and final preparation can all lead to contamination. Significant morbidity, mortality, and financial losses are caused worldwide by gastrointestinal diseases brought on by harmful microorganisms like bacteria, viruses, parasites, and fungus [4]. Outbreaks connected to contaminated food are often linked to common

foodborne pathogens such as *Salmonella spp.*, *Escherichia coli*, *Listeria monocytogenes*, and *Staphylococcus aureus* [29,31]. Every year, foodborne diseases impact millions of people and result in a significant number of fatalities, especially in vulnerable populations such children, the elderly, pregnant women, and persons with impaired immune systems. Food security and economic stability are impacted by contaminated food, which also has negative effects on productivity, healthcare expenditures, food quality, and waste [5]. The risk of contamination has increased due to the complexity of contemporary food supply chains, urbanization, globalization, and shifting dietary preferences, particularly the growing desire for minimally processed and ready-to-eat foods [38]. Poor sanitation, inadequate hygiene practices, low awareness, and insufficient infrastructure exacerbate food safety challenges in developing countries such as India [48]. Additionally, the emergence of antibiotic resistance in foodborne bacteria poses a significant threat to effective treatment [23]. While contemporary rapid procedures like PCR, immunological assays, and biosensors offer quicker and more effective findings, traditional detection techniques like culture-based approaches are still dependable but take time. To guarantee safe food and safeguard public health, effective food safety management necessitates integrated approaches, such as Hazard Analysis and Critical Control Points (HACCP), Good Manufacturing Practices (GMP), robust regulatory frameworks, surveillance systems, and public awareness [22].

### Sources of microbial contamination in food



**Figure 1:** Sources of microbial contamination in food [34].

### Raw materials

Raw materials are the primary source of microbial contamination in the food supply chain. During primary production, soil, manure, irrigation water, animal waste, and ambient dust expose crops and animals to microorganisms such bacteria, viruses, parasites, and fungi. Fresh vegetables can be contaminated by untreated manure, contaminated irrigation water, and interaction with animals or wildlife [33]. Plant surfaces may harbour pathogens like *Salmonella*, *Listeria monocytogenes*, and *Escherichia coli* until harvest. Pathogens can enter the food chain early in animal-derived foods due to contamination from sick animals, contaminated feed, water, and animal skin [4].

### Water and environment

The main source of microbial contamination in the food supply chain is raw materials. Microorganisms such bacteria, viruses, parasites, and fungi are exposed to crops and animals during primary production through soil, manure, irrigation water, animal waste, and ambient dust. Untreated manure, tainted irrigation water, and interaction with cattle or wildlife can all contaminate fresh food. Plant surfaces may harbour bacteria including *Salmonella*, *Listeria monocytogenes*, and *Escherichia coli* until harvest [49]. Pathogens can enter the food chain early in animal-derived foods due to contamination from sick animals, contaminated feed, water, and animal skin [46].

### Food handlers and equipment

Microbial contamination, especially in ready-to-eat meals, is primarily the fault of food handlers. Poor hygiene habits, including incorrect handling, coughing, sneezing, and insufficient handwashing, can lead to direct contamination [27]. When workers move between clean and contaminated locations without proper sanitation, cross-contamination frequently occurs. Microorganisms may also be present in poorly built or cleaned equipment [35,44]. *Salmonella* and *Listeria monocytogenes* are two pathogens that can linger on surfaces, resist cleaning techniques, and develop biofilms, which can lead to recurrent contamination [39].

### Storage and transportation conditions

Inadequate storage and transportation conditions greatly enhance microbial growth and contamination. Pathogen proliferation is facilitated by temperature abuse, poor hygiene, and insufficient humidity management [11]. For perishable items,

maintaining the cold chain is crucial [52]. The risk of contracting a foodborne illness is increased when raw and processed foods come into contact during storage and transportation. Microorganisms can also proliferate across the food supply chain due to common transportation methods and dirty containers [56].

### Common foodborne pathogens in microbial contamination of food

A few bacterial infections that are widely distributed throughout the food chain and frequently associated with antibiotic resistance are the primary cause of foodborne illnesses [32]. Their low infectious doses, persistence in food environments, and propensity to cause severe or systemic infections all contribute to their importance for public health [21,30].

#### *Salmonella* spp.

One of the most common foodborne illnesses worldwide, *salmonella* causes millions of instances of gastroenteritis and a significant number of deaths each year [9,32]. It is mostly transmitted via contaminated animal products like poultry, eggs, pigs, and beef, even if it is increasingly associated with fresh vegetables and seafood. Particularly in susceptible populations including children, the elderly, and those with compromised immune systems, clinical signs can range from mild fever and diarrhea to serious invasive infections and septicemia. Non-typhoidal strains of the more than 2,500 serovars that have been identified, such as *S. Enteritidis* and *S. Typhimurium*, are most associated with outbreaks and are growing increasingly resistant to antibiotics, making treatment and control strategies more challenging [23].

#### *Escherichia coli*

Numerous extraintestinal and diarrheagenic *Escherichia coli* strains are considered harmful [52]. Shiga toxin-producing *E. coli* (STEC), particularly O157:H7 and non-O157 serotypes, are particularly harmful because they can cause haemolytic uremic syndrome (HUS), a potentially deadly condition, and bloody diarrhea. These illnesses are often associated with undercooked meat, unpasteurized dairy products, contaminated fresh fruit, and contaminated water [48,51]. Because of their tiny infectious dose and major health risks, many food safety regulations employ a "zero tolerance" approach for STEC in ready-to-eat foods [16].

#### *Listeria monocytogenes*

*Listeriosis*, a relatively rare but serious foodborne infection with high hospitalization and mortality rates, is caused by *Listeria monocytogenes*. The primary populations impacted include immunocompromised patients, elderly people, pregnant women, and newborns. One important characteristic of *Listeria* is its ability to survive and grow under harsh environmental conditions such as low pH, high salt concentrations, and refrigeration temperatures [35,44]. Additionally, biofilms of *Listeria monocytogenes* on food processing equipment may lead to persistent infection in food production contexts [39]. Common food sources include fish, dairy products, fresh produce, and ready-to-eat meats. Severe infections can result in meningitis, septicemia, or pregnancy complications [55].

#### *Staphylococcus aureus*

*Staphylococcus aureus*, which is commonly present on human skin and mucous membranes, can contaminate food when it is handled improperly [31,36]. It grows well in foods heavy in protein, such as meat, dairy, and baked items, especially when stored at the wrong temperature. This bacterium produces heat-stable enterotoxins, which can cause food poisoning even after cooking [31]. Rapid-onset symptoms include nausea, vomiting, cramping in the abdomen, and diarrhea often appear within a few hours of ingestion [55]. Since the sickness is caused by ingestion of pre-formed toxins rather than bacterial infection, prevention through proper food storage conditions and excellent hygiene is essential.

#### *Vibrio cholerae*

*Vibrio cholerae*, particularly the deadly O1 and O139 strains, produce cholera, which is characterized by severe watery diarrhea and dehydration [48]. Although contaminated water is the primary means of transmission, raw or undercooked seafood, especially shellfish, and foods washed with contaminated water can also cause foodborne illness [48]. The prevalence of this virus in coastal and estuary environments highlights the intimate relationship between food safety, water quality, and environmental hygiene. The fact that outbreaks are more common in places with inadequate food handling practices, poor sanitation, and limited access to clean water emphasizes the importance of integrated food and water safety management systems.

Pathogen	Sources	Characteristics	Symptoms/Diseases
<i>Salmonella spp.</i>	Poultry, eggs, pork, meat, seafood, fresh produce	Large number of serovars (>2,500); survives in various environments; often multi-drug-resistant	Diarrhea, fever, abdominal cramps; severe cases: septicemia
<i>Escherichia coli</i> (STEC)	Undercooked beef, unpasteurized milk, contaminated vegetables, water	Produces Shiga toxin; very low infectious dose	Bloody diarrhea, abdominal pain; severe: Hemolytic Uremic Syndrome (HUS)
<i>Listeria monocytogenes</i>	Ready-to-eat meat, dairy products, seafood, fresh produce	Can grow at refrigeration temperature; tolerates low pH and high salt.	Listeriosis: meningitis, septicemia, miscarriage in pregnant women
<i>Staphylococcus aureus</i>	Human skin, nasal passages; meat, dairy, bakery products	Produces heat-stable toxins; grows in protein-rich foods	Rapid nausea, vomiting, cramps, diarrhea
<i>Vibrio cholerae</i>	Contaminated water, raw/undercooked seafood (shellfish)	Found in coastal and aquatic environments; linked to poor sanitation	Cholera: severe watery diarrhea, dehydration

**Table 1:** Common Foodborne Pathogens in Microbial Contamination of Food [14,18,54].

**Foods most commonly affected by microbial contamination**

Certain food types are significant transmitters of foodborne illnesses because they offer the perfect environment for the development and survival of viruses and spoiling bacteria. Moisture content, processing techniques, storage circumstances, and nutrient composition all affect the risk [32].

**Dairy products**

Dairy products like milk, cheese, and yogurt are perfect for microbial growth because of their high protein, fat, and moisture content. These products are frequently linked to pathogens as *Bacillus cereus*, *Listeria monocytogenes*, *Salmonella*, *Escherichia coli*, and *Staphylococcus aureus* [31]. *Pseudomonas* and spore-forming bacteria are examples of spoilage organisms that worsen product quality. Particularly susceptible to contamination include raw milk and conventionally processed dairy products, particularly in settings with insufficient refrigeration and unsanitary conditions.

**Meat and poultry**

Meat and poultry products are among the most contaminated food categories due to contamination during handling, processing, and slaughter. Common pathogens include *Salmonella*, *Campylobacter*, *Listeria monocytogenes*, *Staphylococcus aureus*, pathogenic *Escherichia coli*, and *Clostridium perfringens* [9]. Cross-

contamination from surfaces, cutting boards, and blades remains a major issue, particularly in small-scale slaughterhouses and retail establishments with poor hygiene requirements.

**Seafood**

Seafood, which includes fish, shellfish, and shrimp, is particularly susceptible to microbial contamination due to its watery origin and handling conditions. Common infections include *Vibrio species*, *Escherichia coli*, *Salmonella*, and *Listeria monocytogenes* [49]. Shellfish, particularly bivalves, that are consumed raw or undercooked pose a significant risk since they can carry viruses and diseases from contaminated water [14].

**Fresh vegetables and fruits**

Fresh vegetables is increasingly recognized as one of the primary causes of foodborne diseases. Post-harvest handling, irrigation water, soil, and manure can all introduce pathogens such *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes* [27]. Ready-to-eat salads and hardly processed vegetables are particularly dangerous because there is no cooking stage.

**Ready-to-Eat (RTE) and street foods**

Ready-to-eat and street foods like salads, sandwiches, prepared meats, sushi, and dairy-based treats are particularly susceptible

to contamination since they are consumed without further heat treatment. Common pathogens include *Listeria monocytogenes*, *Salmonella*, *Vibrio*, and *Staphylococcus aureus* [50]. Poor hygiene, inadequate temperature control, and contaminated raw materials significantly raise the risk of foodborne disease, especially in street vending situations.

### Mechanism of contamination

Food contamination is caused by several interrelated processes that allow germs to spread and proliferate throughout the food supply chain. Comprehending these mechanisms is crucial for creating efficient control plans and safeguarding public health.

### Cross-contamination

Cross-contamination is one of the primary ways that foodborne viruses propagate in food systems. When germs are transported from contaminated raw materials, water, equipment, or food-contact surfaces to ready-to-eat foods, pathogens such as *Escherichia coli*, *Salmonella enterica*, and *Listeria monocytogenes* can survive and spread. Cross-contamination is intimately linked to inadequate sanitation, reusing tainted wash water, and neglecting to keep raw and processed foods apart in both home and industrial settings [33]. Thus, strict sanitary design, effective sanitation practices, and preventive control systems like HACCP are necessary to reduce microbial translocation across the food chain.

### Environmental aspects

Environmental factors have a major impact on the survival and spread of diseases. Temperature, humidity, pH, oxygen availability, and nutrient content all have a significant impact on microbial growth and persistence in food systems [11]. Some bacteria, like *Listeria monocytogenes*, can grow at refrigerator temperatures, while others, like *Staphylococcus aureus*, produce heat-stable toxins that persist even after thermal processing. Environmental reservoirs that contribute to pollution and promote the formation of biofilms, which enable long-term survival and resistance to cleaning solutions, include soil, irrigation water, air, and surfaces that come into touch with food [39]. Furthermore, the development of agricultural production systems, the expansion of the global food trade, and climate change are accelerating the emergence and spread of foodborne illnesses [45].

### Human handling

Human handling, especially during food preparation and serving, is the main cause of microbial contamination. Poor hygiene habits, such as inadequate handwashing, improper glove use, and handling food when ill, can introduce and transfer harmful bacteria to foods that are ready to eat [33]. *Staphylococcus aureus* is frequently found on human skin, nasal passages, and mucosal membranes. It can produce heat-stable enterotoxins that lead to outbreaks of food poisoning and is frequently connected to food contamination incidents during handling [31]. International food safety frameworks continue to prioritize temperature control, cross-contamination prevention, and personal hygiene to reduce the hazards of human-related contamination in food systems [22].

### Public health implications of foodborne microbial contamination

Because foodborne microbial contamination increases risks for vulnerable populations and results in widespread illness, death, and financial hardship, it has a significant impact on public health. In addition to its effects on individual health, foodborne infections have an impact on international trade, productivity, healthcare systems, and global food security [32]. Therefore, strengthening surveillance, risk assessment, and preventative food safety systems is necessary to reduce this cost at the national and international levels systems [5].

### Foodborne diseases and outbreaks

Acute gastroenteritis, the main symptom of foodborne illnesses, frequently manifests as fever, diarrhea, vomiting, cramping in the abdomen, and nausea [35]. Severe infections can cause renal failure (such as hemolytic uremic syndrome caused by *Escherichia coli*), neurological conditions including Guillain-Barré syndrome, sepsis, or even death [29].

### Economic burden

Foodborne illnesses have a significant economic impact both nationally and internationally. According to the World Health Organization, there are over 600 million cases and 420,000 deaths every year, which means that approximately 33 million disability-adjusted life years (DALYs) are lost [55]. The burden is especially heavy in low- and middle-income nations, where annual economic losses from healthcare expenses, lost productivity, and trade disruptions approach US\$95–100 billion [3]. Foodborne infections

cause around 48 million cases, 130,000 hospital admissions, and over 3,000 fatalities yearly in affluent nations like the United States, with an estimated annual economic cost of US\$75–78 billion [25]. Hospitalization, long-term health issues, and early death are the main causes of these expenses.

**Antimicrobial resistance (AMR)**

A growing issue in foodborne infections is antimicrobial resistance (AMR), which makes treatment extremely difficult and makes illnesses worse. Due to the misuse of antibiotics in both human medicine and animal production systems, pathogens such as *Salmonella enterica*, *Escherichia coli*, and *Campylobacter jejuni* have shown increasing resistance to commonly used antimicrobial drugs [23]. Because antimicrobial resistance (AMR) prolongs illness, increases hospitalization rates, increases death, and drives up healthcare costs, it poses a severe danger to world health. Improving surveillance, One Health-based interventions, and antimicrobial stewardship are essential to preventing the emergence of resistant foodborne illnesses.

**Detection methods for foodborne pathogens**

Ensuring food safety, stopping outbreaks, and protecting public health all depend on the prompt and accurate identification of foodborne pathogens. Modern detection strategies include both traditional culture-based methods and state-of-the-art rapid technologies such as PCR, immunoassays, biosensors, microfluidics, and next-generation sequencing; each has a unique sensitivity, turnaround time, and field applicability [43]. Although they take a lot of time, culture methods are still the best. On the other hand,

early outbreak control can benefit from the quicker and more sensitive detection provided by molecular and biosensor-based technologies [24,40]. The combination of many technologies is becoming increasingly crucial to improve detection accuracy and real-time food safety monitoring in complex food matrices.

**Conventional methods**

**Culture-based techniques**

The “gold standard” for diagnosing foodborne pathogens is still conventional microbiota and logical approaches. Sample enrichment, plating on selective and differential media, colony separation, and biochemical identification using assays like IMViC, catalase, and oxidase are some of these methods [20,26]. These techniques allow for the detection of living microorganisms and additional characterization, such as strain type and antibiotic susceptibility testing. When used in controlled settings, culture-based techniques are incredibly sensitive, accurate, and specific. They are crucial for confirmatory testing, legal documentation, and epidemiological research and are widely approved by regulatory bodies. These techniques also enable the storage of isolates for later research and offer quantitative data on microbial load. Conventional procedures are time-consuming despite their dependability; results may take several days, up to a week for slow-growing organisms, or 18 to 24 hours [35]. Moreover, they require a lot of work and might miss pathogens or viable but non-culturable (VBNC) organisms that are present in trace numbers in complicated food matrices.

Method	Process	Advantages	Limitations
Culture-Based Techniques	Sample enrichment → plating → colony isolation → biochemical tests (IMViC, catalase, oxidase)	Highly accurate and reliable; gold standard; detects live microorganisms; allows further testing (AMR, strain typing)	Time-consuming (1–7 days); labor-intensive; cannot detect VBNC organisms; less effective for low-level pathogens

**Table 2:** Conventional Culture-Based Methods for Detection of Foodborne Pathogens [21,35].

**Rapid detection techniques**

**PCR (Polymerase Chain Reaction)**

For quick detection, molecular methods including multiplex PCR, quantitative PCR (qPCR), loop-mediated isothermal amplification (LAMP), and nucleic acid sequence-based amplification (NASBA)

are frequently employed. Many infections can be found in a matter of hours instead of days thanks to these methods’ remarkable sensitivity and specificity [24,40,43]. They require DNA extraction, specialized equipment, and trained personnel because they might not be able to distinguish between living and dead cells [21,53].

### Immunological assays (ELISA)

Reducing foodborne illness rates and safeguarding public health require effective management and prevention of microbial contamination in food systems [48]. International research and laws place a high importance on risk-based, preventive methods such as Hazard Analysis and Critical Control Points (HACCP) and Good Manufacturing Practices (GMP) [22]. Supply chain transparency, risk governance frameworks, and capacity-building programs in food safety systems all support these strategies [5,38]. A well-known, scientifically grounded method for identifying, evaluating, and controlling food safety risks is the Hazard Analysis and Critical Control Points (HACCP) system.

### Biosensors

To identify infections, biosensor-based detection techniques integrate biological recognition elements (such as antibodies, aptamers, or nucleic acids) with transducers (optical, electrochemical, or mass-based) [6]. With little sample preparation, these techniques provide quick, real-time, and possibly on-site detection. Despite their potential, biosensors are rarely used since they frequently need pre-enrichment and validation and may be impacted by the complexity of the food matrix.

Method	Principle	Advantages	Limitations
PCR (Molecular Methods)	Detects pathogen DNA (PCR, qPCR, multiplex PCR, LAMP, NASBA)	Very high sensitivity and specificity; rapid (few hours); detects multiple pathogens	Requires skilled personnel, expensive equipment; cannot distinguish live/dead cells
Immunological Assays (ELISA)	Antigen-antibody reaction detection	Simple, cost-effective; suitable for field and large sample screening	Lower sensitivity than PCR; risk of false results (cross-reactivity)
Biosensors	Biological recognition + signal transducer (optical/electrochemical)	Rapid, real-time detection; minimal sample preparation; potential on-site use	Requires validation; affected by food matrix; limited widespread use

**Table 3:** Rapid Detection Methods for Foodborne Pathogens [6].

### Comparison of methods

#### Sensitivity and specificity

The highest sensitivity and specificity are offered by molecular techniques like PCR, which can identify infections at low doses. However, the efficacy of the assay may be impacted by inhibitors found in food samples. Culture-based methods may miss stressed or non-culturable cells despite their great specificity [44]. While biosensors differ based on design and validation, immunological tests provide a reasonable level of sensitivity.

#### Time efficiency

In contrast to the days needed for traditional culture procedures, rapid detection approaches produce results in a matter of hours, greatly reducing analysis time (4). Pre-enrichment processes, however, continue to be a time-limiting problem and are necessary for numerous quick approaches.

### Cost and infrastructure

Conventional methods are appropriate for routine testing because of their low cost and minimal requirements for laboratory infrastructure, particularly in environments with limited resources [48]. However, quick processes like PCR and biosensors are less accessible in underdeveloped nations because to their greater equipment, reagent, and labor costs [6,28].

### Control and prevention

To lower foodborne illness rates and safeguard public health, microbial contamination in food systems must be appropriately controlled and prevented [7]. International research and laws place a high importance on risk-based, preventive methods like Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP), which are backed by sanitation

Criteria	Conventional Methods	PCR (Molecular)	Immunological (ELISA)	Biosensors
Sensitivity and Specificity	High specificity; moderate sensitivity	Very high sensitivity and specificity	Moderate	Variable (depends on design)
Time Required	Slow (1–7 days)	Fast (few hours)	Fast	Very fast (real-time possible)
Cost	Low	High	Moderate	High
Infrastructure	Basic lab needed	Advanced equipment required	Moderate setup	Advanced/innovative setup
Detection Type	Live organisms	DNA (live and dead)	Antigens/antibodies	Biological signals

**Table 4:** Comparative Analysis of Conventional and Rapid Detection Methods for Foodborne Pathogens [6].

and hygiene programs [19]. A well-known, scientifically grounded method for locating, assessing, and managing risks to food safety is the Hazard Analysis and Critical Control Points (HACCP) system [22].

**HACCP**

HACCP was created by the Codex Alimentarius Commission and emphasizes risk prevention over end-product testing alone. Hazard analysis, critical control point (CCP) identification, critical limit setting, monitoring strategies, corrective actions, verification procedures, and documentation are the seven fundamental tenets of HACCP. These regulations are utilized to manage biological hazards including *Salmonella*, *Listeria monocytogenes*, and *Escherichia coli* at every stage of the food chain, from the manufacture of raw materials to ultimate consumption [9]. Research has shown that HACCP greatly lowers the risk of contamination, improves process control, and improves food safety results [19,57]. It is widely used in the food industry and required by numerous international regulatory systems. Its efficacy, however, depends on appropriate documentation, training, and regular monitoring—all of which can be difficult in small-scale and unofficial businesses [48].

**Good manufacturing practices and sanitation practices**

Food is regularly manufactured and inspected in accordance with quality and safety standards in accordance with basic rules known as Good Manufacturing Practices (GMP) [19]. Important topics covered by GMP include raw material handling, personnel hygiene, equipment maintenance, facility architecture, and process control. These procedures reduce the possibility of contamination

and make it possible to apply HACCP systems successfully. To stop germs from growing and spreading in food environments, sanitation measures like washing and disinfection techniques are essential. According to fundamental guidelines known as Good Manufacturing Practices (GMP), food is routinely produced and inspected in compliance with quality and safety requirements [19]. Raw material handling, staff hygiene, equipment maintenance, facility architecture, and process control are all significant subjects addressed by GMP. These processes lower the risk of contamination and enable the effective implementation of HACCP systems. Sanitation practices including washing and disinfection methods are crucial to preventing the growth and transmission of germs in food environments.

**Public health implications**

By lowering contamination at crucial stages in the food chain, HACCP and GMP adoption dramatically lowers the incidence of foodborne illnesses. Preventive measures improve food quality, save costs, and boost consumer trust. However, in low-resource settings in particular, inadequate implementation is still a contributing factor to foodborne outbreaks and public health hazards [27]. To maximize the effectiveness of these control measures, infrastructure, training, and regulatory enforcement must be strengthened [5,48].

**Food safety regulations and standards**

Strong regulatory frameworks, dependable laboratory systems, and consistent testing procedures are necessary for effective food safety management. Together, these elements guarantee food

items' safety, quality, and compliance, safeguarding public health and promoting global trade.

## Regulatory framework in India

### Food safety and standards authority of India guidelines

The Food Safety and Standards Authority of India, created under the Food Safety and Standards Act, 2006, oversees overseeing food safety in India. This Act became the main regulatory authority in charge of overseeing food safety by combining a number of previous food regulations into a single, comprehensive framework. In addition to regulating the production, storage, distribution, sale, and import of food, FSSAI creates science-based standards for food items and uses licensing and registration procedures to guarantee compliance. Guidelines for food safety, labelling, packaging, and allowable limits of pollutants and additives are also published. In order to guarantee food safety harmonization and promote international trade, FSSAI is crucial in coordinating its standards with worldwide standards like the Codex Alimentarius Commission [22]. However, there are still issues with implementation, such as a lack of qualified personnel, inadequate lab equipment, and limitations on the control of the sizable informal food industry [48].

### Indian standards (IS Methods)

The Bureau of Indian Standards (BIS) created Indian Standards (IS procedures), which offer approved and standardized analytical techniques for food testing. For official control, quality assurance, and compliance verification, labs frequently employ these techniques. They guarantee that the outcomes are consistent, dependable, and repeatable across various testing facilities [17].

### Laboratory accreditation

#### National accreditation board for testing and calibration laboratories

In India, testing and calibration facilities are accredited by the National Accreditation Board for Testing and Calibration Facilities. It guarantees that laboratories adhere to global standards of proficiency and dependability, particularly in food testing. In addition to supporting regulatory enforcement activities like recalls and legal procedures, accreditation improves the reliability of laboratory data [42].

### ISO/IEC 17025

The widely accepted standard for testing and calibration labs is ISO/IEC 17025. It outlines specifications for personnel proficiency,

equipment calibration, method validation, traceability, and quality management systems [20]. International trade, regulatory compliance, and food safety monitoring all depend on accurate and repeatable results from labs accredited under this standard.

### Role of regulations in food safety

#### Quality assurance

Regulations pertaining to food safety guarantee that food items fulfil specific safety and quality requirements. Regulatory systems preserve uniformity and dependability in food testing and control procedures through set standards, validated techniques, and accredited laboratories.

#### Compliance and monitoring

To verify adherence to food safety regulations, regulatory bodies carry out testing, monitoring, and inspections. Systems that help identify possible risks and stop tainted food from reaching consumers include licensing, audits, and routine monitoring [28]. To lower the risk of foodborne illness and preserve public confidence, effective enforcement measures are crucial [3].

#### Global alignment

To safeguard public health and promote international trade, food safety rules are getting closer to international norms. Global food safety systems are supported by organizations like the Food and Agriculture Organization and the World Health Organization, which also provide scientific assistance (WHO, 2024). International trade agreements accept the international standards set by the Codex Alimentarius Commission as benchmarks for national rules [8].

### Challenges in food safety

Globalization, changing food production systems, and infrastructure and technology limitations all have a direct impact on the management of microbial contamination and associated public health hazards [30].

### Growing food supply chain complexity

Production, processing, packing, shipping, and international distribution are all crucial components of today's complex food supply chains. Globalization raises the likelihood of contamination at multiple stages and complicates traceability [1]. Foodborne diseases, such as *Salmonella* and *Listeria monocytogenes*, can spread swiftly across international boundaries through contaminated

food products. The increasing demand for minimally processed and ready-to-eat foods increases the risk of contamination [38].

### Lack of infrastructure in developing regions

Inadequate infrastructure continues to be a significant obstacle to effective food safety management in many low- and middle-income countries [2,48]. Lack of cold chain systems, limited laboratory capacity, poor sanitation, and contaminated water sources all increase the risk of microbiological contamination [25]. Foodborne infections can also be caused by informal food markets and noncompliance with regulations.

### Limited technical expertise

Microbiologists, food technologists, and quality control specialists are among the specialized workers needed for efficient food safety management [35]. However, the lack of qualified workers in many places makes it difficult to apply advanced detection techniques and systems like Hazard Analysis and Critical Control Points (HACCP). Inadequate training for food handlers also contributes to poor hygiene standards and increased contamination [51].

### Limitations of detection

Despite advancements in detection technologies, a number of limitations remain in existence. Rapid techniques like PCR and biosensors require costly equipment and skilled personnel, while traditional processes still take a long time [43]. Detection accuracy is affected by low pathogen concentrations, complex dietary matrices, and difficulties distinguishing between viable and non-viable cells [41]. These limitations may make it more challenging to promptly monitor food safety and result in a delay in responding to outbreaks [24].

### Future perspectives and recommendations

A comprehensive and integrated strategy that incorporates capacity building, enhanced regulatory frameworks, and continuous technological innovation is required to effectively address current food safety concerns and assure sustainable public health protection [7].

### Adoption of advanced technologies

Food safety could be greatly enhanced by new technologies including biosensors, artificial intelligence (AI), whole genome

sequencing (WGS), and Internet of Things (IoT)-based monitoring systems [6]. These technologies aid in risk assessment and pandemic prevention by enabling quick detection, real-time monitoring, and improved food product traceability [47].

### Strengthening laboratory capacity

Reliable food testing requires building laboratory infrastructure and expanding access to accredited laboratories to ensure consistent and reliable results [42]. Compliance with international standards such as ISO/IEC 17025 and accreditation by organizations such as the National Accreditation Board for Testing and Calibration Laboratories ensure that test findings are accurate, reproducible, and accepted globally [37]. Improving laboratory performance requires consistent investment in state-of-the-art equipment, dependable quality control systems, and the training of skilled technical personnel [20].

### Improved surveillance and monitoring

For foodborne outbreaks to be identified early and effectively managed, robust surveillance systems are essential. Global food safety monitoring is facilitated by international collaboration and data-sharing networks supported by organizations such as the World Health Organization [54]. Strengthening national surveillance programs and integrating modern data analytics and digital technology can significantly improve risk assessment, timely outbreak response, and overall food safety management [32].

### Training and awareness programs

To improve food safety procedures, extensive education and training programs are required for industry workers, food handlers, and regulatory agencies [23]. Continuous capacity-building initiatives improve knowledge of hygiene practices, safe food handling, sanitation, and hazard reduction techniques. Awareness campaigns that emphasize proper food preparation and hygiene significantly reduce the risk of microbiological contamination and foodborne disease, especially in developing countries. Furthermore, promoting internationally recognized standards like GMP and HACCP enhances compliance and preventive control systems. Furthermore, training programs assist food handlers in changing their behavior, which improves the culture of food safety and reduces the risk of cross-contamination. Increasing education and awareness is generally still necessary to ensure a safer food supply chain and protect public health [57].

## Conclusion

Food safety is a major global public health concern due to the prevalence of microbial contamination throughout the food supply chain. Foodborne illnesses brought on by bacteria like *Salmonella*, *Escherichia coli*, and *Listeria monocytogenes* continue to be a significant global health and financial burden. Globalization, the increasing complexity of food systems, and emerging risks like antibiotic resistance and climate change make managing food safety more challenging. Rapid detection methods require advanced equipment and expertise, but they provide speedier and more sensitive alternatives. Conventional detection techniques are limited by time constraints but produce reliable results. To reduce contamination and ensure food safety, robust regulatory frameworks and preventive methods like HACCP and Good Manufacturing Practices (GMP) are crucial. The Food Safety and Standards Authority of India and approved laboratories that follow ISO/IEC 17025 standards play a major role in maintaining food quality and safety in India. To properly address current issues, integrated strategies involving state-of-the-art technologies, expanded laboratory capacity, enhanced monitoring systems, and greater training and awareness initiatives are needed. International organizations, corporations, governments, and researchers must work together to develop sustainable food safety systems. In a world that is becoming more interconnected by the day, ensuring safe food is crucial for promoting economic growth, food security, and consumer confidence in addition to protecting public health.

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