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Review

Impacts of Climate Change on Food Safety and Pathogen Management

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Abstract

Climate change poses an increasing challenge to food safety by altering environmental conditions that influence the survival, growth, and virulence of foodborne pathogens. Rising temperatures, extreme heat events, and irregular precipitation patterns can promote the proliferation of bacteria such as *Campylobacter* spp., *Salmonella* spp., *Escherichia coli*, *Listeria monocytogenes*, *Vibrio* spp., and *Staphylococcus aureus*, while also favouring the persistence of antimicrobial-resistant strains. These environmental shifts impact microbial dynamics throughout the supply chain, from pre-harvest contamination in crops and livestock to post-harvest handling, processing, and storage, increasing the likelihood of outbreaks, compromising cold chain integrity, and reducing shelf life. To mitigate these emerging hazards, food safety management must adapt. Traditional frameworks, including the HACCP (Hazard Analysis and Critical Control Points) system and GHP (Good Hygiene Practices), can be strengthened by incorporating climate-sensitive predictive modelling and real-time monitoring. Tools such as quantitative microbial risk assessment, Monte Carlo simulations, and environment-informed risk models allow for proactive assessment and targeted control measures. Additional interventions—including environmental surveillance, optimised cold chain operations, and adaptive production protocols—enhance resilience across the food supply chain. This review synthesises current evidence on climate-driven changes in microbial risks and outlines practical approaches for maintaining microbiological safety and product quality. A coordinated, multi-level approach integrating predictive insights, monitoring, and responsive management is essential to protect public health under a warming climate.

Keywords: environmental change; foodborne pathogens; food safety; microbial risk assessment; mitigation strategies

1. Introduction

Climate change, driven by both natural variability and anthropogenic activities such as industrialisation, energy production, transportation, and modern agriculture, has led to increasing atmospheric CO_2 concentrations and rising global temperatures, primarily due to fossil fuel combustion, deforestation, and land-use change [1]. Observed impacts include persistent warming, altered precipitation patterns, sea-level rise, and a higher frequency of extreme weather events, trends that are expected to intensify in the coming decades [2]. These changes threaten food production and distribution, particularly in regions prone to droughts, heatwaves, or flooding, while compromising water quality, storage, and hygiene in areas with limited infrastructure [3]. Reduced precipitation and water scarcity may further concentrate microbial contaminants in shrinking water bodies, thereby increasing the risk of contamination in irrigation systems and subsequent transfer along the food chain.

Pathogens respond differently to environmental fluctuations. Bacteria such as *Escherichia coli*, *Salmonella* spp., and *Campylobacter jejuni* generally thrive under warmer and more humid conditions, whereas viral agents, including Norovirus, may be influenced by additional environmental drivers. Rainfall variability can modulate the transmission of protozoan pathogens, whereas warming coastal waters favour marine species such as *Vibrio* spp. Heat stress in livestock may further enhance shedding of enteric bacteria, increasing contamination risks [4]. Microorganisms can also sense environmental cues to regulate virulence, biofilm formation, and mutation rates, thereby influencing antimicrobial resistance (AMR) and persistence in food products and their surrounding environments [5].

In addition to microbiological hazards, climate-sensitive conditions can influence mycotoxin occurrence, a group of chemically stable, low-molecular-weight secondary metabolites produced by filamentous fungi such as *Aspergillus*, *Fusarium*, *Penicillium*, and *Alternaria*. Compounds such as aflatoxins, deoxynivalenol (DON), zearalenone (ZEA), and ochratoxin A (OTA) can persist in food matrices even after fungal elimination, exerting diverse toxicological effects. Human intake, primarily through contaminated plant- and animal-derived products, may result in gastrointestinal, dermatological, and reproductive disorders, as well as long-term outcomes such as immunotoxicity, neurotoxicity, and cancer. Climate stressors such as higher temperature, elevated humidity, and plant physiological stress promote fungal proliferation and mycotoxin synthesis, altering host susceptibility and expanding the geographic range of toxigenic species [6]. For instance, rising temperatures in Southern Europe are expected to increase aflatoxin contamination in maize, while Northern and Central Europe may face higher DON and ZEA levels in wheat,

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illustrating emerging regional challenges for food safety under shifting climatic conditions [7].

Concurrently, environmental changes influence the fate, chemical forms, and availability of heavy metals and radionuclides in soils, sediments, and aquatic ecosystems. Elements such as cadmium, lead, mercury, and caesium may be mobilised from previously stable reservoirs, undergo chemical transformations that enhance solubility or uptake, and accumulate in crops, livestock, and aquatic organisms. These processes can elevate human dietary intake, potentially affecting renal and hepatic function, neurodevelopment, and reproductive health. Simultaneously, modifications in soil properties (i.e., pH, redox potential, organic matter content, and moisture) affect metal retention and mobility, while radionuclide transport may be accelerated through ground- and surface-water pathways. Importantly, agroecological stressors that facilitate fungal toxin production may also enhance chemical contaminant transfer along the food chain, creating overlapping biological and chemical risks [8].

Alongside contaminant dynamics, extreme weather events, such as prolonged heat, extended droughts, intense rainfall, and strong winds, can directly compromise food production and processing facilities. Such events disrupt irrigation and water management and impair storage and handling, leading to increased contamination risks and postharvest losses. Rising sea levels and reduced freshwater availability further stress irrigation and aquaculture systems, while shifting climatic zones may alter crop suitability and livestock performance. Collectively, these factors influence not only microbial safety but also nutritional quality and equitable food access, disproportionately affecting populations with limited adaptive capacity [9].

Food safety—the management of food handling, preparation, and storage to prevent foodborne illnesses—and food security—access to sufficient, safe, and nutritious food—are intrinsically linked. Climate change exacerbates risks to both, particularly by altering nutrient content and safety during distribution. Preventive frameworks, such as the Codex Alimentarius guidelines and the Hazard Analysis and Critical Control Points (HACCP) system, remain crucial to mitigate microbial hazards and preserve food quality.

The magnitude and impact of these changes vary geographically, reflecting differences in climate, agricultural practices, infrastructure, and socioeconomic context [10]. Despite clear disruptions in yield and supply chains, the consequences of changing environmental conditions on food safety remain insufficiently explored. The aim of this structured narrative review is to provide an updated and comprehensive overview of the impact of climate change on food safety, microbial risk management, and foodborne disease control.

2. Literature Review

This review was conducted following a structured methodological approach. The main research topics were first identified, focusing on the effects of environmental changes on food systems, their implications for food safety and microbiological quality, and the strategies adopted by the food industry to mitigate these negative effects. Relevant publications were retrieved from Scopus, PubMed, Google Scholar, and ResearchGate.

The following search query was used in this study:

TITLE-ABS-KEY (

"foodborne pathogens" OR "microbial hazards" OR "*Campylobacter*" OR "*Salmonella*" OR "*Listeria monocytogenes*" OR "*Escherichia coli*" OR "*Vibrio*" OR "*Staphylococcus aureus*" OR "foodborne viruses" OR "marine biotoxins"

)

AND TITLE-ABS-KEY (

"climate change" OR "climate"

)

AND TITLE-ABS-KEY (

"food quality" OR "shelf life" OR "food safety" OR "public health" OR "antimicrobial resistance" OR "adaptive strategies" OR "HACCP"

)

AND TITLE-ABS-KEY (

"review" OR "study" OR "evaluation" OR "analysis"

)

AND PUBYEAR > 2000 AND PUBYEAR < 2026

AND (LIMIT-TO (LANGUAGE, "English"))

Publications were included only if they met the following criteria: (i) provided clear information on study design and data analysis; (ii) reported data on the impact of climate change on one or more food-related parameters. Exclusion criteria comprised duplicate records, non-English publications, studies with unclear methodologies, and those not relevant to the scope of this review. Moreover, grey literature, such as PhD theses and white papers, was excluded due to limited peer review and variable data reliability.

Two reviewers independently screened titles, abstracts, and full texts. The selection process is shown in Fig. 1. A total of 772 records were identified, of which 177 duplicates were removed. After title and abstract screening, 328 articles were excluded as not relevant to the subject of this review. The remaining studies were systematically assessed for eligibility. For each publication, the following data were extracted: the first author's name, country, year of publication, type of study, sampling period, and key results. These data were used to critically evaluate the studies in terms of relevance, coherence with the topic, and data quality. Only full-text articles providing detailed insights into the effect of environmental changes on food safety and microbial risks such as AMR and the performance of quality management systems, were considered.

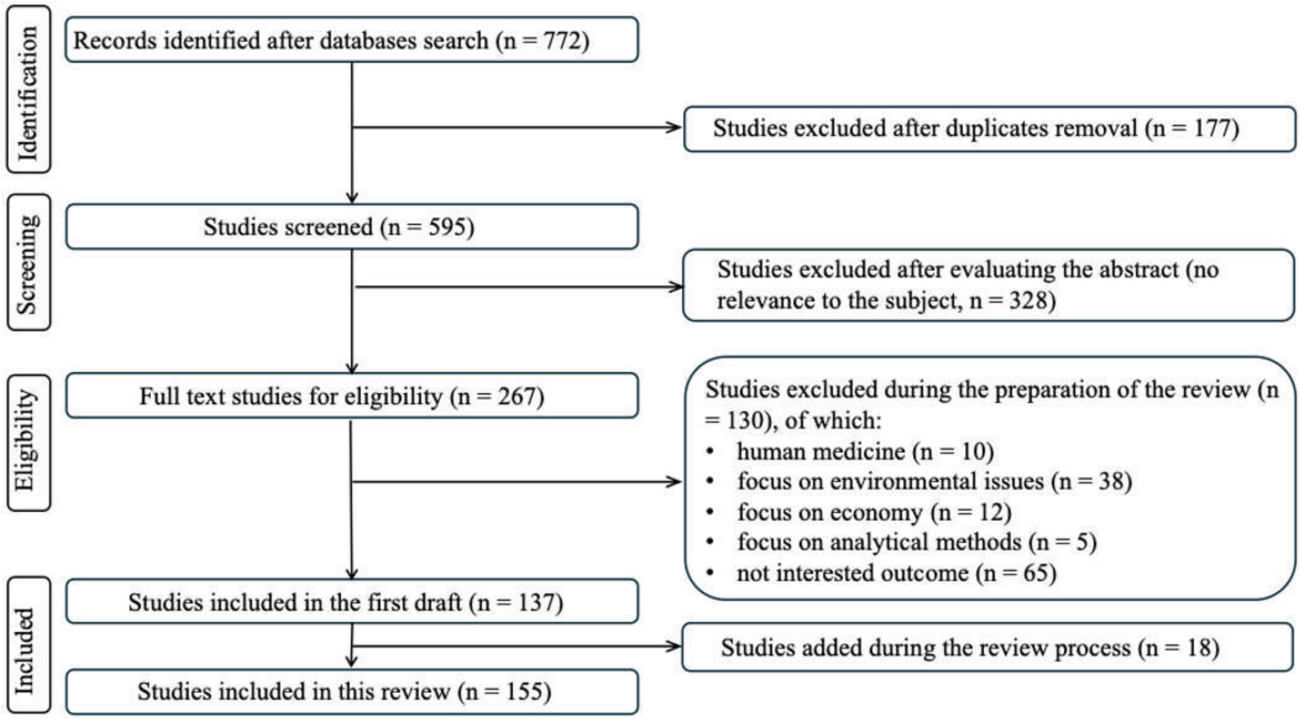

Fig. 1. Flow diagram of the study selection process.

During the eligibility assessment, 130 articles were excluded for reasons detailed in Fig. 1. In total, 155 studies were included in the final analysis. Given the structured but non-systematic nature of this review, no formal risk-of-bias assessment was performed. The findings were organised into thematic sections, including (i) the dynamics of foodborne pathogens under changing environmental conditions, (ii) industry adaptation strategies, and (iii) predictive approaches to manage climate-related risks. This structure provides an overview of food safety challenges under evolving environmental pressures.

3. Climatic Drivers Shaping Food Safety Along the Food Chain

Although more than one hundred zoonotic agents have been identified along the food chain [11], the global burden of foodborne illness in humans is largely driven by a limited number of bacterial pathogens. The dynamics of these hazards are strongly shaped by climatic drivers, which influence pathogen persistence, environmental dissemination, and contamination pathways at multiple stages of the food chain (Fig. 2, Ref. [12]).

3.1 Campylobacter

Campylobacter spp. is the leading bacterial cause of gastroenteritis in humans in Europe, with particularly high incidence in Nordic countries, including Denmark, Finland, and Sweden [13]. In 2024, the European Union (EU) reported 168,396 confirmed cases, corresponding to a notification rate of 55.6 cases per 100,000 population, which represents an 11.9% increase compared with 2023 and confirms a statistically significant upward trend from 2020 to 2024 [14]. Globally, *Campylobacter* remains a major public health concern, causing an estimated 48 million diarrhoeal episodes annually among children under five [15]. Transmission occurs primarily through contaminated food, especially poultry meat, unpasteurised milk, and cross-contaminated vegetables [16,17]. Environmental exposure pathways, including recreational waters, occupational contact in poultry farms or slaughterhouses, and domestic animals, further contribute to infection risk [18,19].

A pronounced seasonal pattern is observed, which reflects changes in animal reservoir prevalence, environmental exposure, and food-handling practices [20,21]. Temperature and sunlight levels in the weeks preceding infection have been shown to influence poultry colonisation and indirectly affect human case occurrence [9]. Climatic factors play a central role in shaping *Campylobacter* transmission. Elevated ambient temperatures are consistently associated with increased incidence, with estimates suggesting that a 1 °C rise may result in approximately a 5% increase in reported cases [22]. Sustained high temperatures in tropical and subtropical regions further accelerate bacterial growth and environmental persistence. In contrast, the effect of precipitation is more complex and depends on intensity, timing, and antecedent conditions [23,24]. Heavy rainfall events near animal production sites have repeatedly been linked to outbreaks by facilitating pathogen dissemination through runoff, flooding, and compromised water systems [25,26]. Conversely, dry conditions and increased

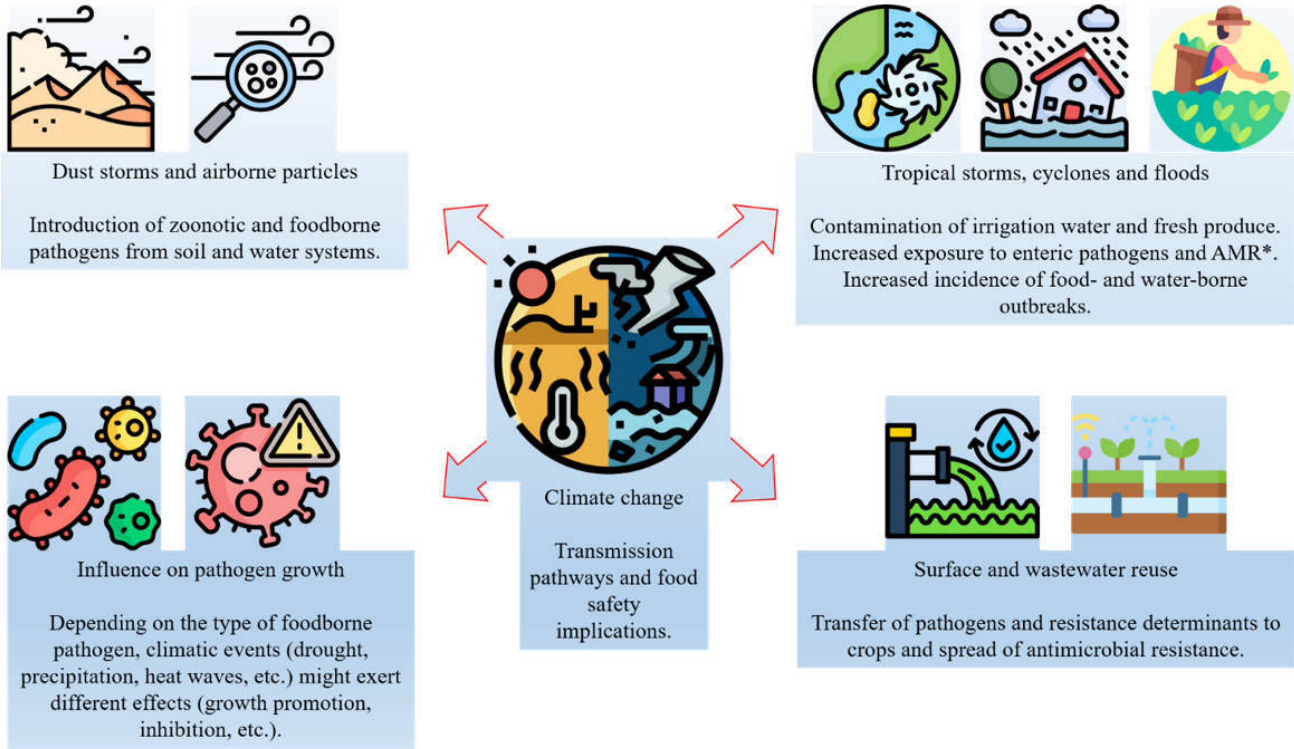

Fig. 2. Environmental pathways of foodborne pathogen transmission (adapted by Balta et al., 2024 [12]). Icons designed from Freepik, nangicon, Iconjam, Konkapp and pongsakornRed, toempong from www.flaticon.com. Legend: * = antimicrobial resistance.

solar radiation tend to reduce environmental survival. This highlights the multifactorial nature of meteorological influences.

Climate projections suggest that *Campylobacter* infections in Northern Europe could increase by up to 200% by 2100, mainly due to rising temperatures and extended summer-autumn transmission periods [13,27]. Heat stress in livestock, particularly poultry, weakens immune defences, impairs gut function, and alters microbial balance, leading to increased shedding of pathogens (including *Campylobacter*) into the environment and promoting vector activity, such as flies, thereby elevating contamination risks along the slaughter and processing chain [28,29]. Targeted on-farm interventions are crucial, as poultry (the main reservoir) exhibits temperature-sensitive colonisation, to prevent campylobacteriosis outbreaks.

The growing prevalence of AMR *Campylobacter* strains adds further complexity. Climate-driven pressures, combined with antimicrobial use in livestock, have selected for resistance to fluoroquinolones, macrolides, and tetracyclines. Elevated temperatures and extreme weather events may accelerate bacterial growth, biofilm formation, and horizontal gene transfer, promoting AMR dissemination [30]. These challenges are particularly pronounced in low- and middle-income countries, where limited sanitation and informal food markets facilitate environmental contamination and spread [31]. The increasing reuse of treated wastewater for agricultural irrigation, often driven by water scarcity, also represents a climate-linked exposure route, especially for crops consumed raw, despite existing regulatory standards such as Regulation (EU) No. 2020/741 [32].

Mitigation requires coordinated interventions across the food chain, including strengthened farm biosecurity, water management, carcass decontamination, vaccination strategies, and responsible antimicrobial use [15]. Although mortality remains low, with 76 deaths (0.07%) reported in the EU in 2025 [14], *Campylobacter* continues to impose a substantial public health and economic burden. In the EU, control measures and healthcare costs total € 2.4 billion per year, while globally, human illness and contaminated animal products are associated with losses of 8.6 billion and 12.6 billion US dollars, respectively [33]. Therefore, understanding the complex interactions between climate, environmental pathways, and bacterial ecology is essential to improve surveillance, anticipate outbreaks, and implement effective preventive measures throughout the food chain [13].

3.2 Salmonella Same as Above (for Campylobacter), spp. Should not be Italicized

Salmonella spp. is a prominent foodborne pathogen in the *Enterobacteriaceae* family, responsible for gastroenteritis in humans and capable of infecting a wide range of animals [34]. Human infection primarily occurs through the consumption of contaminated food or water, with poultry, eggs, meat, and low-moisture products being the most

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common sources [35]. Animals act as reservoirs and vectors of *Salmonella*, with young poultry and livestock particularly susceptible. The pathogen's ability to persist in diverse environments, including animal feed, water, and farm settings, combined with its survival under both dry and moist conditions, facilitates widespread transmission along the food chain [36]. Biofilm formation further enhances environmental persistence, promoting indirect spread via contaminated surfaces, utensils, and intermediate vectors such as insects, rodents, and wild animals [37].

Globally, *Salmonella* causes an estimated 200 million to 1 billion infections annually, resulting in around 93 million cases of foodborne gastroenteritis and 155,000 deaths, mainly linked to foodborne transmission [38]. In the EU, salmonellosis is the second most reported foodborne gastrointestinal infection in humans. In 2024, 79,703 confirmed cases were reported across 27 Member States, corresponding to a notification rate of 18.6 cases per 100,000 population, slightly higher than 2023. Most cases (86.7%) were domestically acquired, with a seasonal peak in summer months. Surveillance data indicate that poultry products and meat are the main sources of contamination along the production and distribution chain, with the highest prevalence at manufacturing and the lowest at distribution [14].

Climate and temperature exert a strong influence on *Salmonella* transmission and outbreaks. The pathogen grows optimally at 35–37 °C, with minimal proliferation below 15 °C [39]. Studies show that a 1 °C increase in mean weekly maximum or minimum temperatures is associated with an 8.8% and 5.8% rise in cases, respectively [40,41]. Higher temperatures accelerate bacterial multiplication in food and increase the risk of cold chain disruptions during storage and preparation, particularly during outdoor activities such as barbecues or picnics [41]. Heatwaves have been linked to spikes in salmonellosis, with more severe outbreaks in late summer than in early warm-season months [42].

Climate change is expected to further affect *Salmonella* prevalence through multiple pathways. Warmer temperatures may expand the pathogen's geographic range toward higher latitudes and altitudes, where cooler conditions limit its growth, increasing exposure risk for humans and animals [43].

Regarding AMR, high temperatures can significantly promote horizontal gene transfer in *Salmonella*. For instance, Zhao et al. [44] investigated the influence of different temperatures (17, 27, 37, and 42 °C) on the conjugative transfer of antibiotic resistance genes in the presence of residual chlorine among various recipient bacterial strains, including *Salmonella enterica*. The transfer frequencies at 27, 37, and 42 °C increased by 1.07–2.43, 1.20–4.80, and 1.24–2.82 times, respectively, compared to 17 °C. The authors suggested a multiple pathway mechanism, such as the generation of reactive oxygen species, which triggered the SOS response and facilitated pilus channel formation, ultimately enhancing the transfer of resistance genes between cells [44]. Aviv et al. [45] observed how warmer temperatures mediated transfer properties advantageous to *Salmonella* Infantis concerning resistance genes. In particular, the conjugation and transcription of pESI pilus genes (a megaplasmid carrying resistance and virulence genes) were suppressed at ambient temperature (27 °C) but significantly enhanced at body temperatures of 37–41 °C.

As climate change elevates ambient temperatures, these mechanisms accelerate the dissemination of resistance genes (such as tetracycline and colistin resistance genes, plasmid-mediated quinolone resistance genes, etc.) through food systems.

Extreme weather events, including heavy rainfall and floods, can deteriorate water quality, spreading *Salmonella* from human sewage, animal waste, and contaminated runoff into the environment [46]. Flooding has been shown to increase microbial contamination in surface waters, alter soil microbiomes, and enhance the mobility of waterborne pathogens, sometimes including multidrug-resistant *Salmonella* strains [47,48]. Increased humidity and soil moisture associated with altered precipitation patterns can favour bacterial survival and dissemination in agricultural environments [49]. Climate-driven shifts in insect populations, which can act as vectors, and warmer ocean temperatures that expand marine species harbouring *Salmonella* further compound outbreak risks [50]. Predictive modelling, including regression and artificial neural network approaches, has demonstrated strong correlations between temperature increases and *Salmonella* outbreaks. Neural network models have proven effective for anticipating climate-driven trends in infection rates. Projections suggest that, under climate change scenarios, the incidence of salmonellosis in Europe could rise substantially in the coming decades, potentially adding tens of thousands of temperature-related cases per year [43]. These findings highlight the need for continuous surveillance, climate-informed predictive tools, and adaptive food safety measures to mitigate the impacts of rising temperatures and extreme weather events on *Salmonella* transmission along the food chain.

3.3 Escherichia coli

E. coli is a ubiquitous inhabitant of the intestinal tract of humans and other warm-blooded animals. While most strains are harmless commensals contributing to gut homeostasis, a subset has acquired virulence traits enabling intestinal and extraintestinal disease. Through faecal contamination, *E. coli* is widely disseminated in the environment, where it can persist in water, soil, animal housing, and food production settings [51]. Livestock, particularly cattle and poultry, represent the main reservoirs, facilitating transmission along the food chain. Human infection occurs primarily through the consumption of contaminated food or water, with undercooked meat, raw milk, fresh produce, and low-moisture foods acting as common vehicles of exposure [52,53]. Direct contact with animals or contaminated environments further contributes to infection risk. The public health relevance of *E. coli* is amplified by its ability to survive under diverse environmental conditions and form biofilms, which enhance persistence on food-contact surfaces and within processing environments [54]. Moreover, *E. coli* represents a key reservoir of AMR genes. Both pathogenic and commensal strains can acquire and disseminate resistance determinants via mobile genetic elements, linking human, animal, and environmental compartments [55]. Globally, pathogenic *E. coli* remains a major cause of foodborne illness and diarrhoeal disease, accounting for substantial morbidity and mortality, particularly among young children, the elderly, and immunocompromised individuals [56]. Notably, infections in children have been shown to increase during periods of elevated temperatures and heatwaves, with higher risks observed on days when the maximum temperature exceeds the 90th percentile [57].

Climate variability and long-term warming trends are increasingly recognised as key drivers of diarrhoeagenic *E. coli* transmission. Epidemiological studies consistently report pronounced seasonality, with higher incidence during warmer months, reflecting the temperature sensitivity of enteric pathogens. Elevated temperatures promote bacterial replication and environmental persistence, increase pathogen loads in animal reservoirs, and amplify human exposure through contaminated food and water [58]. Experimental evidence suggests that, under climate change scenarios with temperature increases of +2, +4, and +6 °C, pathogenic *E. coli* strains (O157:H7, O104:H4, and O26) can persist on fresh produce at levels that often exceed the infectious dose for humans. Persistence is particularly pronounced when contamination occurs at later stages of plant growth, and bacterial survival does not decline significantly across the studied temperature ranges [59].

Changes in precipitation further modulate transmission dynamics. While average rainfall shows a weaker association, extreme events such as heavy rainfall and flooding have been repeatedly linked to outbreaks by mobilising faecal contamination and compromising water quality. The public health impact of climate-driven increases in *E. coli* infections is expected to be greatest in low- and middle-income settings, where baseline diarrhoeal burden is high and water, sanitation, and food safety infrastructures are particularly vulnerable to climatic stressors. Even modest temperature-related increases in risk may therefore translate into a substantial number of additional cases [58].

3.4 Listeria Monocytogenes

L. monocytogenes is distinctive among major foodborne pathogens due to its ability to grow over a wide temperature range, from near-freezing temperatures to approximately 45 °C [60]. Refrigeration at around 4 °C generally slows bacterial growth; however, temperature fluctuations along the cold chain may allow even low contamination levels in ready-to-eat (RTE) foods to exceed safety thresholds [12]. Biofilms formed under refrigeration conditions, although less extensive, can display increased tolerance to heat and chemical disinfectants, complicating sanitation and control in chilled food systems [61]. Failures in cooling systems, such as power interruptions during extreme climatic events, may further enhance bacterial stress tolerance and potentially increase virulence [41]. Environmental and climate-related factors play a key role in shaping *L. monocytogenes* transmission. Elevated temperatures and increased humidity support its persistence in soil, water, and food-processing environments, while prolonged survival under warmer outdoor conditions may facilitate cross-contamination across food production systems, increasing the likelihood of contamination of crops, livestock, and RTE products [62]. Processing facilities may face increased risks under climate change scenarios, as extreme weather events can disrupt sanitation procedures, water availability, and hygiene practices, favouring pathogen establishment and persistence [63].

Surface water used for irrigation represents an important transmission route for *L. monocytogenes*. The pathogen is frequently detected in ponds, wastewater, and other non-potable water sources. Evidence from Switzerland showed that 13% (25/191) of water samples from rivers, streams, and canals were positive, including hypervirulent lineages previously associated with human and animal listeriosis worldwide [64]. When access to safe water is limited, industrial cleaning and household hygiene practices may be compromised, further increasing the risk of food contamination [65]. Heavy rainfall and flooding events can mobilise environmental reservoirs, facilitating pathogen transfer to agricultural fields and food production systems [66].

Post-harvest contamination constitutes another critical exposure pathway. Studies in the United States have shown that washing cantaloupe melons with contaminated water, followed by hydrocooling, allowed *L. monocytogenes* to enter the fruit through the stem or stem scar and reach internal edible tissues via the vascular system. Once internalised, the pathogen can utilise plant sugars for growth, and its psychrotrophic nature enables proliferation even under chilled storage conditions [67].

Although extensive evaluations examining the effects of climate change on *L.- monocytogenes* AMR are scarce, the phenomenon of stress-induced AMR in *L. monocytogenes* is well-documented in the literature. Wang et al. [68] examined how *Listeria* species respond to various stress conditions, demonstrating that different stressors induce increases in minimum inhibitory concentrations (MICs) of multiple antimicrobial agents. Heat stress elevates the MICs of tetracycline during aerobic incubation and of gentamicin, ciprofloxacin, and trimethoprim-sulfamethoxazole during anaerobic incubation. Acidic and alkaline pH environments elevate the MICs of gentamicin, ciprofloxacin, and trimethoprim-sulfamethoxazole, especially during anaerobic incubation. Osmotic stress elevates the MICs of tetracycline and ampicillin in aerobic environments and of gentamicin, tetracycline, and trimethoprim-sulfamethoxazole in anaerobic settings [68]. Therefore, even if not directly linked, the temperature-dependent survival and stress responses of *L. monocytogenes* provide a crucial mechanistic link to climate change impacts.

Overall, while climate change may not directly alter the ecological niche of *L. monocytogenes*, it can indirectly increase human exposure through temperature variability, cold chain disruptions, extreme precipitation events, and water management challenges. These observations suggest that climate-driven temperature fluctuations may increase human exposure to this pathogen, highlighting the need for strengthened environmental monitoring, adaptive processing practices, and robust control measures to mitigate contamination risks, as well as the consistent implementation and enforcement of existing food safety standards.

3.5 Vibrio spp. the Abbreviation spp. Should not be Italicized

Vibrio spp. are naturally occurring bacteria in marine, brackish, and estuarine environments worldwide, and are commonly associated with aquatic organisms [69]. Human exposure occurs primarily through direct contact with contaminated water or the consumption of contaminated seafood, particularly raw or undercooked shellfish such as mussels and oysters. Among the species of greatest public health concern are *Vibrio cholerae*, *Vibrio parahaemolyticus*, and *Vibrio vulnificus*, which can cause gastrointestinal illness, wound infections, or severe septicaemia, with mortality rates for primary bloodstream infections sometimes exceeding 50% [41,70].

The occurrence, abundance, and pathogenicity of *Vibrio* spp. are strongly influenced by environmental factors, including water temperature, salinity, and seasonal variability. Optimal growth is typically observed in waters above 12 °C with low to moderate salinity (1–25 g/L), conditions that are increasingly reported in European coastal waters during the summer months [41]. Rising sea surface temperatures and more frequent marine heatwaves associated with climate change have been consistently linked to increased concentrations *Vibrio* spp. in coastal and estuarine environments, thereby elevating the risk of human infections [71].

In Northern Europe, outbreaks of *Vibrio*-associated soft tissue infections, particularly in Sweden, Finland, and Denmark, have coincided with periods of elevated temperatures and reduced salinity [72,73]. Similar seasonal patterns have been reported in Asia, where *V. parahaemolyticus* foodborne outbreaks in the Republic of Korea occur predominantly during the summer and correlate with air temperature, precipitation, and regional warming trends [74].

Additional environmental drivers, such as rainfall, runoff, turbidity, and wind dynamics, further influence *Vibrio* spp. proliferation. For instance, studies conducted in the Florida Keys have demonstrated that dust deposition and nutrient enrichment of seawater can enhance the growth of *Vibrio alginolyticus* and *V. cholerae*, illustrating how climate-induced changes in coastal environments may amplify bacterial abundance [75]. Climate-driven alterations in salinity, particularly those associated with sea-level rise, have also been shown to substantially increase *V. vulnificus* exposure in estuarine systems, with modelling studies predicting a fourfold increase in risk in previously low-incidence areas [76].

Shellfish can efficiently accumulate pathogenic *Vibrio* spp. through filter feeding, representing a significant food safety concern, especially for vulnerable populations such as children, the elderly, pregnant women, and immunocompromised individuals. Mitigation strategies rely on limiting human exposure through adequate processing, effective thermal treatments, strict hygiene measures, robust cold chain management, and timely monitoring of seafood after harvest or import. Increasing evidence also highlights the emergence of AMR in *Vibrio* spp., with isolates from seafood and aquatic environments showing reduced susceptibility to commonly used antibiotics, particularly β-lactams such as ampicillin, and, in some cases, multidrug-resistant profiles. The aquatic environment, including wastewater inputs and horizontal gene transfer, represents an important reservoir for resistance determinants, potentially facilitating their spread throughout the food supply system [77].

In summary, rising sea temperatures and altered salinity patterns can elevate *Vibrio* spp. prevalence and human exposure, emphasising the importance of targeted harvest-area monitoring, timely seafood testing, and climate-informed handling practices to reduce infection risks [78].

3.6 Staphylococcus Aureus

S. aureus is a ubiquitous Gram-positive bacterium of major relevance to food safety. Its foodborne significance primarily derives from the production of heat-stable enterotoxins, which are responsible for intoxication even at low bacterial counts [79]. Staphylococcal enterotoxins (SEs) are extracellular proteins that can induce nausea, vomiting, and diarrhoea. They include classical types (SEA-SEE), most frequently associated with outbreaks, as well as a growing number of enterotoxin-like proteins identified in clinical and food isolates. Their production is influenced by cell density, environmental conditions, and genetic regulation, highlighting the importance of controlling *S. aureus* growth along the food chain [80].

The pathogen is able to survive and grow under a broad range of environmental conditions commonly encountered during food production, processing, and distribution. Growth and persistence of the pathogen are modulated by both intrinsic and extrinsic factors, including temperature, water activity, salinity, pH, nutrient availability, and interactions with other microorganisms [9].

Temperature is a key driver of *S. aureus* survival and proliferation in foods. Although low temperatures limit bacterial growth, the pathogen can persist and replicate slowly under refrigeration-like conditions, while optimal growth occurs at temperatures associated with temperature abuse during handling and storage, i.e., when foods are exposed to temperatures above recommended refrigeration limits due to improper storage or cold chain failures [81,82]. Under changing climate conditions, rising ambient temperatures and more frequent heatwaves may therefore increase the likelihood of *S. aureus* proliferation and enterotoxin production, particularly when cooling systems fail or cold chain management is suboptimal.

Temperature variability can also affect *S. aureus* at the molecular level. Experimental evidence indicates that environmental temperature shifts can influence gene expression and stress-response pathways, potentially facilitating the transition from commensal carriage to pathogenic behaviour and enhancing virulence-associated traits relevant to foodborne disease [62,83]. Taken together, these findings highlight that rising temperatures and climate variability can enhance *S. aureus* survival and toxin production, emphasising the importance of adaptive on-farm practices, careful handling, and temperature-controlled processing to mitigate contamination risks along the food chain [9].

In addition to its toxigenic potential, *S. aureus* is increasingly relevant in the context of AMR. Methicillin-resistant *S. aureus* (MRSA), including livestock-associated strains, has been detected in food products such as raw meat and dairy, with contamination originating from both colonised and infected food handlers. This highlights the role of the food chain as a potential interface for AMR transmission. MRSA is responsible for over 300,000 infections and more than 10,000 deaths annually in the United States, while in Europe it is estimated to affect around 150,000 patients each year, with substantial associated healthcare costs. Resistance is mainly mediated by the *mecA* gene, which encodes the altered penicillin-binding protein PBP2a, conferring reduced susceptibility to β-lactam antibiotics [84]. Overall, these aspects emphasise the need for effective control measures to mitigate *S. aureus* risks under changing environmental conditions.

3.7 Foodborne Viruses

Foodborne viruses are major causes of illness from contaminated food and water worldwide, posing significant public health and economic burdens. Key agents include Norovirus, Rotavirus, Hepatitis A and E viruses, Adenovirus, astroviruses, and sapoviruses, with Noroviruses responsible for most acute gastroenteritis cases [85]. In 2024, 20 EU Member States reported 677 virus-related foodborne outbreaks, with Norovirus alone causing 14,297 cases in 631 outbreaks, a sharp rise from 2023. Outbreaks were most often linked to seafood (shellfish, crustaceans, molluscs), mixed dishes, fruits, and vegetables, primarily in restaurants and households [14]. One of the most well-known cases of climate-driven foodborne viral transmission is the infestation of bivalve molluscs with Norovirus. Ferri et al. [86], in a study on farmed mussels (*Mytilus galloprovincialis*) in the Central Adriatic Sea, reported seasonal variation, with peak genetic equivalent (GE) concentrations of Norovirus genogroup I (1.0×10^3 GE/g) and Hepatitis E virus (1.0×10^2 GE/g) observed in winter, demonstrating statistically significant differences when compared with summer and spring. Oh et al. [87] also found a seasonal pattern in Pacific oysters (*Crassostrea gigas*) from Korean shellfish production areas. During the winter months, 22.1% of samples tested positive for Norovirus. However, samples from areas that followed food safety standards for raw consumption showed a negative correlation between high bacterial loads and Norovirus prevalence. Winter peaks in viral contamination are attributed to a direct seasonal climate-disease correlation, characterised by reduced viral inactivation rates in colder waters and increased human sewage output throughout the winter months.

Transmission occurs via the faecal-oral route. While viruses cannot multiply in food, they can remain infectious for days or weeks, often resisting refrigeration, freezing, irradiation, and chemical treatments. Seasonal trends are evident, with Norovirus peaking in winter and Hepatitis A and E more frequent in summer [88].

Control strategies focus on preventing contamination and reducing infectivity along the food chain. Key measures include hand hygiene, excluding symptomatic workers, proper cleaning and disinfection, washing produce, thorough cooking, vaccination where available, and avoiding minimally processed or exotic meats. Ensuring water quality and safe handling further limits transmission [85].

Climate change may influence the occurrence and spread of foodborne viruses. Rising temperatures, extreme weather events, and altered rainfall patterns can enhance viral survival and contamination of water and food. Flooding may introduce viruses to new areas, while warmer waters and shifting ecosystems can affect seasonality and zoonotic transmission, as seen with Hepatitis E. Wang et al. [89] discovered a significant correlation between accumulated precipitation and Adenovirus prevalence in water reservoirs used for irrigation in Gyeonggi Province, South Korea. Foodborne virus levels significantly increased when precipitation ranged from 20 to 60 mm. This mechanism operates through multiple pathways: heavy rainfall overwhelms wastewater treatment infrastructure, causing untreated sewage containing enteric viruses to contaminate irrigation water sources used for fresh produce cultivation. Similarly, Abid et al. [90] reported a strong influence of flooding events on the occurrence of enteric viruses (e.g., Norovirus genogroup II) in both surface and well water samples in Saudi Arabia. Flooding-related outbreaks have been documented across multiple regions, with waterborne diseases such as Norovirus and Hepatitis A being more likely to spread in extreme weather conditions such as floods [91]. Addressing these climate-related risks is essential for effective food safety and outbreak prevention [9].

3.8 Marine Biotoxins

Marine biotoxins (phycotoxins) are naturally occurring toxic compounds produced by certain species of marine phytoplankton, particularly during harmful algal blooms (HABs) [92]. These blooms, often referred to as "red tides" due to discolouration of surface waters, are influenced by environmental conditions, such as nutrient availability (nitrogen and phosphorus), temperature, salinity, and CO_2 concentrations, as well as human activities including aquaculture and transport of ballast water. Of the thousands of microalgal species, more than 100 are known to produce toxins capable of accumulating in marine organisms and posing risks to public health [93]. While species such as *Noctiluca scintillans* and *Skeletonema costatum* mainly alter water quality and can cause fish mortality, genera such as *Alexandrium*, *Gymnodium*, *Dinophysis*, and *Pseudo-nitzschia* are recognised as key producers of marine toxins that affect humans [94].

These toxins enter the human food chain primarily through contaminated seafood. Bivalve molluscs, including mussels, clams, and oysters, are the primary vectors due to their filter-feeding behaviour, although fish and crustaceans may also accumulate toxins through trophic transfer [95]. Marine biotoxins vary in chemical composition and solubility and can be classified as hydrophilic (e.g., saxitoxins, domoic acid) or lipophilic (e.g., okadaic acid, azaspiracids, pectenotoxins, yessotoxins), with additional compounds including palytoxin and ciguatoxins. Clinically, they are classified according to the human illnesses they induce, such as paralytic shellfish poisoning (PSP), amnesic shellfish poisoning (ASP), diarrhoeic shellfish poisoning (DSP), ciguatera fish poisoning (CFP), and neurotoxic shellfish poisoning (NSP). The consumption of contaminated seafood can provoke acute gastrointestinal symptoms, neurological effects, and, in severe cases, cardiovascular or neurotoxic complications [93]. Recent EU surveillance data have reported 29 foodborne outbreaks linked to marine biotoxins in France, Spain, and Sweden in 2024, with ciguatoxins implicated in six of these events [14]. Although maximum levels have been established for many toxins in bivalve molluscs, monitoring of fish and crustaceans remains limited, despite their potential role as additional toxin carriers. Climate-related environmental stages, including rising ocean temperatures, increased frequency of marine heatwaves, acidification, stratification, and sea-level rise, are altering the distribution and intensity of HABs. These shifts can affect seawater temperature, salinity, pH, and nutrient dynamics, thereby promoting the proliferation of toxin-producing phytoplankton and facilitating toxin accumulation across multiple trophic levels [96].

The interaction of multiple stressors, such as heat stress and HAB events, may further intensify these impacts, threatening aquaculture productivity and seafood safety. Overall, these developments underscore the importance of expanding monitoring programs beyond traditional bivalve vectors, improving risk assessment approaches for non-bivalve seafood, and implementing adaptive management strategies that account for the complex interplay between climate-driven environmental changes and marine toxin dynamics.

4. Adaptation of the Food Industry to Climate Change

To ensure the microbiological quality and safety of food products, the food industry relies on comprehensive, multistage food safety and quality management systems designed to prevent, monitor, and control potential contamination throughout the food chain. Most internationally recognised certification schemes and standards, including IFS (International Featured Standard - Food), BRC (British Retail Consortium - Global Food Safety Standard), ISO 22000 (International Organization for Standardization - Food Safety Management Systems - Requirements), and those benchmarked by the Global Food Safety Initiative (GFSI), are built upon the seven principles of HACCP. These principles encompass hazard analysis, identification of critical control points (CCPs), establishment of critical limits, monitoring procedures, corrective actions, verification activities, and documentation [97].

According to the Codex Alimentarius guidelines for the application of HACCP [98], food business operators (FBOs) are required to conduct verification activities to confirm that GHP are effectively implemented, monitoring is performed as planned, and corrective actions are taken when deviations occur. Verification activities typically include the review of procedures and records, reassessment following changes in products or processes, and evaluation of sanitation efficacy. As such, periodic reassessment of food safety management systems is already embedded within HACCP-based frameworks, accounting for inherent process variability and unavoidable deviations from standard performance [99]. However, climate variability and the increasing frequency of extreme weather events pose novel challenges to the effective implementation of Good Animal Husbandry Practices (GAHP), Good Agricultural and Aquaculture Practices (GAP), and GHP. Climate-driven disruptions can undermine established biosecurity measures, increase environmental contamination, and elevate the prevalence of chemical and microbiological hazards in pre-harvest products, thereby heightening the risk of cross-contamination and compromising hygienic conditions across the food chain [100].

Table 1. Cause-effect relationships between climate-driven environmental changes, pathogen ecology, and food safety risks along the food chain.

Climate-dependent factor	Effects on pathogen behaviour	Impact on food safety	Reference
Temperature increase	Enhances the growth, survival, and replication rates of pathogens like *Salmonella* spp. in poultry and *Vibrio* spp. in seafood. It also favours the colonization of broiler flocks.	Increases the risk of foodborne infection and intoxication, shortens the shelf life of chilled foods, and may lead to outbreaks in new geographic locations as pathogens expand their distribution.	[32,43,63]
Temperature decrease	Sharp decreases in temperature are associated with increased incidence of pneumonia and can lead to higher contamination of berries by viruses.	Heightened risk of viral contamination (e.g., Norovirus and Hepatitis A virus) in specific produce commodities.	[32,104]
Precipitation and humidity increase	Promotes the internalization of enteric pathogens (e.g., *E. coli* and *Salmonella* spp.) into leafy green vegetables and increases splash dispersal onto fresh produce. Heavy rains also cause sewage overflows and runoff into water bodies.	Contaminates irrigation water and seafood with faecal indicator organisms, leading to a higher prevalence of waterborne and foodborne diseases.	[32,105,106]
Precipitation decrease (drought)	Induces biotic stress in plants, making them more vulnerable to infection by xerophilic fungi (e.g., *Aspergillus flavus*).	Significant rise in mycotoxin contamination (especially aflatoxins) in staple crops.	[32]
Ocean acidification (pH decrease)	A decrease in pH levels favours the proliferation of HABs (e.g., more favourable environment, metabolic advantage).	Leads to the production of neurotoxic phycotoxins that bioaccumulate in the seafood chain, causing illnesses like paralytic shellfish poisoning.	[32]
Salinity changes	Decreased salinity can increase the bioaccumulation of toxic metals in molluscs.	Compromises the safety of seafood through heavy metal exposure.	[32,62]
Light increase	Provides conditions that favour the rapid spread of microalgal cells, contributing to HABs (e.g., increased photosynthesis, competitive advantage over non-toxic phytoplankton).	Indirectly increases the risk of seafood-associated toxins entering the human food chain.	[32]

This section examines how climate change affects the robustness of existing food safety and quality management systems, with a particular focus on food manufacturing and processing. Subsections address critical areas, including microbiological quality assessment, shelf life determination, cold chain integrity, and logistics. For each topic, system vulnerabilities under climate stress are discussed alongside adaptive strategies and potential alternatives to enhance food system resilience.

4.1 Microbiological Quality and Shelf Life Assessment

Among climate-related variables, increasing air and water temperatures and altered precipitation patterns, in both frequency and intensity, are the primary drivers influencing the microbiological quality and shelf life of food products. These factors affect the abundance, growth, geographic distribution, and environmental persistence of foodborne pathogens and spoilage microorganisms across crops, livestock, and surrounding ecosystems [63]. Climate change also reshapes soil and aquatic microbial communities by modifying key biogeochemical processes, including carbon sequestration and greenhouse gas cycling, while elevated atmospheric CO_2 levels and rising temperatures pose increasing threats to aquatic ecosystems and their associated microbiota [101]. Several studies have demonstrated direct links between climate conditions and food safety hazards at the primary production level. Increased temperatures have been associated with a higher prevalence of OTA in crops such as grapes and maize, highlighting the sensitivity of mycotoxin-producing fungi to climate warming [102,103]. Table 1 (Ref. [32,43,62,63,104,105,106]) summarises selected cause-effect scenarios illustrating how elevated temperatures and variable precipitation influence microbiological risks along the food chain.

More broadly, higher temperatures accelerate microbial metabolic pathways, potentially reducing microbial diversity and favouring the dominance of fast-growing groups such as *Enterobacteriaceae* and faecal coliforms when contamination occurs [107]. Conversely, lower temperatures tend to preserve higher microbial diversity [108].

Climate-driven changes in raw materials may also compromise the technological performance of food processes. Wheat flours produced in hotter and more humid regions are more prone to elevated loads of thermoresistant spore-formers, such as *Bacillus* spp., which are not reduced during baking and may increase the susceptibility of baked goods to spoilage defects such as "ropy bread" [109]. In fact, spore-formers, and especially *Bacillus* spp., are particularly resistant to heat and even to high-pressure treatments [110]. Recent genomic studies on this microorganism have shown that antimicrobial treatments such as essential oils stimulate the expression of genes associated with membrane integrity and quorum sensing [111]. Similarly, in fermented products, elevated temperatures reduce sugar and polyphenol content in the fruit, impairing lactic acid fermentation and increasing susceptibility to spoilage [112].

Despite growing evidence at the primary production stage, limited data are available on the impact of climate change on the spoilage dynamics and shelf life of processed, packaged, refrigerated, and non-refrigerated foods. Most studies focus on the pre- and post-harvest quality of raw commodities, particularly fruit, vegetables, and cereals. Even relatively stable raw commodities such as aromatic plants can be severely damaged by weather conditions such as dew, high humidity and rainfall, especially during harvest [113]. Nevertheless, climatic stressors may alter the microbiological and physicochemical properties of raw materials to an extent that compromises the expected shelf life and safety of finished products, especially when combined with temperature abuse during storage and distribution.

In animal-derived foods, heat stress (HS) represents a major climate-related concern. In ruminants, HS can induce intestinal inflammation and increased gut permeability, facilitating endotoxin translocation and bacterial dissemination, including contamination of edible offal [114]. Moreover, HS has been linked to quality defects in meat, such as pale-soft-exudative (PSE) and dark-firm-dry (DFD) conditions [115]. In dairy systems, HS in lactating cows is associated with increased mastitis incidence, reduced milk yield, and alterations in milk microbiology and physicochemical properties. Mastitis-related infections commonly involve *S. aureus*, *E. coli*, *Streptococcus* spp., and *L. monocytogenes* [116]. Collectively, these effects underscore how climate-induced physiological stress in livestock translates into increased contamination pressure along the production chain, with downstream consequences for product safety and shelf life.

4.2 Cold Chain Challenges Under Climate Change

The cold chain encompasses the temperature-controlled supply chain that maintains perishable products at safe temperatures from production through transportation and storage to the end user [117]. Managing this system is increasingly challenging due to inherent variability in temperature profiles across its stages, from precooling to domestic refrigeration [118]. Fluctuations or failures in maintaining appropriate temperatures can reduce shelf life and promote the growth of pathogens and spoilage microorganisms, depending on the type of food product, such as fresh-cut fruits, RTE plant- or animal-based products, and semi-ripened cheeses [119]. Seasonal and climate-induced temperature variations may also alter microbial generation times and metabolite production, increasing contamination risk from pathogens including *Campylobacter* and *Salmonella* [32]. Awad et al. [9] examined climate change impacts on multiple foodborne pathogens, including *S. aureus*, *C. perfringens*, *E. coli*, and various viruses, and suggested changes in regulations, surveillance programmes, agricultural practices, and water management.

Rising ambient temperatures can further compromise refrigerant efficiency, increasing energy consumption, heat gain, and the risk of mechanical breakdown. Refrigerant properties such as transport characteristics, critical temperature, and latent heat of vaporisation, influence performance under warmer conditions and may necessitate updated refrigeration designs [120]. Current refrigerated vehicles often rely on simple on-off temperature control, generating non-uniform conditions within cargo. Placing thermometers at the warmest point may fail to capture the full range of temperature variability, while factors such as door openings, load distribution, and insulation quality further affect thermal stability [121,122]. Overall, rising temperatures and seasonal variability can decrease cold chain effectiveness. Consequently, predictive monitoring and adaptive operational strategies are needed to ensure safety and shelf life.

4.3 Quality Management Systems

A comprehensive HACCP plan involves the identification of potential hazards in raw materials, ingredients, the production environment, and the food itself [98]. However, hazard analysis should consider not only intended uses but also foreseeable unintended scenarios, such as undercooking or extended storage [123]. Food safety management systems rely on prerequisite programmes (PRPs)—including GHP, GAP, and good manufacturing practices (GMP)—integrated with HACCP principles to ensure safe handling at critical points along the supply chain. Early-stage interventions, such as proper farming, milking, and primary production practices, are particularly important for mitigating risks before products enter processing and distribution stages [124].

Within Quantitative Microbial Risk Assessment (QMRA), concepts such as the Appropriate Level of Protection (ALOP) and Food Safety Objectives (FSO) are translated into Performance Objectives (POs), Performance Criteria (PC), Process Criteria (PrC) and Product Criteria (PdC). Variability in seasonal conditions, geographic regions, and temperature profiles can alter the physical, chemical, and microbiological characteristics of raw materials. Thus, changes in contamination risks need to be managed through tailored strategies for storage, transportation, and distribution. To address these challenges, early-warning systems and real-time monitoring should be incorporated into food safety programmes. Adaptive hazard analysis and responsive corrective actions enable the supply chain to adjust proactively to climate-driven variability, ensuring that control measures remain effective under evolving environmental conditions [125]. In summary, these climate-driven variations highlight the importance of flexible and anticipatory food safety strategies to maintain effective control throughout the supply chain.

5. Proposal of Alternatives

5.1 Climatic Variables in Predictive Microbiology

Probabilistic exposure assessment considers all possible circumstances, each characterised by a probability distribution and intrinsic variability, and relies on mathematical models describing the relationship between the environmental factors and microbial behaviour [126]. Monte Carlo simulations are widely applied to integrate effects of climate change into such assessments. For example, Mahmudiono et al. [127] used Monte Carlo simulations to evaluate the impact of climate change on Bulgarian agricultural products, finding that lentils were at a higher risk of reduced crop performance compared with beans. This procedure is an example of how predictive methods could be employed for safeguarding food security aspects.

Koutsoumanis et al. [128] assessed the spoilage risk of heat-processed fruit drinks under climate variability by combining a predictive growth model of *Alicyclobacillus acidoterrestris* [129] with hourly temperature data from online weather databases. Similar approaches have been applied to other microorganisms, including *Geobacillus stearothermophilus* in evaporated milk [130] and *A. flavus* and *Aspergillusparasiticus* on corn [131]. A detailed workflow for plant-based milk alternatives contaminated by *G. stearothermophilus* has been proposed by Misiou et al. [132], with potential applications in the canned food industry. Identifying the most influential climatic variables enables targeted, product-specific modelling, although further expertise is needed to close current knowledge gaps [133].

5.2 Predictive and Sustainable Cold Chain Strategies

Refrigeration systems contribute to climate change via energy consumption, direct emissions of refrigerants and associated greenhouse gases. Several improvements are possible, including the selection of low-impact refrigerants, optimised refrigeration designs, and the use of predictive methods. Table 2 (Ref. [120,134,135]) compares the use of "old" and "new" refrigerants in various food application settings.

For instance, substituting R452A with R290 and R744 in mobile refrigeration systems, combined with an indirect expansion configuration using two separate circuits, resulted in lower carbon emissions, improved efficiency, and maintained performance [136].

Predictive modelling has also been applied in supermarket refrigeration. Sarabia et al. [137] developed a modelling approach by integrating a Hybrid Model Predictive Controller (HMPC) with an optimised physical design of a supermarket's compressor rack for the refrigeration system, achieved through Response Surface Methodology (RSM). This approach improved the management of temperature fluctuations, energy consumption, machinery wear, and overall cost efficiency. Similarly, Poks et al. [138] applied a fault detection and isolation scheme for a secondary loop refrigeration system in a refrigerated transport vehicle. By applying a grey-box method, parametric faults (dirt/ice buildup and secondary loop pump failure) and sensor faults (four temperature sensors in the secondary loop) were detected, and threshold values were selected to avoid false alarms, ensuring correct system functioning during both transient and steady-state operations. Predictive applications for improved management of temperature and flow rates, energy efficiency, and system optimisation have also been developed for use in food manufacturing [139].

5.3 Implementation of Climate Variables Into Modelling Approaches

Several studies demonstrate the integration of climatic variables into QMRA for diverse food products. Table 3 (Ref. [140,141,142,143,144,145]) summarises several applied approaches.

Janevska et al. [146] described the implementation of a predictive approach integrating HACCP with QMRA and a shelf life predictor (SLP) model to manage the impact of climate change in supply chains by detecting the effects of the climatic variables on food stability before they are detected by HACCP or the supply chain operators. By integrating historical data on biological and climatic parameters, real-time monitoring with temperature sensors, and data collected from monitoring and verification activities, the model can generate predictions and support adaptive supply chain management by identifying when risk levels increase due to temperature trends, triggering a review of procedures to bring risks back to acceptable levels [146]. Schijven et al. [147] presented a location-specific QMRA tool that generates Monte Carlo samples for each day of the year using climate inputs. This allows pathogen behaviour to be predicted and enables informed strategic risk management. Predictive approaches are also applied to crop yield management applications, pest and disease forecasting, and plant responses to abiotic stress [148]. Proteomic analyses reveal changes in protein expression and post-translational modifications that help plants adapt to climatic stressors [149]. Coupled with advanced predictive modelling approaches (e.g., machine learning and deep learning), an integrated framework capable of accu-

Table 2. Comparison of old vs. new refrigerants in food applications.

Application	Old refrigerants	New refrigerants	Key characteristics	References
Domestic refrigerators and freezers	R12, R134a	R600a, R290, R1234yf	R600a is widely adopted for domestic use due to high energy efficiency and negligible GWP. R290 is highly efficient but restricted by charge limits due to flammability. R1234yf is an option but produces TFA upon decomposition.	[120,134,135]
Commercial refrigeration (Supermarkets, Centralized systems)	R22, R404A, R507A	R744, R717, R448A/R449A, R450A/R513A	R744 (CO_2) is a leading option for centralized systems but requires high-pressure components. R448A/R449A serve as non-flammable retrofits for R404A but still have moderate GWP (~1300). R717 is energy efficient but toxic.	[120,134]
Self-contained units (Vending machines, Ice cream freezers, Beverage coolers)	R134a, R404A	R290, R744, R1234yf/R1234ze(E)	R290 is considered ideal for small units. It offers higher efficiency and lower charge requirements than R134a/R404A. R744 is also a non-flammable option for display cabinets.	[120,135]
Transport refrigeration (Refrigerated trucks/vehicles)	R134a, R404A	R290, R452A, R744	R290 reduces energy consumption and provides better COP than R404A but requires safety measures for flammability. R452A is a non-flammable (A1) alternative for R404A with a GWP of ~2140 (lower than R404A's 3922).	[134,135]
Industrial food processing and cold storage	R22, R404A	R717, R1270, R744	R717 is dominant in industrial settings due to efficiency, despite toxicity. R1270 is an emerging flammable alternative for cold storage warehouses.	[134]

Legend: GWP, Global Warming Potential; TFA, Trifluoracetic Acid; R12, Dichlorodifluoromethane; R22, Chlorodifluoromethane; R134a, 1,1,1,2-Tetrafluoroethane; R290, Propane; R404A, blended hydrofluorocarbon refrigerant; R507A, blended hydrofluorocarbon refrigerant; R600a, Isobutane; R717, Ammonia; R744, CO_2; R1234yf, 2,3,3,3-Tetrafluoropropene; R1270, Propylene; R1234ze(E), trans-1,3,3,3-Tetrafluoroprop-1-ene; R448A/R449A - R450A/R513A - R452A, refrigerant blend of hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs) designed as lower GWP refrigerants; COP, coefficient of performance.

rately predicting genotype-to-phenotype relationships, accelerates breeding for augmented stress tolerance and dissects genotype-by-environment interactions critical for climate adaptation resilience [150].

5.4 Environmental Surveillance

Novel epidemiological surveillance systems can detect early signs of climatic changes, disasters, or unusual outbreaks, allowing proactive food safety interventions (e.g., AI-driven, satellite-informed early warning systems for drought prediction). Therefore, potential food safety hazards (e.g., HABs, microbial contamination on primary products, power outages in certain areas, heavy metals, etc.) could be anticipated and mitigated through targeted monitoring and testing [151]. In ecologically compromised areas, environmental monitoring has proven successful in better identifying which CCPs and contextual monitoring procedures to implement in the respective HACCP plans. Baikadamova et al. [152] were able to reduce heavy metal content and radionuclide content in a traditional meat pate by considering the environmental variables of the manufacturing plant premises, which had a long history of radiation contamination due to the presence of the former Semipalatinsk Nuclear Test Site in Kazakhstan. Other examples include supply chains affected by nuclear disasters (e.g., the Japanese seafood supply chain affected by Fukushima's nuclear wastewater), where seafood monitoring networks (seawater, marine ecology, and seafood) or a shift from marine aquaculture to land farming must be established [153]. Other adaptations of HACCP procedures include determining appropriate analyses and CCPs to establish, depending on the provenance of the raw materials. Oguntoyinbo [154] identified different microbial hazards and different CCPs and changed some unit operations to produce fermented legume-based condiments, depending on the supplier of the raw materials. Ngure et al. [155] were able to reduce the content of aflatoxins in groundnut flour by implementing two CCPs and an operational prerequisite programme

Table 3. Structural Changes in QMRA and predictive modelling for climate change adaptation.

Proposed structural change	Description and methodology	Rationale for climate change preparation	References
Adoption of a "system approach" (holistic modelling)	Moving beyond isolated pathogen models to integrate diverse drivers of change, including climate, economics, and agricultural practices, into a single framework.	Climate change affects food safety through complex interactions (e.g., how temperature affects pesticide use or trade). A holistic view reveals cause-effect relationships and enables mitigation of risks driven by external factors.	[140,141]
Implementation of bayesian networks (BNs)	Using probabilistic graphical models (BNs) to link historical data, expert knowledge, and diverse variables (e.g., temperature, precipitation, trade volumes).	BNs can integrate heterogeneous data sources and handle uncertainty. They effectively capture complex dependencies between climatic factors (e.g., precipitation) and food safety hazards (e.g., chemical contaminants).	[140,141]
Integration of machine learning algorithms	Utilising algorithms like Random Forest (RF) and Classification Trees (CT) alongside traditional regression.	These methods handle complex, unbalanced ecological data better than traditional regression. They help identify "high-risk weather" rules (e.g., specific wind speeds or rainfall thresholds) that predict pathogen presence.	[142,143]
Inclusion of specific meteorological vectors	Structuring models to include specific weather events as transmission vectors, such as rain splashing (transferring soil to plants) and wind-driven dust.	Climate change alters weather patterns. Models must explicitly account for how phenomena like heavy rainfall or high winds physically transport pathogens (e.g., *L. monocytogenes*, *E. coli*) from reservoirs to crops.	[142,143,144]
Differentiation by seasonality	Structuring exposure assessments to compare risks between specific growing seasons (e.g., spring vs. autumn/winter) rather than using annual averages.	Bacterial loads and solar radiation (which inactivates pathogens) vary significantly by season. Climate change may shift these seasonal windows, requiring models that can differentiate risks based on time of year.	[142,143,144,145]
Modelling bacterial fitness and decay via solar radiation	Incorporating solar radiation intensity and duration as explicit variables for pathogen inactivation in the field.	Solar radiation is a critical factor for bacterial decay in open fields. Changes in cloud cover or growing seasons due to climate change will directly impact pathogen survival rates.	[144]
Use of time-lagged meteorological variables	Including weather data from specific timeframes prior to harvest (e.g., "30-day average precipitation" vs. "precipitation 2 days prior").	Different climate factors have different effects: long-term averages may influence growth/survival, while short-term events (2 days prior) may influence physical transfer (contamination) events.	[142,143]

QMRA, Quantitative Microbial Risk Assessment.

(OPRP) in the HACCP plan at a Tanzanian food company. Once again, the knowledge of the area's environmental conditions and suppliers was a key driver for successfully applying a corrected and revised quality management plan.

6. Conclusions

Climate change is reshaping food safety through interconnected risks along the entire food supply chain. Based on an extensive literature review, evidence suggests that traditional reactive approaches are becoming insufficient to manage emerging microbial hazards, environmental variability, and increasingly complex food systems. Current evidence indicates that rising global temperatures and increased climate variability may further exacerbate food safety risks. Projected scenarios suggest that global warming could exceed 2 °C by 2100, highlighting the need for proactive adaptation strategies. Emerging trends suggest the potential integration of climate-informed modelling, real-time monitoring, adaptive processing technologies, and resilient agricultural and cold chain management systems as tools to reduce system vulnerabilities. However, these approaches are still largely under development and require further validation and large-scale implementation.

From a broader perspective, these projections should be interpreted with caution, as future outcomes will strongly depend on policy decisions and governance frameworks. Ensuring food safety under climate change is therefore not only a technical challenge but also a regulatory and societal one.

In this context, coordinated policies, robust regulatory systems, and equitable access to safe and nutritious food are essential to strengthen resilience, particularly for vulnerable populations. Overall, harmonising preventive, predictive, and adaptive strategies will be key to ensuring safe, sustainable, and resilient food systems under future environmental change.

Author Contributions

GDA, MS & AP: Writing–review & editing, Writing–original draft, Visualization, Supervision, Methodology, Investigation, Conceptualization. All authors have read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

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