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REVIEW ARTICLE

Climate changes and food-borne pathogens: the impact on human health and mitigation strategy

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Abstract
Climate change has emerged as a major pressing global issue with far-reaching implications for human health, such as the emerging and spread of food-borne pathogens. Food-borne pathogens are microorganisms that can cause illness in humans, from mild discomfort to life-threatening diseases, through the consumption of contaminated food or water. The impact of climate change on food-borne pathogens is multifaceted and includes changes in the environment, agriculture, and human behavior. This review article examines the effect of climate change on food-borne pathogens, explores the connection between climate change and food-borne illness, records the current evidence on the effects of climate change on food-borne pathogens and potential consequences for human health, highlights knowledge gaps and areas for further research, and summarizes the strategies for mitigation and adaptation. Understanding the delicate relationship between climate change and food-borne infections makes it possible to maintain food systems and defend the health and well-being of populations worldwide.

Keywords Food safety · Disasters · Food-borne illnesses · Climate action · Sustainability

1 Introduction

Climate change is a pressing issue that significantly affects all ecosystems. The interactions between climate change and local human impacts can have detrimental effects on ecosystems, leading to their impairment and decimation (He and Silliman 2019).

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Food-borne pathogens are microorganisms that can cause illness when consumed through contaminated food or water sources. These pathogens include bacteria, viruses, and parasites and can lead to significant outbreaks and health complications (Keerthana et al. 2022). Food-borne pathogens are responsible for millions of illnesses and thousands of deaths globally each year, and the World Health Organization estimates that 1 in 10 people fall ill every year because of eating contaminated food (WHO 2022a). Globally, contaminated food causes 600 million foodborne diseases and 420,000 deaths annually (Lee and Yoon 2021).

Common pathogenic bacteria responsible for food-borne illnesses *include Campylobacter jejuni, Clostridium perfringens, Escherichia coli, Salmonella* spp., and *Staphylococcus aureus* (Bintsis 2017). Other important food-borne pathogens are viruses, such as human *norovirus*, *hepatitis A virus* (HAV), and food-borne parasites (Koutsoumanis et al. 2018; Pexara and Govaris 2020).

The changing climate affects the existence and persistence of all microorganisms and their vectors, leading to increased pathogenic microbial contamination of water and food that, in turn, threatens animal health, including humans, by laying direct and indirect effects on food security (War et al. 2022).

Climate change has the potential to impact food systems and food quality and safety, including the prevalence of food-borne pathogens, and there is sufficient evidence to suggest that climate change affects not only food yields but also food quality and safety (Vermeulen et al. 2012). Climate change can alter the distribution and prevalence of food-borne pathogens and affect the quality and safety of food (Lake and Barker 2018; Caminade et al. 2019).

Rising temperatures and changing precipitation patterns are the primary drivers of disease impact, leading to increased bacterial, viral, and pathogenic contamination of water and food (Singh et al., 2022, 2023). Global warming and its effects on Earth's weather patterns are expected to lead to warmer average global temperatures and a higher frequency of extreme weather events. Approximately three-quarters of infectious diseases are expected to be impacted by climate change (Nel and Richards 2022).

Observational studies suggest that rising temperatures will increase disease pressure, whereas drying conditions can mitigate disease risk (War et al. 2022). The abundance, growth, range, and survival of pathogens are modified by climate change, which affects the prevalence of foodborne diseases (Peng et al. 2023). The range of pathogens can shift, increasing the spread of plant diseases in new areas (Smith and Fazil 2019).

As climate change continues, the risk of adverse effects on food safety increases, ranging from an increased public health burden to new risks in the food chain. Interventions to mitigate these impacts require careful management, and integrated policies are required to address the ecological and socioeconomic risks of climate change and contaminants. Enhancing preparedness through the traceability and early detection of foodborne illnesses is also crucial. As a result, the goal of this review article is to investigate the effect of climate change on food-borne pathogens, to investigate the science behind the link between climate change and food-borne illness, to record current evidence on the effects of climate change on food-borne pathogens and potential consequences for human health, to highlight knowledge gaps and areas for further research, and to summarize mitigation and adaptation strategies.

2 The link between climate change and food-borne pathogens

Climate change and variations affect the prevalence of climate-sensitive infectious diseases, particularly those transmitted through water and food. There are concerns that climate change trends worsen the health risks associated with inadequate water, sanitation, and hygiene in many regions of the world (Cissé et al. 2011). The impact of climate change on human health is influenced by various social, environmental, ecological, and economic factors, with the spread, survival, and growth of pathogens playing central roles in disease transmission.

2.1 Temperature and humidity

The risks to health, livelihoods, food security, water supply, human security, and economic growth due to climate change are expected to increase with 1.5 °C of warming and further increase at 2 °C. According to this analysis, any increase in global warming will have a negative impact on human health (IPCC 2022).

Temperature and moisture play a critical role in the growth and survival of foodborne pathogens. Higher temperatures and changing precipitation patterns caused by climate change create ideal conditions for the proliferation of many foodborne pathogens. For example, *Salmonella*, *Escherichia coli* (*E. coli*), and *Campylobacter jejuni* are the most common food-borne pathogens that thrive in warm and humid environments (Dietrich et al. 2023). Warmer temperatures also increase the metabolic activity of microorganisms, allowing them to grow and reproduce more rapidly (Qiu et al. 2022).

Many pathogens thrive in warm environments, with optimal growth temperatures ranging from 20 to 45 °C (Bintsis 2017). As temperatures rise owing to climate change, the range and distribution of food-borne pathogens are also expected to shift (Smith and Fazil 2019). The continuous release of greenhouse gases amplifies various climatic hazards within the Earth's climate system, which in turn can worsen the occurrence of human pathogenic diseases (Mora et al. 2018). It is widely accepted that climate change can increase incidence of emerging foodborne pathogens causing pathogenic diseases (Patz et al. 2005). However, the extent of human vulnerability to pathogenic diseases influenced by climate change has not yet been fully quantified.

Ocean warming and intense precipitation, which reduce the salinity of coastal waters, seem to create favorable conditions for *Vibrio vulnificus* and *Vibrio cholera*, potentially explaining outbreaks of vibriosis and cholera, respectively, in areas where this disease is uncommon (Vezzulli et al. 2013; Burge et al. 2014; Guzman Herrador et al. 2015).

Furthermore, changes in temperature and precipitation patterns can alter the geographic distribution of certain foodborne pathogens. For example, the fungal pathogen Fusarium, which produces mycotoxins that can contaminate grains and nuts, is becoming more prevalent in areas with warmer temperatures and changing moisture levels (Perrone et al. 2020).

The increase in Earth's temperature due to climate change has significant implications for humidity levels and the prevalence of foodborne diseases. As temperatures rise, there is a corresponding increase in humidity levels (Matthews 2018). This rise in temperature and humidity can lead to a higher incidence of foodborne diseases, such as Salmonella infections, which have been found to have a linear association with temperature (Ebi 2011). The relationship between temperature and humidity is crucial as it affects the survival and spread of pathogens in food products (Smith et al., 2019).

Furthermore, the changes in temperature and humidity can also impact the spread of vector-borne diseases, as observed in regions like Bangladesh where rising temperatures and altered rainfall patterns contribute to higher cases of such diseases (Rahman et al. 2021). The combination of elevated temperature and humidity creates conditions that favor the proliferation of disease-causing agents, increasing the risk of foodborne illnesses (Semenza et al. 2012b).

Additionally, the impact of climate change on humidity levels can have broader health implications beyond foodborne diseases. High humidity levels contribute to human heat stress during heat events, potentially exceeding the body's ability to self-regulate temperature through evaporative cooling (Poppick and McKinnon 2020). Changes in humidity can also affect the thermal environment of buildings, as evidenced in the case of rammed-earth dwellings, where walls play a role in regulating indoor humidity and temperature (Jia-hua et al. 2022).

2.2 Extreme weather events and sea level rise

Extreme weather events and sea-level rise caused by climate change can also impact food safety. Extreme weather events such as hurricanes, tornadoes, and wildfires can damage food production and processing infrastructure, increasing the risk of contamination and food-borne illness outbreaks (El Samra 2017; Duchenne-Moutien and Neetoo 2021). Flooding can contaminate crops, livestock, and aquaculture with saltwater, sewage, and other pollutants, thereby creating an ideal environment for the growth of food-borne pathogens (IPCC 2022). Flooding can spread pathogens from agricultural fields, livestock operations, and water treatment facilities to surface waters and soil (Okaka and Odhiambo 2018). Increases in waterborne and foodborne diarrheal diseases have been reported in India, Brazil, Bangladesh, Mozambique, and the USA following flooding episodes (Tirado et al. 2010).

Storm surges and coastal flooding can destroy infrastructure such as refrigeration units and food storage facilities, leading to food spoilage and increasing the likelihood of food-borne illness outbreaks (Wisner and Adams 2002). Floods and storms often result in the overflow of wastewater, leading to direct and food-borne transmission of norovirus, hepatitis, and Cryptosporidium (Patz et al. 2000; Boxall et al. 2009; Semenza et al. 2012b; Yavarian et al. 2019).

Droughts can lead to decreased water availability, resulting in increased pathogen concentrations in the water used for irrigation, processing, and cleaning. Droughts can concentrate pathogens in water sources, making them more accessible to crops and animals (Yusa et al. 2015; Wang et al. 2022). Conversely, heavy rainfall and flooding can contaminate water sources with pathogens from animal waste, sewage, and other sources (Okaka and Odhiambo 2018).

Power outages and disruptions to refrigeration systems during Hurricane Sandy in 2012 led to a large outbreak of salmonellosis in the northeastern United States (NYSERDA 2018). Moreover, displacement and migration of people due to natural disasters can increase the likelihood of food-borne illness transmission (McMichael 2015).

Sea-level rise caused by climate change threatens coastal communities, increasing the likelihood of saltwater intrusion into freshwater resources. Moreover, brackish water, a mixture of fresh water and saltwater, can support the growth of unique microbial communities, including opportunistic pathogens (Oppenheimer et al. 2022).

2.3 Shifting distributions and emergence of new pathogens

Climate change can facilitate the movement of food-borne pathogens into new regions, potentially introducing them into naïve populations with little immunity or exposure (Kendrovski and Gjorgjev 2012). For instance, the vector-borne disease Vibrio cholerae has been linked to rising sea levels and increased coastal flooding, allowing it to spread beyond traditional geographic boundaries (Wade and ClimAtlantic. 2022). Additionally, climate change may accelerate the evolution and emergence of new food-borne pathogens, as microorganisms adapt to changing environmental conditions (Lake and Barker 2018) (Fig. 1).

3 Impact on food-borne pathogens

3.1 Foodborne bacteria

3.1.1 *Salmonella* spp

Climate change significantly impacts the safety of the global food supply. One of the most important food hazards i is *Salmonella enterica*. This bacterium causes salmonellosis, which is a common foodborne illness. *Salmonella* is a bacterium that causes foodborne illnesses in humans. It is commonly found in contaminated foods, such as eggs, poultry, and meat. Climate change has been linked to increased *Salmonella* outbreaks, which have significant implications for public health (He et al., 2023; Sabeq et al., 2022).

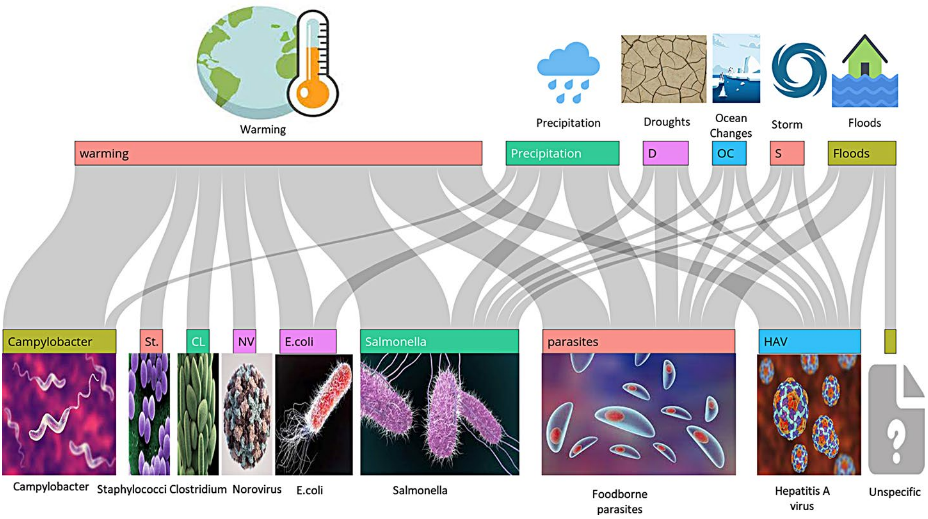

Fig. 1 Foodborne pathogens aggravated by climatic change events. The thickness of the lines is proportional to the number of studies mentioned the relation between climate changes and specific foodborne pathogens

Salmonella spp. are commonly associated with poultry products, eggs, and production. As climate change affects crop yield, food security, and livestock production, it may also influence the prevalence of *Salmonella* in these products. Warmer temperatures and changing precipitation patterns can reduce crop yields and compromise quality, increasing reliance on imported goods that may be contaminated with *Salmonella* (Paz et al. 2021).

One of the main ways in which climate change affects *Salmonella* is through changes in the temperature and precipitation patterns. Warmer temperatures can increase Salmonella growth and survival rates, making it more likely for them to spread and multiply in food products (Dietrich et al. 2023). However, as climate change leads to an increase in global temperatures, the distribution of *Salmonella* is expected to shift towards higher latitudes and altitudes, where cooler temperatures have previously limited its growth (Akil et al. 2014). This means that regions that were once too cold for *Salmonella* may now be suitable for its growth, leading to an increased exposure risk for humans and animals.

Milazzo et al. (2016) investigated the association between heatwaves and salmonellosis because of the increasing frequency of heatwaves and growing public health concerns about foodborne disease. The severity of the heat wave, rather than its duration, had a greater impact on daily Salmonella infections. Salmonella cases were less common in the early warm season than in later months.

Climate change has been identified as a significant factor contributing to the increase in Salmonella outbreaks. Studies have shown that as temperatures rise due to climate change, there is a corresponding increase in the rates of Salmonella infections (Akil et al. 2014). Specifically, in the United States, warming trends, especially in southern states, have been linked to higher rates of Salmonella infections (Akil et al. 2014). Furthermore, a European study projected that under a climate change scenario, the number of Salmonella cases could potentially increase by 9.3–16.9% by the 2080s, depending on the level of mitigation efforts (Lake 2017). This indicates a clear association between climate change parameters and the prevalence of Salmonella outbreaks. Additionally, the frequency and intensity of insect outbreaks, including those that act as vectors for diseases like Salmonella, are expected to increase with projected changes in global climate (Stireman et al. 2005). Climate change not only influences the direct transmission of diseases like Salmonella but also affects the dynamics of disease vectors and their interactions with the environment.

Furthermore, warmer ocean temperatures can expand marine species that harbor *Salmonella*, further increasing the potential for outbreaks (Morgado et al. 2021a). Additionally, extreme weather events, such as floods, can affect the prevalence of *Salmonella*. For example, heavy rainfall can contaminate water sources, leading to the spread of *Salmonella* in agricultural areas (Akil et al. 2014).

Floods can indeed have a significant impact on Salmonella contamination in various environments. Studies have shown that flooding can lead to increased levels of microbial contamination, including Salmonella, in water sources (Dzodzomenyo et al. 2022). During flooding events, surface water samples have been found to contain higher levels of Salmonella compared to post-flood samples (Yard et al. 2014). Additionally, floods can alter the topsoil microbiome, potentially enhancing the mobility of water-borne pathogens such as Salmonella (Divakaran et al. 2019).

The aftermath of floods can also result in the presence of multidrug-resistant pathogenic species like Salmonella typhi/typhimurium in the environment (Divakaran et al. 2019). Furthermore, flooding can lead to increased Salmonella contamination in produce fields, as seen in a study following extensive flooding in New York State (Bergholz et al. 2016). This highlights the importance of understanding and managing Salmonella contamination in various settings post-flooding.

Moisture is another factor that affects *the growth of Salmonella*. *Salmonella* thrives in humid environments and can survive in water and wet soils. Climate change alters precipitation patterns worldwide, leading to more frequent extreme weather events such as floods and droughts. These changes can lead to an increase in the spread of *Salmonella* in contaminated surface water and agricultural runoff (Jiang et al. 2015; Morgado et al. 2021b).

Temperature and rainfall were positively associated with the frequency of salmonellosis cases in subtropical and tropical locations; however, the mechanisms underlying the observed seasonality in foodborne diseases are not fully understood, although they are likely a complex interplay of numerous elements. The observed seasonality and climate correlations, although ambiguous, should not be overlooked; they may result in increased hazards (Liu et al., 2013).

3.1.2 Campylobacter

Campylobacter is a gram-negative, spiral-shaped bacterium commonly found in food and the environment. It is known to cause gastroenteritis and inflammation of the digestive tract in humans and is often transmitted through contaminated food and water (Epps et al. 2013). The emergence of multidrug-resistant *Campylobacter* strains and expansion of their host range pose significant public health concerns. The World Health Organization estimates that approximately 5.5 million people worldwide fall ill each year with *Campylobacter* enteritis, resulting in up to 125,000 hospitalizations and 180,000 deaths (WHO 2022a). Given the projected continued warming of the planet, it is crucial to develop effective strategies to reduce the risk associated with *Campylobacter* transmission.

Climate change can potentially affect the transmission and incidence of *Campylobacter* infections. Several studies have investigated the relationship between climate variability and *Campylobacter* infection rate. Climate change is predicted to affect *Campylobacter* infections (Kuhn et al. 2020).

Climate-induced trends, such as increased heat waves and storm intensity, may affect the persistence and dispersal of food-borne pathogens including *Campylobacter* (Sterk et al. 2016). Predictive models are being developed to quantify the complex relationships between climatic factors and Campylobacter activity in outdoor environments (Hellberg and Chu 2015). Assessing the local and regional impacts of climate change on Campylobacter is important for initiating timely public health management and adaptation strategies (Nichols et al., 2016).

Governments and farmers alike should focus more on the high-yield, high-efficiency, and sustainable development of agriculture; in addition, strategies for nitrogen fertilization and adaptive distributed irrigation should be implemented to guarantee food security (Chen et al. 2023). Additional strategies for adaptation should be designed to plant drought-tolerant crops, plant early, diversify crops, harvest rainwater, respond to market changes with income-diversification and credit schemes, improve agricultural markets and information availability, and develop meteorological forecasting capabilities (Gebre et al. 2023).

Sari Kovats et al. (2005) conducted an international study to examine the association between climate variability and *Campylobacter* infection. They found that all countries in the study showed distinct seasonality in *Campylobacter* transmission, with many populations experiencing a peak in spring. The timing of the peak varied geographically, suggesting that climate may have contributed to *Campylobacter* transmission. The study also identified a weak association between the timing of the peak and high temperatures three months prior. This suggests that milder winters and higher temperatures may lead to earlier peaks in infection. However, the main driver of seasonality and transmission of *Campylobacter* remains unclear, highlighting the need for further research to identify the major serotypes and routes of transmission of this disease.

Patrick et al. (2004) investigated the effects of climate on the incidence of *Campylobacter* in humans and the prevalence in broiler flocks in Denmark. They found that temperature and sunlight were significant predictors of *Campylobacter* incidence in humans, with average temperature and sunlight four weeks before infection being the best predictors. The average and maximum temperatures three weeks before slaughter were the best predictors for broilers. The study also highlighted the need to examine the effects of temperature on human incidence after accounting for the contribution of broilers as a source of campylobacteriosis. This suggests that climatic factors may influence the prevalence of *Campylobacter* in broiler flocks, which in turn can affect human infections.

Overall, these studies suggest that climate variability and changes can influence the transmission and incidence of *Campylobacter* infections. The seasonality of *Campylobacter* transmission and its association with temperature and sunlight indicates that changes in climate patterns may lead to shifts in the timing and intensity of *Campylobacter* outbreaks.

3.1.3 Clostridium perfringens

Clostridium perfringens is a gram-positive bacterium that causes food poisoning and intestinal infections in humans and animals. It is primarily associated with contaminated meat and products stored at improper temperatures prior to consumption (Wilson and Wilson 2021). The symptoms of *Clostridium Perfringens* infections include watery diarrhea, stomach cramps, and severe dehydration (War et al. 2022). In addition to food poisoning, *Clostridium Perfringens* can also cause enteritis, enterocolitis, and enterotoxemia in livestock and poultry (Bhunia 2018). The bacterium produces toxins, including the enterotoxin CPE, which alters membrane permeability and can lead to diarrhea. Climate change can potentially impact the distribution and transmission of enteric pathogens (Lal et al. 2015); however, there is no specific mention of the effect of climate change on *Clostridium perfringens* in the abstracts provided (Maraldo and Holmstrup 2010; Leddin and Macrae 2020).

3.1.4 Staphylococcus aureus

Staphylococcus aureus is a gram-positive bacterium that can cause many human diseases, including pneumonia, skin infections, and food poisoning (Hamad et al. 2019). *Staphylococcus aureus*, a bacterium commonly found in various environments, exhibits growth influenced by a range of conditions. Research has shown that factors such as water activity, temperature, salt concentrations, pH levels, glucose concentrations, and the presence of other microorganisms can significantly impact the growth of *S. aureus* (Elahi and Fujikawa 2018; Ahmed et al. 2022; Luo et al. 2020; Sihto et al. 2016). For instance, the growth of *S. aureus* is inhibited by lower temperatures (Ahmed et al. 2022). Additionally, the optimal temperature for *S. aureus* growth was found to be around 38.5 °C (Medveďová et al. 2009). On the other hand, studies have also highlighted the slow growth of *S. aureus* at temperatures as low as 7 °C (Lu et al. 2009; Medveďová et al. 2009). Furthermore, the growth kinetics of S. aureus indicated estimated minimum, optimum, and maximum growth temperatures of 5.9, 42.0, and 49.2 °C, respectively (Xie et al. 2020).

Climate change has led to changes in temperature, precipitation patterns, and other environmental factors that may affect *the S. aureus* populations. Temperature changes can influence *S. aureus* gene expression by altering its transcriptome and proteome (Hellberg and Chu 2015). These changes in gene expression can affect the transition of *S. aureus* from commensal to pathogenic, potentially contributing to its ability to cause invasive infections (Bastock et al. 2021). However, the exact mechanisms by which climate change affects *S. aureus* populations remain unclear and require further investigation. The impact of climate change on *S. aureus* populations and their ability to cause diseases remains an area of active research. While some studies have suggested that climate change may enhance the growth and virulence of *S. aureus*, others have indicated that it may reduce the prevalence of certain strains. Further research is required to fully understand the effects of climate change on *S. aureus* populations and their interactions with humans.

3.1.5 Escherichia coli

Escherichia coli (*E. coli*) is a gram-negative bacterium commonly found in the intestines of humans and animals. E. coli is also a significant etiological agent of food-borne illnesses worldwide (Lee and Yoon 2021). Climate change can significantly affect the behavior and survival of *E. coli* (Lamenew and Ameha 2019). Several studies have explored the relationship between climate change and *E. coli*, highlighting the various mechanisms by which climate change can affect the bacterium. Climate change can potentially affect the presence and concentration of *E. coli* in the environment (Samut et al. 2023). Studies have shown that increasing temperature is associated with an elevated incidence of diarrheagenic *E. coli*, indicating a positive relationship between ambient temperature and the risk of *E. coli*-related diseases (Iqbal et al. 2019). Changes in temperature and precipitation patterns can influence the fate and transport of enteric bacteria as well as their growth and survival, increasing the prevalence of *E. coli* on pre-harvested leafy green vegetables (Philipsborn et al. 2016).

The survival and growth of *E. coli* are influenced by environmental factors such as temperature and moisture. *E. coli* can survive and grow outside the host in environments with high concentrations of nutrients and warm temperatures, and the addition of nutrients, such as manure, can increase the concentration of *E. coli* in soil, suggesting that favorable conditions in temperate environments can support the growth of *E. coli* (Ishii and Sadowsky 2008). Furthermore, unusual extremes in meteorological variables, induced by climate change, can influence the activity and behavior of E. coli in cattle feces (Oliver and Page 2016).

3.2 Food-borne viruses

3.2.1 Noroviruses

Norovirus is a common cause of gastroenteritis in humans, affecting people of all ages. Infections caused by noroviruses are usually mild and self-limiting but can be more severe in infants and the elderly (Stoyanova 2022). Norovirus can be transmitted through contaminated food, contaminated water, and infected handlers (Velebit 2020). Although noroviruses can remain infectious in foods and food packaging materials for a certain period, they are less persistent than other food-borne viruses such as human noroviruses (Li et al. 2021). Climate change has the potential to affect the transmission and prevalence of norovirus infections (Kim et al. 2021). Changes in temperature could increase the incidence of norovirus outbreaks in previously unaffected regions.

According to several studies, climate change can potentially affect the transmission and prevalence of norovirus (Chiu et al. 2022b; Lafferty 2009). Norovirus outbreaks have been shown to exhibit seasonal patterns, with peaks typically occurring during winter. Temperature is a crucial factor that influences the patterns of epidemic outbreaks caused by different norovirus genotypes (Chiu et al. 2022b). Climate change can impact the transmission and prevalence of norovirus infections. Studies have indicated that climate change can influence the seasonality of norovirus outbreaks by affecting factors such as transmissibility, host susceptibility, and the resistance of norovirus to environmental conditions (Ahmed et al. 2013).

The activity of norovirus varies seasonally, and the impact of climate change on the incidence of norovirus outbreaks is acknowledged but not fully understood (Chiu et al. 2022b). Moreover, the prevalence of norovirus infections tends to be higher during colder seasons, suggesting a seasonal pattern that may be influenced by climate change (Louya et al. 2019).

Research has suggested that changes in the prevalence and spread of infectious diseases, including norovirus, are potential effects of climate change that could have significant consequences for human health and society (Chan et al. 1999). The relationship between climate change and norovirus transmission is intricate and may involve various factors such as weather patterns, human behavior, and socioeconomic changes (Kim et al. 2021). Additionally, the prevalence of norovirus infections in different geographical locations and their association with childhood diarrhea have been well established (Palit et al. 2022). Therefore, changes in temperature due to climate change could affect the occurrence and spread of norovirus infections.

The dynamics of norovirus outbreak epidemics depend on the complex interactions of different variables, including genetic and environmental factors (Marshall and Bruggink 2011). The ecology of climate change and infectious diseases shows that norovirus habitat suitability may increase into temperate areas as a result of global temperature change (Lafferty 2009). This expansion could lead to an increase in the incidence of norovirus outbreaks in the previously unaffected regions.

Furthermore, climate change-related migration and the influx of migrant workers to meet the workforce demands of climate change adaptation infrastructure initiatives could also contribute to the spread of infectious diseases, including norovirus. Relocation to crowded areas increases the risk of diarrheal diseases, including norovirus infections (McMichael 2015). In Nordic countries, water-related sectors and urban water infrastructure are particularly vulnerable to climate change impacts (Silvast et al. 2021). Public water supply systems in England and Wales have been studied for their adaptation to climate change, highlighting the importance of reducing vulnerability through adaptation measures (Arnell and Delaney 2006).

It is important to note that there are still gaps in scientific knowledge regarding norovirus, especially in low-income settings (Lopman et al. 2016). However, with the development of norovirus vaccines, addressing these gaps in knowledge has become increasingly pressing (Lopman et al. 2016). Genotyping norovirus is also important for monitoring circulating strains and improving vaccine design (Yu et al. 2022).

3.2.2 Hepatitis a virus

Hepatitis A virus (HAV) is a highly contagious liver infection affecting millions worldwide (Bosch and Pintó 2014). While HAV infections have been declining globally due to improved sanitation and vaccination efforts, there is growing concern about the potential impact of climate change on the spread of this disease (Di Cola et al. 2021; Guerra Veloz and Agarwal 2023).

Climate change can influence the spread of HAV through various mechanisms, including changes in temperature, precipitation patterns, and sea level rise. These alterations can lead to an increase in vector-borne diseases, water scarcity, and contamination of water sources, which in turn can contribute to the propagation of HAV. Temperature plays a crucial role in the survival and replication of HAV. Studies suggest that warmer temperatures may enhance the stability and infectivity of the virus, potentially leading to increased transmission rates (Tarek et al. 2019).

Precipitation anomalies and flooding can significantly impact HAV outbreaks. Heavy rainfall and rising sea levels can contaminate water supplies, creating ideal conditions for spreading water-borne pathogens like HAV (Saad-Hussein et al. 2022). Understanding the projected changes in precipitation patterns and their effects on local water resources is critical for managing future HAV outbreaks.

Climate change and HAV transmission have far-reaching implications for public health. Rising temperatures, changing precipitation patterns, and increased frequency of extreme weather events can lead to higher rates of HAV infection, especially among vulnerable populations such as children, the elderly, and those with preexisting medical conditions (Adibin et al. 2021).

3.3 Foodborne parasites

Food-borne parasites, many of which are zoonotic, are found worldwide and are often transmitted by humans (Gajadhar 2015; Robertson et al. 2018). Parasites transmitted by humans to food can pose significant risks to public health that infected food handlers have been implicated as vehicles for parasitic transmission, leading to outbreaks in food establishments with poor sanitation practices (Kamau et al. 2012). The transmission of parasites to food can occur through contaminated water, food, or direct oral-fecal contact (Kristensen et al. 2016). Food and water remain major sources of intestinal parasites, with food handlers serving as reservoirs and agents for transmission (Ogolla 2018). Furthermore, asymptomatic carriers of diseases can contaminate food, water, fruits, and vegetables, leading to the spread of intestinal parasitic infections (Bunza et al. 2020). Contaminated food is a common source of transmission for parasites, with parasites being frequently transmitted to humans through ingestion of contaminated food (Torgerson et al. 2015). Additionally, parasites can be indirectly transmitted through the consumption of contaminated water with parasite cysts (Hedman et al. 2020). Climate change significantly impacts the spread and prevalence of food-borne parasites, which can cause serious illnesses in humans. Climate change leads to rising temperatures and changing precipitation patterns, which create an ideal environment for the growth and survival of food-borne parasites. For instance, warmer temperatures can increase the metabolic rate of parasites, allowing them to reproduce faster and reach higher populations (Dietrich et al. 2023). Additionally, altered precipitation patterns can increase humidity, enhancing parasite survival and dispersal (Polley 2015). In various geographical areas Climate variability, such as strong rainfall and fluctuations in precipitation, affects the occurrence of parasitical foodborne and water-borne diseases transmitted by protozoan parasites such as cryptosporidiosis and giardiasis in the United States and Europe (Tirado et al. 2010).

Climate change also affects the distribution and behavior of hosts, such as animals and plants, which can influence the transmission of food-borne parasites. For example, changes in temperature and precipitation patterns can cause shifts in the geographic range of host species, leading to the expansion of parasite populations into new areas (Selstad Utaaker & Robertson, 2015). Moreover, alterations in host behavior, such as changes in migration patterns, can increase the likelihood of parasite transmission (Lafferty 2009). The effects of climate change on food-borne parasites have significant implications for food safety. The increased prevalence and distribution of parasites can contaminate food sources, posing a risk to human health (Short et al. 2017; Pandey et al. 2023).

Warming and high temperatures result in a diminution of eggs. Because of higher temperatures and longer dry periods, Echinococcus granulosus, Echinococcus multilocularis, Taenia saginata, and Taenia solium survive in the environment, as do Fasciola spp. cercariae and oocysts of Cyclospora cayetanensis, Cryptosporidium spp., and Giardia duodenalis, resulting in a decrease in the prevalence of human infections with foodborne parasites. While flooding, the rising occurrence of human infections with Fasciola spp. caused by increased torrential rains. (Pozio 2020).

4 Surveillance of food and food-borne diseases

The main objective of surveillance is to identify the presence and levels of pathogens in food and assess the associated disease burden. This information then shapes public policies and prevention strategies (WHO 2017). Effective laboratories and the sharing of expertise play a crucial role in these efforts (WHO 2008). With climate change, there is a need to strengthen the existing system (Jones et al. 2004) while also giving specific attention to food-borne pathogens that may be influenced by climate change. Additionally, focusing on food originating from regions experiencing rapid environmental changes is important. Furthermore, enhancing molecular surveillance is essential to improving preparedness (Franz et al. 2016).

Advanced molecular techniques, particularly whole genome sequencing (WGS), enable precise tracking and tracing of microorganisms globally, allowing for the timely identification of emerging trends (Hendriksen et al. 2011). Furthermore, effective preparedness in the food system requires a commitment to extensive data management and sharing. Initiatives like the Global Microbial Identifier and GenomeTrakr (a US Food and Drug Administration initiative utilizing WGS for food safety management) support this progress and contribute to mitigating the impact of climate change on food-borne pathogens (Wielinga et al. 2017).

5 The challenges posed by climate change to human health

Climate change is recognized as a significant threat to public health today (DeJarnett et al. 2018). Numerous studies indicate that climate change will have a global impact on the occurrence of food-borne diseases, water-borne diseases, and specifically diarrheal diseases (Schijven et al. 2013; Lake and Barker 2018; Levy et al. 2018). In the African region alone, food-borne diseases contribute to 91 million cases of illness and 137,000 deaths annually (WHO 2022a). Among these diseases, diarrheal diseases account for 70% of the overall burden.

According to Levy et al. (2018), extreme temperature and precipitation will impact enteric pathogens, specifically those transmitted through fecal-oral routes, increasing the risk of gastrointestinal and diarrheal diseases.

According to the World Health Organization (WHO 2014a), in countries like Mauritania, approximately 2150 individuals, including 1700 children under the age of 5, die each year from diarrheal diseases, with nearly 90% of these deaths directly linked to poor water, sanitation, and hygiene (WASH) conditions. The West Africa Sahel region, including Burkina Faso and Mauritania, is considered highly vulnerable to climate change, with projected temperature increases 1.5 times higher than the global average (USAID 2018). Low- and middle-income countries, particularly in West Africa, face significant challenges in dealing with infectious diseases under climate change conditions, leading to various international collaborative efforts to assess risks and reduce the burden in different contexts.

The World Health Organization (WHO 2014b)estimates that climate change will result in 48,000 deaths in children under 15 due to diarrheal diseases by 2030 and 33,000 deaths by 2050. The impact of climate change on diarrheal diseases is expected to be more significant in Asia and Africa. By 2030, sub-Saharan Africa is projected to bear the highest burden of mortality impacts related to climate change, with Southeast Asia likely taking over by 2050.

Climate change is projected to bring out an increase the incidence of food-borne illness globally. According to the Intergovernmental Panel on Climate Change (IPCC), climate change is likely to lead to an increase in the frequency and severity of heatwaves, droughts, and heavy precipitation events, all of which can contribute to the growth and spread of food-borne pathogens (IPCC 2022). The World Health Organization (WHO) estimates climate change is already responsible for an additional 150,000 deaths annually, mainly due to malnutrition, malaria, diarrhea, and heat stress (WHO 2022a).

Certain populations are more vulnerable to the effects of food-borne pathogens, including young children, the elderly, pregnant women, and people with weakened immune systems. When infected with a food-borne pathogen, these groups may experience more severe symptoms or longer recovery. A study published in the Journal of Food Protection found that projected temperature and precipitation variability increases could result in a 30% increase in food-borne illness outbreaks in the United States by 2050 (Mills et al. 2010).

6 Mitigation strategies

Mitigating the effects of climate change on food-borne pathogens requires a multipronged approach that combines prevention, adaptation, and management strategies such as Food Safety Management Systems and HACCP system. Hazard Analysis and Critical Control Points (HACCP) is a preventive system crucial for ensuring food safety (Widodo et al. 2022). Studies have shown that HACCP-based procedures, along with good hygiene practices and production practices, have been effective in managing microbiological hazards in food and drinking water, even in the face of climate change impacts (Svanström et al. 2022). Climate change poses significant challenges to food safety, with studies indicating that it can impact microbiological hazards in food and water (Svanström et al. 2022). The application of a HACCP–Quantitative Microbiological Risk Assessment (QMRA) approach has been suggested to manage the effects of climate change on food quality and safety (Xiong et al. 2020). Adopting sustainable agricultural practices may improving sanitation and hygiene, establishing early warning systems, and fostering policy coordination and research, we can reach a safer and more resilient food system in the face of climate change.

6.1 Improved food safety systems and regulations

To mitigate the effects of climate change on Food-borne pathogens, it is essential to implement effective food safety measures. This includes proper handling and storage of food products, regular testing for contamination, and adequate regulation of food production and processing facilities. Implementing and enforcing strict food safety regulations can help mitigate the impact of climate change on food-borne pathogens. Regulations should cover the entire food chain, from farm to table, and include guidelines for proper handling, storage, and food preparation (FAO 2008).

Enforcing regulations can play a crucial role in mitigating the impact of climate change on food-borne pathogens. Climate change has been identified as a significant factor influencing the dynamics of infectious diseases, including food-borne pathogens (Caminade et al., 2019). The emergence and spread of food-borne diseases are closely linked to environmental conditions affected by climate change, particularly in low- and middle-income countries (Cissé, 2019). As climate change affects the persistence and dispersal of water- and food-borne pathogens, regulatory measures become essential to address these evolving challenges (Chersich et al., 2018).

Regulations can help in several ways. Firstly, they can ensure the implementation of food safety management systems, such as the Global Microbial Identifier and GenomeTrakr, which are crucial in monitoring and controlling food-borne pathogens (Lake and Barker 2018). Secondly, regulations can focus on improving environmental conditions related to food production and distribution, which are vital in reducing the exposure risks to food-borne diseases under changing climatic conditions (Cissé, 2019). Additionally, regulations can address the globalization of the food market, changing consumption patterns, and other factors exacerbated by climate change that contribute to the spread of food-borne pathogens (Abebe et al., 2020).

Furthermore, regulations can support research efforts aimed at understanding the complex interactions between climate change and food-borne pathogens. By fostering multidisciplinary research teams, regulations can facilitate studies on the effects of climate change on zoonotic diseases (Mills et al. 2010). Strengthening healthcare systems and response mechanisms, as suggested in studies focusing on infectious disease epidemics in the context of climate change, can also be part of regulatory strategies to mitigate the impacts of climate change on food-borne diseases (Noorunnahar et al., 2023).

By integrating regulatory frameworks with scientific research, environmental management strategies, and public health initiatives, it is possible to enhance preparedness and resilience against the evolving threats of food-borne diseases in a changing climate.

Governments and regulatory agencies must work together to ensure compliance with food safety standards and conduct regular inspections to minimize the risk of contamination. Developing and implementing policies that support sustainable agricultural practices, responsible antibiotic use, and strong food safety regulations can help ensure a more resilient food system. This requires close collaboration among policymakers, industry stakeholders, and scientists (WHO 2022b). Proper water management is essential for reducing the risk of food-borne pathogens. This includes ensuring adequate water quantity and quality for irrigation, livestock, and aquaculture and managing runoff and wastewater properly (Medlicott et al. 2020).

6.2 Climate-smart agriculture

Climate-smart agriculture involves implementing practices that enhance agricultural productivity and resilience in the face of climate change. Such practices include using drought-tolerant crops, improving soil health, and implementing conservation agriculture techniques (FAO 2021). By adopting climate-smart agriculture methods such as integrating agronomic practices, soil fertility management, conservation agriculture, irrigation techniques, and pest management strategies, farmers can reduce the impact of climate change on their crops and minimize the likelihood of food-borne pathogen contamination.

Climate-Smart Agriculture (CSA) is essential for enhancing food safety and protecting against foodborne pathogens by implementing sustainable agricultural practices that increase productivity, improve resource efficiency, and reduce vulnerability to climate change (Aryal et al., 2018). By adopting CSA, agricultural systems can support food security under changing climatic conditions, thereby contributing to the mitigation and adaptation to climate change while ensuring food safety (Akamani, 2021).

In the context of food safety and protection from foodborne pathogens, the adoption of CSA practices can lead to the development of novel surveillance methods for detecting and intervening in foodborne outbreaks more effectively (Lake and Barker 2018). Additionally, the integration of plant, animal, and human surveillance systems under the One Health approach enhances the identification of threats to food safety (Lake and Barker 2018). The transformative changes brought about by CSA not only aim to achieve food security and poverty alleviation but also involve stakeholders in public and private sectors to ensure long-term commitment and investment in sustainable agricultural practices (Steenwerth et al., 2014). By implementing CSA, agricultural systems can adapt to climate change, improve food security, and enhance resilience to climate variability, thereby contributing to the protection against foodborne pathogens and ensuring food safety.

Implementing sustainable agricultural practices, such as reduced tillage, cover cropping, and integrated pest management, can help minimize greenhouse gas emissions while improving soil quality and reducing the risk of pathogen contamination (Cárceles Rodríguez et al., 2022; van der Fels-Klerx et al. 2015).

Technological and digital advancements such as long-term innovation sustainability and the fundamental obligation to ensure that communities affected by the disease are involved in the design of the technology and directly benefit from its application. These technologies have allowed for the incorporation of meteorological data into surveillance systems, improving their ability to predict trends in outbreak prevalence and location (Pley et al. 2021).

6.3 Education and outreach

Educating consumers, food handlers and producers about the risks associated with food-borne pathogens and the steps they can take to prevent contamination is critical for adapting to the impacts of climate change. Public awareness campaigns, training programs, and extension services can all promote food safety practices and reduce the risk of food-borne illness (Faour-Klingbeil and C. D. Todd 2019).

Developing targeted interventions and educational programs tailored to specific vulnerabilities can help improve community resilience against climate change-induced food-borne pathogens. This includes providing information on safe food handling, storage, and cooking practices and promoting awareness of the link between climate change and food safety (Chandorkar 2023).

Investing in research and innovation can provide valuable insights into the underlying mechanisms of climate change-pathogen interactions and novel solutions for mitigating these effects. This includes developing new technologies and tools for detecting, tracking, and managing food-borne pathogens in a changing environment (Pires and Devleesschauwer 2021).

Education and outreach are essential in addressing the impact of climate change on foodborne pathogens. Health promotion campaigns can help prevent foodborne diseases by informing individuals about the health issues associated with climate change (Lake and Barker 2018). Outreach initiatives also play a crucial role in enhancing public understanding of how climate change affects the persistence and dispersal of foodborne bacterial pathogens in the environment (Hellberg and Chu 2015). Climate change influences the abundance, growth, range, and survival of foodborne pathogens, thereby impacting the prevalence of foodborne diseases (Smith and Fazil 2019).

Public health decision-makers are increasingly encouraged to implement preventative actions, such as public education and outreach, to mitigate health risks linked to climate change (Clarke & Berry, 2011). Mitigation strategies for antimicrobial-resistant microorganisms can be developed through a risk analysis framework, aiding in combating resistant foodborne pathogens (Pérez-Rodríguez & Taban, 2019). As the effects of climate change become more pronounced, prioritizing outreach education is crucial for addressing the challenges posed by climate change (Sansoulet et al., 2019).

Climate change not only impacts the transmission of foodborne pathogens but also influences their growth and persistence on various food materials, soil, and water (Samut et al. 2023). By engaging stakeholders and providing educational information on the long-term impacts of climate change, outreach efforts can help enhance resilience against future climate impacts (Chatrchyan et al., 2017). Changes in climate factors are significant drivers of pathogen introduction, food contamination, and foodborne diseases, underscoring the importance of outreach in addressing these issues (Tirado et al. 2010).

Therefore, education and outreach initiatives are vital components of efforts to mitigate the impact of climate change on foodborne pathogens. By raising awareness, providing information, and implementing mitigation strategies, education and outreach can significantly contribute to reducing the prevalence and risks associated with foodborne diseases in the context of a changing climate.

7 Knowledge gaps and future directions

Despite growing evidence of the impact of climate change on food-borne pathogens, several knowledge gaps remain. Understanding the complex interactions between climate variables, food systems, and pathogen populations is essential for effective policy development and public health preparedness. Some key areas for future research include enhanced surveillance systems necessary to detect and monitor food-borne pathogen trends under changing climatic conditions. Integration of data from various sources, such as weather stations, agricultural monitoring systems, and human health surveillance programs, could provide early warnings of emerging pathogen threats (Feliciano et al. 2022).

Developing effective adaptation strategies requires understanding how climate change will impact different food systems and pathogen populations. Research focusing on specific food types, production methods, and regional differences can inform targeted interventions to minimize food safety risks (Fawzy et al. 2020).

In addition to adaptation measures, identifying effective mitigation strategies to reduce greenhouse gas emissions and slow climate change is crucial for long-term food safety (Abbass et al. 2022). Investigating the impact of sustainable agriculture practices, renewable energy sources, and reduced meat consumption on food-borne pathogen populations may contribute to a broader strategy for reducing the burden of food-borne illnesses in a changing climate.

8 Conclusion

Climate change threatens public health by affecting the distribution and spread of food-borne diseases. Changes in temperature and precipitation patterns, shifting consumer behavior, and altered distributions of food-borne pathogens increase exposure risk for humans and animals. In contrast, changes in food production and trade can introduce new sources of contamination. It is essential to monitor the impact of climate change on food-borne pathogens and develop strategies to mitigate its effects on human health. Understanding the science behind the link between climate change and food-borne diseases is critical for designing successful mitigation and adaptation strategies. Such efforts might include improving food safety protocols and regulations, enhancing surveillance programs, climate-smart agriculture practices, proper water management, supporting sustainable aquaculture, education and outreach initiatives, and investing in research better to understand the relationship between climate change and food-borne illness. Addressing these knowledge gaps through continued research and collaboration between public health professionals, agricultural specialists, and policymakers is vital for protecting human health in a warming world. By taking all these proactive steps, it may be minimize the consequences of climate change on public health and protect vulnerable populations from its adverse effects.

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Declarations

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