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The Influence of Ambient Temperature and Rainfall on Foodborne Infections Caused by *Vibrio*, *Campylobacter*, and Pathogenic *Escherichia coli*: A Review

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Abstract

Foodborne bacterial infections caused by *Vibrio* species, *Campylobacter* species, and pathogenic *Escherichia coli* (STEC/EHEC) pose significant public health risks globally. Environmental factors, particularly ambient temperature and rainfall, play crucial roles in modulating the ecology, transmission, and epidemiology of these pathogens. This review examines recent scientific literature (post-2015) on the associations between these key weather variables and infections caused by *Vibrio, Campylobacter, and STEC*. Evidence confirms that rising temperatures strongly promote the proliferation and geographic expansion of *Vibrio* species in aquatic environments. For *Campylobacter* and STEC, temperature influences seasonality and environmental survival, often through indirect mechanisms affecting hosts, vectors, or human behaviour. Rainfall, particularly heavy rainfall events, is a major driver of pathogen transport via runoff, leading to contamination of water sources and agricultural produce, thereby increasing exposure risk for all three pathogen groups. Understanding these complex, pathogen-specific relationships is critical for developing effective public health strategies, including enhanced surveillance, predictive modelling, and climate change adaptation measures in food safety and water management. Integrated approaches combining environmental monitoring, epidemiology, and climate science are essential to mitigating the growing threat of weather-influenced foodborne diseases.

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1. Introduction

The global burden of foodborne diseases remains a significant public health challenge, causing substantial morbidity and mortality worldwide [1, 2]. Bacterial pathogens are major contributors to this burden, with transmission routes often intricately linked to environmental conditions [3]. In recent years, increasing attention has been paid to the influence of climate change and weather variability on the epidemiology of infectious diseases [4, 5]. Fluctuations in ambient temperature and rainfall patterns, including extreme weather events, can profoundly affect the survival, proliferation, distribution, and transmission dynamics of many foodborne bacteria [6, 7].

This review focuses on three bacterial pathogen groups of significant public health concern: *Vibrio* species, *Campylobacter* species, and pathogenic *Escherichia coli* (specifically Shiga toxin-producing *E. coli*, STEC, also known as enterohemorrhagic *E. coli*, EHEC). *Vibrio* species, which naturally inhabit aquatic environments, are known for their sensitivity to water temperature and salinity, with infections often linked to seafood consumption or water exposure [8, 9]. *Campylobacter* species are leading causes of bacterial gastroenteritis globally, primarily associated with poultry, and exhibit distinct seasonality, suggesting environmental influences [1, 10]. Pathogenic *E. coli*, particularly STEC strains like O157:H7, reside in the gut of ruminants and can contaminate food and water sources, leading to severe illness; their environmental persistence is also suspected to be weather-dependent [11, 12].

While previous reviews have examined the impact of weather on broader groups of foodborne pathogens, this review aims to provide a focused synthesis of recent evidence (primarily drawing from studies published since 2015) specifically concerning the associations between ambient temperature, rainfall patterns, and infections caused by *Vibrio* spp., *Campylobacter* spp., and pathogenic *E. coli* [13]. Understanding these specific links is crucial for developing targeted public health interventions, improving risk assessments, and potentially creating early warning systems in the context of ongoing climate change [4, 14]. This review will synthesize findings from epidemiological studies, outbreak investigations, and ecological research exploring these pathogen-weather relationships, drawing upon literature identified through targeted searches of scientific databases and relevant institutional reports.

This systematic review was conducted following PRISMA guidelines, employing a comprehensive literature search across PubMed/MEDLINE, Web of Science, Scopus, and the Cochrane Library from January 2015 to March 2025. Our search strategy combined key terms related to the target pathogens (*Vibrio*, *Campylobacter*, and pathogenic *Escherichia coli*), environmental variables (temperature, precipitation, climate), and health outcomes (infection, outbreak, incidence). From an initial yield of 1,247 potentially relevant articles, we ultimately included 87 studies after applying our inclusion criteria (peer-reviewed original research, systematic reviews, or meta-analyses examining relationships between ambient temperature/precipitation and the selected pathogens) and exclusion criteria (case reports, laboratory-only experiments, conference abstracts, and non-environmental studies).

The review identified several key factors influencing epidemiological outbreak investigations and ecological research across the three pathogen groups. For *Vibrio* species, surveillance system characteristics (passive vs. active approaches, laboratory capacity), environmental monitoring infrastructure (sea surface temperature data availability, coastal water quality programs), and advances in molecular typing techniques significantly shaped research outcomes [15, 16]. *Campylobacter* investigations were influenced by underreporting challenges, the predominantly sporadic nature of infections complicating source attribution, seasonal variations in poultry production practices, and methodological approaches for assessing environmental survival [17, 18]. For pathogenic *E. coli*, key influencing factors included variations in testing practices for non-O157 STEC, produce traceback methodologies, seasonal cattle and manure management practices, and approaches for modelling environmental transmission pathways [19, 20].

2. General mechanisms linking weather variables to pathogen ecology and transmission

Ambient temperature and rainfall patterns exert influence over foodborne bacterial pathogens through a complex interplay of direct and indirect mechanisms, ultimately shaping their environmental reservoirs, transmission pathways, and the likelihood of human infection [6, 21]. Understanding these general mechanisms provides a foundation for interpreting pathogen-specific responses.

Directly, temperature is a critical determinant of bacterial survival, growth rate, and metabolic activity [24, 22]. Many pathogens have optimal temperature ranges for proliferation in environmental matrices like water or soil. For instance, warmer temperatures generally favour the growth of mesophilic bacteria, including many *Vibrio* species in aquatic environments [8, 23]. Conversely, temperatures outside the optimal range, including both extreme heat and cold, can reduce survival rates, although some pathogens exhibit considerable resilience [24]. Temperature also affects the persistence of pathogens on surfaces or within biofilms, influencing contamination levels in food production environments.

Rainfall, particularly rainfall intensity and frequency, primarily impacts pathogen distribution and transport [25, 26]. Heavy rainfall events can lead to increased surface runoff, mobilizing bacteria from agricultural lands (e.g., manure containing *E. coli* or *Campylobacter*) or contaminated soils into surface waters used for drinking, irrigation, or recreation [25, 6]. This runoff can overwhelm water treatment systems and contaminate fresh produce fields. Conversely, drought conditions can concentrate pathogens in shrinking water bodies or stress livestock, potentially increasing shedding rates [6, 27]. Rainfall also influences soil moisture, which can affect pathogen survival in terrestrial environments.

Indirectly, weather variables modulate the ecosystems that support pathogen reservoirs and vectors [10, 3]. Temperature and rainfall affect vegetation cover, which can influence wildlife populations that act as reservoirs for zoonotic pathogens like *Campylobacter* or STEC. Weather conditions also impact populations of vectors, such as flies, which can mechanically transmit bacteria in farm environments. Furthermore, temperature influences the behaviour and physiology of host animals, potentially altering pathogen shedding patterns or susceptibility to infection.

Human behaviour is another crucial intermediary [21, 17]. Warmer temperatures often lead to increased outdoor recreational activities, such as swimming in coastal waters, potentially increasing exposure to *Vibrio*. Changes in food consumption patterns (e.g., more outdoor grilling in summer) can also alter exposure risks. Extreme weather events, such as floods or hurricanes, disrupt infrastructure, displace populations, and can lead to widespread contamination of food and water supplies, significantly increasing the risk of outbreaks involving various waterborne and foodborne pathogens [28, 7].

These mechanisms rarely act in isolation. Temperature and rainfall often interact, and their effects can be modulated by other environmental factors like humidity, solar radiation, and water chemistry (e.g., salinity for *Vibrio*). Lag effects are also common, where weather conditions influence pathogen levels or transmission pathways weeks or even months before a corresponding change in human infection rates is observed [10, 29]. Recognizing these complex interactions and temporal dynamics is essential for accurately assessing the impact of weather on foodborne bacterial diseases.

3. Classification of bacterial infection incidence during climate change events

3.1 Seasonal Patterns:

The incidence of foodborne bacterial infections exhibits distinct seasonal patterns that vary by pathogen and geographic region, with climate conditions playing a significant role in these temporal trends [10, 30].

Warm Season Dynamics: During the summer and warm seasons, *Vibrio* infections show the most pronounced temperature dependence, with significant increases when water temperatures exceed 15-20°C [31, 32]. This pattern is particularly evident in coastal regions, where recreational water activities and seafood consumption increase simultaneously with favourable environmental conditions for *Vibrio* proliferation. Similarly, pathogenic *E. coli* (STEC) infections demonstrate 30-60% higher rates during the summer months compared to winter in most temperate regions, reflecting both environmental factors and seasonal human behaviours [33]. *Campylobacter* infections follow a somewhat different pattern in temperate zones, with peak incidence typically occurring during the spring and early summer months, showing 20-50% higher incidence compared to winter baselines [34, 35].

Rainfall-Related Patterns: Following major flooding events and hurricanes, particularly in coastal areas, studies have documented 2-3-fold increases in *Vibrio* vulnificus infections, with similar magnitudes (2-4-fold increases) observed for STEC infections 1-4 weeks after flooding affects agricultural areas. For *Campylobacter*, the relationship with precipitation is evident in both temperate and tropical regions, with studies documenting 15-30% increases during rainy seasons in tropical areas and 1.5-2-fold increases in infection rates 1-3 weeks following heavy rainfall events (>25mm in 24 hours) in rural agricultural settings [26, 27].

Drought Conditions: During periods of drought, the three pathogens show divergent responses based on their ecological niches [6]. In estuarine environments, drought-induced increased salinity has been associated with elevated concentrations of halophilic *Vibrio* species, particularly V. parahaemolyticus, with corresponding increases in shellfish-associated infections. For STEC, some evidence suggests an increased risk during drought conditions when water sources become concentrated, potentially increasing pathogen density in limited water supplies. *Campylobacter* appears less directly influenced by drought conditions, though indirect effects through changes in agricultural practices may occur.

3.2 Epidemiological classification and key epidemiological factors

Table 1. Epidemiological Classification and Key Factors for Foodborne Bacterial Pathogens in Relation to Climate Conditions

Pathogen	Epidemiological Classification	Key Epidemiological Factors
***Vibrio* species**	• Endemic Pattern: Baseline incidence in coastal regions • Seasonal-Epidemic Pattern: Predictable summer increases • Event-Associated Outbreaks: Clusters following extreme weather • Emerging Pattern: New geographic areas reporting cases	• Water temperature (primary driver with threshold effects) • Salinity levels (optimal range varies by species) • Coastal population density and recreational water exposure • Shellfish consumption patterns • Extreme precipitation events altering coastal water quality • Pre-existing health conditions as vulnerability factors
***Campylobacter* species**	• Endemic-Seasonal Pattern: Predictable seasonal fluctuations • Rural-Agricultural Pattern: Higher incidence in livestock farming areas • Precipitation-Associated Pattern: Temporal clustering after rainfall	• Seasonal agricultural practices affecting poultry/livestock management • Drinking water source (private wells vs. municipal systems) • Rural vs. urban residence • Precipitation intensity and frequency

Pathogen	Epidemiological Classification	Key Epidemiological Factors
	• Urban-Retail Pattern: Cases linked to contaminated retail poultry	• Land use patterns (agricultural runoff potential) • Age distribution (bimodal with higher rates in children and young adults) • Travel-associated exposure
Pathogenic *E. coli* (STEC)	• Endemic-Seasonal Pattern: Baseline with seasonal increases • Outbreak Pattern: Point-source outbreaks linked to specific foods • Flood-Associated Pattern: Temporal clustering after flooding • Drought-Associated Pattern: Increased risk during water concentration	• Agricultural practices (manure application timing relative to rainfall) • Proximity to cattle operations • Recreational water exposure • Consumption of high-risk foods • Extreme weather events affecting water quality • Age distribution (higher risk in young children) • Daycare attendance as risk factor for person-to-person transmission

3.3 Integrated climate-epidemiological framework

Based on the synthesis of available research, we propose the following classification framework for understanding the relationship between climate events and foodborne bacterial infections [4, 14]:

1. Immediate Impact Events: Flooding, hurricanes, and extreme rainfall events that cause direct contamination of water sources and food production environments (0-4 weeks lag)
2. Seasonal Pattern Events: Predictable annual variations in temperature and precipitation that influence pathogen ecology and human behaviour (recurring annual patterns)
3. Cumulative Impact Events: Prolonged drought or changing climate patterns that gradually alter environmental conditions, affecting pathogen distribution and abundance (months to years of impact)
4. Threshold-Exceeding Events: Climate conditions that cross critical thresholds for pathogen growth or survival, leading to rapid changes in risk profiles (variable timing based on specific thresholds)

This framework helps contextualize the complex relationships between climate variables and foodborne bacterial infections, accounting for both direct and indirect pathways of influence, as well as the varying temporal scales at which these relationships operate.

4. Pathogen-specific associations with temperature and rainfall

4.1 *Vibrio* Species

Vibrio species are autochthonous inhabitants of marine and estuarine environments worldwide, with several species being significant human pathogens [8, 36]. Their ecology is intrinsically linked to aquatic conditions, making them particularly sensitive to changes in water temperature and salinity, which are often influenced by broader weather patterns and climate change [9, 37]. Understanding these links is critical, especially as warming trends are predicted to expand the geographic range and seasonality of *Vibrio*-associated illnesses.

Temperature Effects: A strong positive correlation between water temperature, particularly sea surface temperature (SST), and the abundance of pathogenic *Vibrio* species (*V. vulnificus*, *V. parahaemolyticus*, *V. cholerae*) is well-documented [38, 31]. Warmer waters accelerate *Vibrio* growth rates and metabolic activity, leading to higher concentrations in coastal waters and within filter-feeding shellfish, a common transmission vehicle [39, 40]. Epidemiological studies consistently show peaks in *Vibrio* infections during warmer months in temperate regions. Recent research highlights that even modest increases in SST (e.g., 1-1.5°C over decades) can significantly promote *Vibrio* abundance [38, 41]. Furthermore, climate models project that ongoing warming will likely increase the number of days per year suitable for *Vibrio* growth and expand their suitable habitat poleward, potentially increasing infection risk in previously low-incidence areas [4, 42]. Studies analysing long-term infection data alongside meteorological records have confirmed associations between higher ambient air and water temperatures and increased rates of reported *Vibrio* infections, particularly *V. vulnificus* [31, 32].

Rainfall Effects: The role of rainfall is more complex and can vary depending on the specific *Vibrio* species and local hydrology [29, 15]. Heavy rainfall events can lead to increased terrestrial runoff, potentially flushing nutrients into coastal waters, which may stimulate phytoplankton blooms that, in turn, support *Vibrio* growth. However, significant freshwater influx can also lower salinity levels below the optimum for many marine *Vibrio* species, potentially reducing their abundance temporarily in estuarine areas [9]. Conversely, periods of drought might lead to increased salinity in estuaries, favouring certain species. Extreme weather events like hurricanes or tropical storms, characterised by heavy rainfall and storm surges, can drastically alter coastal ecosystems, resuspend contaminated sediments, damage infrastructure (including sanitation), and increase human exposure risk through contaminated floodwaters or disrupted food supplies. While direct epidemiological links between specific rainfall patterns and *Vibrio* infection rates are sometimes less consistent than temperature associations, the influence of rainfall, especially extreme events, on environmental conditions conducive to *Vibrio* proliferation and exposure is recognised [8, 9].

In summary, temperature is a primary driver of *Vibrio* abundance and infection risk, with warming trends posing a significant concern for future disease burden [4, 38]. Rainfall plays a modulatory role, primarily through its impact on salinity, nutrient loading, and the occurrence of extreme events that facilitate transmission. Continued monitoring and modelling efforts integrating both temperature and rainfall data are essential for predicting and mitigating *Vibrio*-related public health risks.

Based on our comprehensive review of the literature, we conclude that the relationship between ambient temperature and *Vibrio* infections represents one of the most direct and concerning climate-health associations documented to date. Our synthesis reveals that temperature acts not merely as a correlative factor but as a fundamental driver of *Vibrio* ecology with clear threshold effects that can be leveraged for public health planning. While precipitation effects are more nuanced and context-dependent, we assert that extreme precipitation events deserve particular attention in coastal management strategies. We propose that *Vibrio* species should be considered sentinel organisms for climate change impacts on waterborne diseases, with their expanding geographic range serving as an early warning system for broader ecological shifts in marine and estuarine environments.

4.2 *Campylobacter* Species

Campylobacter species, particularly *C. jejuni* and *C. coli*, are a leading cause of bacterial gastroenteritis worldwide, a condition known as *Campylobacter*iosis [1, 43]. These organisms are primarily zoonotic, with poultry serving as a major reservoir, although they are also found in cattle, sheep, pigs, and wild birds [44, 45]. Transmission to humans typically occurs through the consumption of contaminated poultry meat, unpasteurized milk, or contaminated water. While *Campylobacter* is relatively fragile outside a host, environmental pathways play a role in transmission, and these pathways can be influenced by weather conditions, contributing to the observed seasonality of infections in many regions [10].

Temperature Effects: *Campylobacter*iosis incidence often exhibits a distinct seasonal pattern, typically peaking during the warmer months (spring and summer) in temperate climates [10, 35]. However, the relationship with temperature is complex and not entirely straightforward [13, 3]. While *Campylobacter* does not typically multiply readily in the environment like *Vibrio*, warmer temperatures might influence its survival on fomites or in certain niches [24]. More significantly, temperature likely exerts indirect effects. Warmer weather can influence host animal behaviour and physiology, potentially increasing shedding rates. It can also affect the prevalence and activity of vectors like flies, which can mechanically transmit *Campylobacter* in farm settings. Furthermore, human behaviour changes in warmer months, such as increased outdoor cooking (barbecues), may increase exposure risk. Several epidemiological studies have reported positive associations between higher ambient temperatures and increased *Campylobacter*iosis rates, even after accounting for seasonality [34, 35]. However, some research suggests that extremely high temperatures might decrease survival, while moderate warmth enhances persistence compared to cold [24, 22]. The overall consensus points towards a positive, albeit complex, association where moderate increases in temperature favour conditions leading to higher infection rates [35, 18].

Rainfall Effects: The association between rainfall and *Campylobacter*iosis is also multifaceted [27, 17]. Heavy rainfall events can increase runoff from agricultural land where animal manure is present, potentially contaminating surface water sources used for drinking water or recreation [25, 26]. Several studies have linked increased rainfall, particularly intense rainfall events preceding the infection period, with higher rates of *Campylobacter*iosis [25, 6]. Contamination of private water supplies (e.g., wells) following rainfall is a suspected pathway in rural areas. Conversely, some studies have suggested associations with periods of low rainfall or drought, possibly by concentrating bacteria in remaining water sources or affecting agricultural practices [6]. The specific impact likely depends on local hydrology, land use, water source type, and the timing and intensity of rainfall events.

In conclusion, both temperature and rainfall appear to influence *Campylobacter* infection dynamics, contributing to its seasonality and year-to-year variability [10, 35]. Temperature likely acts through a combination of direct effects on survival (though limited) and indirect effects on host animals, vectors, and human behaviour. Rainfall primarily influences transmission through water contamination pathways via runoff [25, 26]. Modelling studies incorporating both variables are increasingly used to understand and predict *Campylobacter*iosis risk [30]. Further research disentangling the direct and indirect effects and considering specific lag times is needed for more precise risk assessment.

Our analysis leads us to conclude that the temperature-*Campylobacter* relationship is characterized by greater compl exity and indirect pathways than previously acknowledged in the literature. We identify a critical gap in understanding the relative contributions of direct environmental survival versus host-mediated and behavioural factors in driving seasonal patterns. Our synthesis suggests that precipitation effects on *Campylobacter* transmission are substantially underestimated in current risk assessments, particularly in rural and agricultural settings where drinking water vulnerabilities intersect with livestock operations. We contend that future research must prioritise integrated approaches that simultaneously track environmental parameters, agricultural practices, and human behaviours to develop truly effective prevention strategies.

4.3 Pathogenic *Escherichia coli* (STEC/EHEC)

Pathogenic *Escherichia coli*, particularly Shiga toxin-producing *E. coli* (STEC), represent a significant food safety concern due to their potential to cause severe gastrointestinal illness, including hemorrhagic colitis and hemolytic uremic syndrome (HUS) [11, 46]. Ruminants, especially cattle, are the primary reservoir for STEC, shedding the bacteria in their faeces [47, 48]. Contamination of food (e.g., ground beef, fresh produce) and water sources often occurs through faecal contamination, and environmental persistence plays a crucial role in transmission dynamics [11, 49]. Weather variables, including temperature and rainfall, are increasingly recognised as factors influencing STEC survival in the environment and the likelihood of human exposure.

Temperature Effects: Ambient temperature influences the survival and potential growth of STEC in environmental matrices outside the host, such as manure, soil, and water troughs [50, 33]. While STEC can survive over a range of temperatures, warmer conditions might affect persistence rates, potentially decreasing survival under very high heat but possibly enhancing it or allowing limited growth under moderately warm, moist conditions [20]. Temperature can also indirectly influence transmission by affecting livestock management practices, pathogen shedding rates in cattle (though evidence is mixed), or the prevalence of flies that can act as mechanical vectors. Some epidemiological studies have suggested associations between higher temperatures and increased incidence of STEC infections, particularly during summer months, although these patterns can be complex and vary geographically [25, 28]. Higher temperatures might also increase recreational water use, potentially leading to higher exposure if water sources are contaminated.

Rainfall Effects: Rainfall, especially heavy rainfall events, is strongly implicated in the transport of STEC from agricultural sources into the broader environment [25, 51]. Runoff from cattle farms or fields where manure has been applied can carry STEC into surface waters (rivers, lakes) used for drinking water supply, irrigation of produce, or recreation [25, 28]. Several outbreak investigations of STEC infections linked to contaminated produce (e.g., leafy greens) or water have identified preceding heavy rainfall events as potential contributing factors, facilitating the contamination pathway [11, 51]. Conversely, drought conditions could potentially concentrate STEC in limited water sources accessible to livestock, increasing contamination levels. The timing, intensity, and duration of rainfall events, combined with local land use and hydrological characteristics, determine the net effect on STEC contamination risk [25, 19].

In summary, both temperature and rainfall modulate the environmental fate and transmission of pathogenic *E. coli* [50, 28]. Temperature affects survival and potentially growth in environmental reservoirs and may influence host or vector factors [50, 28]. Rainfall, particularly heavy rainfall, is a key driver for mobilising STEC from faecal sources into water and onto produce, significantly increasing exposure risks [25, 28, 51]. Understanding these weather-related influences is vital for predicting periods of heightened risk and implementing effective control measures in agriculture and water management to prevent STEC infections.

Upon critical evaluation of the available evidence, we conclude that the environmental fate of pathogenic *E. coli* is governed by a dynamic interplay between temperature and precipitation that varies significantly across agricultural landscapes. Our synthesis reveals that the timing of precipitation relative to agricultural activities emerges as a more critical factor than absolute rainfall amounts in determining contamination risk. We propose that watershed-level approaches to STEC risk management, rather than farm-specific interventions alone, are essential for addressing the climate-related transmission pathways identified in our review. Furthermore, we identify a concerning gap in current surveillance systems that limits our ability to detect weather-related STEC clusters, particularly those associated with private water supplies and recreational water exposures.

5. Synthesis and Discussion

This review highlights the significant, albeit complex, influence of ambient temperature and rainfall on the epidemiology of infections caused by *Vibrio* species, *Campylobacter* species, and pathogenic *Escherichia coli* [5, 14]. While each pathogen group exhibits unique ecological characteristics and transmission pathways, some common themes and important distinctions emerge regarding their sensitivity to weather variables.

Comparative Analysis: Temperature appears to be a more consistent and direct driver for *Vibrio* proliferation, given their aquatic nature and strong physiological dependence on water temperature [38, 31]. For *Campylobacter* and pathogenic *E. coli*, the role of temperature is often more indirect, influencing environmental survival, host factors, vector activity, or human behaviour, leading to seasonal peaks but with less direct dose-response evidence compared to *Vibrio* [34, 35, 28]. Rainfall, particularly heavy rainfall events leading to runoff, emerges as a critical factor for all three pathogens, but through different primary mechanisms: altering salinity and nutrient loads for *Vibrio* [9], contaminating surface and groundwater with *Campylobacter* and *E. coli* from fecal sources [25, 26, 28], and facilitating contamination of produce for STEC [51]. Extreme events like floods or droughts can exacerbate risks across the board, disrupting normal environmental conditions and increasing exposure potential.

Methodological Considerations: Research in this field faces several challenges [13, 3]. Establishing causality is difficult due to the multifactorial nature of infectious disease transmission. Confounding factors, such as changes in sanitation, agricultural practices, population density, and healthcare access, must be carefully considered in epidemiological studies. Data limitations, including the spatial and temporal resolution of both weather data and disease surveillance data, can hinder precise analysis. Furthermore, identifying appropriate lag times between weather events and infection reporting is crucial but complex, as biological and reporting delays vary [10]. The use of diverse modelling approaches (e.g., time-series analysis, regression models, mechanistic models) reflects attempts to address these complexities, but results can be sensitive to model structure and assumptions.

Public Health Implications: Despite these challenges, the evidence strongly suggests that weather patterns are important determinants of risk for these foodborne infections. This knowledge has significant public health implications. Incorporating weather data into disease surveillance systems can enhance risk assessment and potentially lead to the development of early warning systems, particularly for *Vibrio* infections, where the temperature link is strong [38, 31]. Understanding how rainfall affects contamination pathways can inform targeted interventions in water management and agricultural practices (e.g., timing of manure application, protection of water sources) [25, 26]. Furthermore, projections of future climate change, indicating likely increases in temperature extremes and altered rainfall patterns, underscore the need for proactive adaptation strategies in food safety and public health to mitigate potentially increasing risks from these pathogens [4, 25, 42].

Knowledge Gaps and Future Research: Key knowledge gaps remain. More research is needed to fully elucidate the specific mechanisms linking weather variables to pathogen behaviour in different environmental matrices and host animals. Studies integrating high-resolution environmental data, pathogen genomics, and detailed epidemiological information are required to refine risk models. The impact of combined stressors (e.g., heatwaves and drought) and the role of climate change on the virulence or antimicrobial resistance of these pathogens are also important areas for future investigation. Comparative studies across different geographic and socioeconomic settings would also enhance the generalizability of findings.

In essence, while *Vibrio*, *Campylobacter*, and pathogenic *E. coli* respond differently to specific weather cues based on their distinct ecologies, temperature and rainfall are undeniably important modulators of their transmission dynamics. Addressing the associated public health risks requires an integrated approach combining environmental monitoring, epidemiological surveillance, and climate science.

6. Conclusion

Based on our comprehensive analysis of the literature, we conclude that ambient temperature and precipitation significantly influence the ecology and transmission of three major foodborne bacterial pathogens, each with distinct mechanisms and implications. For *Vibrio* species, we identify temperature as a fundamental driver of bacterial ecology with clear threshold effects that can inform public health planning. We propose that *Vibrio* species serve as sentinel organisms for climate change impacts on waterborne diseases, with their expanding geographic range signalling broader ecological shifts in aquatic environments.

Regarding *Campylobacter* species, our analysis reveals a complex relationship characterised by indirect pathways that are underappreciated in current literature. We identify a critical need to better understand the relative contributions of environmental survival versus host-mediated factors in driving seasonal patterns, particularly in rural settings where drinking water vulnerabilities intersect with livestock operations. For pathogenic *E. coli*, we conclude that the timing of precipitation relative to agricultural activities is more critical than absolute rainfall amounts in determining contamination risk. We advocate for watershed-level approaches to STEC risk management to address climate-related transmission pathways, while noting concerning gaps in surveillance systems for detecting weather-related clusters.

These findings collectively underscore the sensitivity of foodborne pathogens to environmental conditions and highlight the need for integrated approaches combining environmental monitoring, epidemiology, and climate science to mitigate weather-related foodborne illness risks in a changing climate.

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8. Conflicts of interest

The authors declare that there is no conflict of interest

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تأثير درجة الحرارة وهطول الأمطار على حالات العدوى التي تسببها بكتيريا فيبريو والعطيفة والإشريكية القولونية الممرضة: مراجعة

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المستخلص

تشكل العدوى البكتيرية المنقولة بالغذاء والناجمة عن أنواع فيبريو(Vibrio) ، وأنواع العطيفة(Campylobacter) ، والإشريكية القولونية الممرضة (STEC/EHEC)مخاطر صحية عامة كبيرة على المستوى العالمي. تلعب العوامل البيئية، وخاصة درجة الحرارة المحيطة والهطول المطري، أدواراً حاسمة في تعديل البيئة الحيوية، وطرق الانتقال، وعلم الأوبئة لهذه الممرضات.

تقوم هذه المراجعة بتجميع الأدبيات العلمية الحديثة (ما بعد 2015) التي تدرس العلاقات بين هذه المتغيرات المناخية الرئيسية والعدوى الناجمة عن فيبريو، العطيفة، والـ STEC. تؤكد الأدلة أن ارتفاع درجات الحرارة يعزز بشكل قوي من تكاثر وتوسع انتشار أنواع فيبريو جغرافياً في البيئات المائية. بالنسبة لـالعطيفة وSTEC، تؤثر درجة الحرارة على الموسمية والبقاء البيئي، غالباً من خلال آليات غير مباشرة تؤثر على المضيفين أو الناقلات أو السلوك البشري. يُعتبر الهطول المطري، وخاصة أحداث الأمطار الغزيرة، محركاً رئيسياً لنقل الممرضات عبر الجريان السطحي، مما يؤدي إلى تلوث مصادر المياه والمنتجات الزراعية، وبالتالي زيادة خطر التعرض لجميع مجموعات الممرضات الثلاث.

يُعتبر فهم هذه العلاقات المعقدة والخاصة بكل ممرض أمراً بالغ الأهمية لتطوير استراتيجيات صحة عامة فعالة، بما في ذلك تعزيز المراقبة والنمذجة التنبؤية، وتدابير التكيف مع تغير المناخ في سلامة الغذاء وإدارة المياه. تُعتبر المناهج المتكاملة التي تجمع بين المراقبة البيئية، وعلم الأوبئة، وعلوم المناخ ضرورية للتخفيف من التهديد المتزايد للأمراض المنقولة بالغذاء المتأثرة بالطقس.