Received: 25 June 2019 | Revised: 23 May 2020 | Accepted: 18 October 2020
DOI: 10.1111/zph.12785

REVIEW

WILEY

Influence of weather and climate on cryptosporidiosis—A review

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Abstract

Studies have shown that climatic factors can significantly influence transmission of many waterborne diseases. However, knowledge of the impact of climate variability on cryptosporidiosis is much less certain. Associations between the incidence of cryptosporidiosis and climatic variables have been reported in several countries. Given that the identified relationships were not consistently reported across studies, it is not known whether these were country-specific observations or can be considered more globally. Variation in the disease risk in both low- and middle-income countries and high-income countries presents new challenges and opportunities to enact responsive changes in research and public health policies. Available epidemiological evidence of the influence of weather and climate on cryptosporidiosis is reviewed. Fourteen studies met the inclusion criteria, and most studies showed that the incidence of cryptosporidiosis is highly sensitive to climatic conditions, especially temperature, rainfall and relative humidity. The identified associations varied across studies, with different conditions of importance and lag times across different locations. Therefore, there is a need for countries at risk to assess *Cryptosporidium* transmission routes based on the spatiotemporal patterns of the disease and what role climate and other socio-ecological changes play in the transmission. Information gathering will then allow us to provide information for evidence-based control strategies and mitigation of transmission. This review offers new perspectives on the role of climate variability on *Cryptosporidium* transmission. It highlights different epidemiological approaches adopted and provides the potential for future research and surveillance to reduce the disease burden. By evaluating the epidemiological transmission of this organism in high-income countries, all mitigation strategies, for example filtration and water catchment management, can be used as exemplars of preventing infection in low- to middle-income countries.

KEYWORDS
climate, cryptosporidiosis, public health, waterborne disease, weather

1 | INTRODUCTION

One of the leading causes of morbidity and mortality worldwide is waterborne diseases which affect not only low- and middle-income countries but also high-income countries (Hrudey, 2004; Hunter et al., 2001; Pinsky, 2000; Rizak & Hrudey, 2008). Worldwide, the monthly average temperature is increasing. This could affect the environment and human health in both temperate and tropical regions in different ways (Coumou et al., 2013; Nava et al., 2017). Studies in high-income countries have shown that much of the burden of waterborne diseases is attributable to higher frequency and intensity of heatwaves, prolonged precipitation events, increased floods, storms, droughts and wildfires (Cann et al., 2013; Charron et al., 2004; Funari et al., 2012; Levy et al., 2018; Marcogliese, 2016). Also, change in climate is expected to increase the risk of waterborne diseases by affecting the biological, chemical and physical components of water through different pathways (El Baz & Kholoud, 2019). Projected changes such as these will directly affect the exposure pathways of waterborne diseases like cryptosporidiosis through their influence on the reproduction and survival rate of *Cryptosporidium spp*. Particular attention by public health practitioners is therefore crucial for optimizing intervention strategies, especially in low- and middle-income countries where the burden of disease is disproportionately greater.

Cryptosporidiosis is the most common and widespread protozoan waterborne diarrhoeal infection that has become a global public health challenge. The widely distributed apicomplexan waterborne protozoan parasite *Cryptosporidium spp*. that can live in the intestine of humans and animals is responsible for the disease. There are over 30 species of *Cryptosporidium*, but only two species *Cryptosporidium hominis* (specific to only humans) and *Cryptosporidium parvum* (specific to humans and animals) are thought to be of public health significance (Ramirez et al., 2004). However, sporadic reports of infection with other species can occur (Liu et al., 2020). The Global Burden of Disease Study, conducted in 2016, showed that *Cryptosporidium* caused 57,200 deaths in all age groups, and more than 80% of deaths were in children younger than 5 years (Khalil et al., 2018). Unlike other waterborne parasites, infection depends on several factors involving host, pathogen and environment. The oocysts, which are the infective stage in the parasite's life cycle, have the potential to pose a severe threat to both human and animal health because they are naturally present in the environment. Previous research showed that oocysts could survive for prolonged periods under a range of environmental pressures (Alum et al., 2014; Atherholt et al., 1998; Chalmers et al., 1997; Robertson et al., 1992; Rose, 1997; Rose et al., 2002; Gorospe, 2005). A single oocyst is sufficient to produce infection and disease in susceptible hosts (Ramirez et al., 2004). The time from ingestion to infection is short, taking between 2 and 12 days, with an average of about seven days, which may explain why there is rapid transmission once an outbreak occurs (Hu et al., 2007). Upon excretion in the faeces of the host (either animal or human), the oocyst remains infectious and is transmitted principally through the faecal–oral route either from person to person or animal to person (Fayer, 2010; Fayer & Xiao, 2007; Pollock et al., 2010; Xiao, 2010). The disease is characterized by non-bloody watery diarrhoea accompanied by bloating, abdominal pain, dehydration loss of appetite, nausea, weight loss, fever, nausea and vomiting (Funari et al., 2012; Pollock et al., 2010). It is also associated with long-term health sequelae such as irritable bowel syndrome, reactive arthropathy, headache, joint pain and eye pain (Hunter et al., 2004; Iglói et al., 2018; Stiff et al., 2017). There is currently no effective treatment for or vaccine against cryptosporidiosis (Hu et al., 2007; Hu et al., 2010; Mead, 2014; Bartelt et al., 2016), making prevention the focus of public health interventions.

Impacts

- Cryptosporidiosis is a zoonotic disease and a major global public health problem.
- The increasing concerns about the *Cryptosporidium* transmission due to climate variability are highlighted in this review.
- The association between weather, climate, environmental management and cryptosporidiosis merits further public health efforts in control and prevention of this infection.

The disease distribution is generally expressed in terms of incidence (new cases per year) and prevalence (total number of existing and new cases at a specified time or during a specified period). Several risk factors that influence the spatial and temporal patterns of cryptosporidiosis have been identified. Examples include drinking water from poorly treated public and private supplies, visiting/living on a farm, and contact with farm animals and wild animals. Other factors are swimming in contaminated swimming pools, travel to endemic regions, eating contaminated food, agricultural practices and contact with young children, especially in day-care centres (Hunter & Thompson, 2005; Learmonth et al., 2004; Meinhardt et al., 1996; Putignani & Menichella, 2010; Strachan et al., 2003). In addition to these, land use/land cover type, weather patterns and seasonality are identified as risk factors which influence the intensity of contact between *Cryptosporidium* and susceptible hosts (Hu et al., 2007; Jagai et al., 2012; Lake et al., 2005; Lake et al., 2007; Lake et al., 2008; Hu, Mengersen, & Tong, 2010; Lal et al., 2012; Lal, Baker, et al., 2013; Lal, Ikeda, et al., 2013; Naumova et al., 2005). Indeed, the incidence of cryptosporidiosis varies geographically and seasonally and is linked with weather and climate (Jagai et al., 2012; Lal et al., 2012; Lake et al., 2007). Within regions, cryptosporidiosis can exhibit different seasonal patterns at different locations. A recent meta-analysis by Jagai and colleagues have predicted that changing climate will increase the transmission of cryptosporidiosis infection, and the increase will vary by season and location (Jagai et al., 2009). As the season progresses, the distribution of oocysts through the continuous shedding by infected individuals can lead to cryptosporidiosis transmission. The transmission pattern includes variations in the number of outbreaks and different delays concerning peaks in rainfall and temperature.

Moreover, changes in ambient physical conditions also influence the environmentally mediated *Cryptosporidium* transmission pathways. Furthermore, transmission corresponds to warm months, wet months or rainy seasons (Rose, 1997). In turn, this plays a significant role in driving the seasonality of cryptosporidiosis (Jagai et al., 2009). Moreover, several authors have recognized some differences in the seasonality of cryptosporidiosis cases. However, the mechanisms by which these factors affect the spread of *Cryptosporidium* are not fully understood. Nevertheless, accumulated evidence shows that changes in weather and climatic factors can strongly influence the distribution and transmission of *Cryptosporidium*. This paper reviewed epidemiological studies on the direct and indirect evidence of the influence of weather and climate on cryptosporidiosis. Furthermore, it provides a comprehensive update of worldwide published reports of the associations. Knowledge of this is vital, as it would guide mitigation strategies to alleviate and prevent the spread of the disease effectively.

2 | LITERATURE REVIEW

2.1 | Evidence of seasonality of cryptosporidiosis

Studies in high-income countries have reported a bimodal seasonal pattern but with some differences. Some authors have reported spring and autumn peaks in England (Lake et al., 2005; Naumova et al., 2005), New Zealand (Lake et al., 2008; Lal et al., 2012; Snel et al., 2009; Lal, Baker, et al., 2013), Scotland (Ramsay et al., 2014) and the United States (Jagai et al., 2009, 2012). However, Callaghan et al. (2009) reported spring and summer peaks in Ireland. In England and Scotland, spring and late summer–early autumn peaks have also been recognized (McLauchlin et al., 2000; Pollock et al., 2010; Strachan et al., 2003). Other studies have also reported summer and autumn peaks in Australia (Hu et al., 2007), Canada (Majowicz et al., 2001) and the United States (Naumova, 2000). Some community-based studies in low- and middle-income countries have reported higher *Cryptosporidium* infection during rainy seasons in Brazil (Newman et al., 1999; Pereira et al., 2002), Gambia (Adegbola et al., 1994; Hossain et al., 2019), Guinea-Bissau (Perch et al., 2001), India (Das et al., 2006), Madagascar (Areeshi et al., 2008) and the dry season in Kenya (Gatei et al., 2006). The tendency for cases to exhibit seasonal peaks highlights the potential influence of environmental conditions in the spread of the disease. Environmental conditions modulate the replication of *Cryptosporidium* without the need for host cells. Therefore, the timing of the onset and peak of seasonal transmission, as well as the duration of the transmission season, may depend on annual variability in climatic variables.

It has been indicated that climate variability can affect the seasonal pattern of cryptosporidiosis through its influence on local weather conditions (Lake et al., 2005; Lal et al., 2012). Knowledge of the principal factors controlling the seasonal pattern is thus the first step required to understand the effect of climate variability on the disease. However, only a few studies have looked beyond this seasonal pattern to investigate the association between weather and climate with cryptosporidiosis (Hu et al., 2007; Naumova et al., 2005; Lal, Baker, et al., 2013). Seasonal variation of the frequency of certain levels of temperature, for example high or low temperatures and rainfall may have a direct or indirect impact on the oocysts. The direct impact is through supporting the survival and dissemination of oocysts in the environment, thereby increasing the probability of contact with susceptible hosts to be infected, for example when a susceptible host ingests oocysts on contaminated surfaces via the environment through overland run-off water from agricultural and pasture lands, and urban areas (Cabral, 2010). The indirect impact is through acting on other factors that affect the chances of transmission. Changes in weather events might indirectly influence human behaviour through recreational activities, consumption habits or adaptation behaviours (Semenza et al., 2012). For example, this could be changes in social behaviour, where warmer temperatures encourage people to bathe in pools, which may be contaminated by the oocysts (Morand et al., 2013). Accounting for seasonal temperature and rainfall in the first instance would be a suitable approach before exploring the association. This approach will present an accurate estimation of the actual effect of the climatic variables on cryptosporidiosis transmission. It would increase understanding of the overall risk of climate when establishing long-term public health intervention strategies.

2.2 | Evidence of climatic factors on cryptosporidiosis

Studies have shown that factors such as temperature, rainfall and humidity affect the life cycle of *Cryptosporidium* (both directly and indirectly through ecological changes) and can potentially affect the timing and intensity of the disease outbreak (Patz et al., 2000). Several studies have shown an association between weather and climate and cryptosporidiosis incidence (Britton et al., 2010; Curriero et al., 2001; Eze et al., 2014; Hu et al., 2007, 2010; Hu, Mengersen, & Tong, 2010; Kent et al., 2015; Lake et al., 2005, 2008; Lal et al., 2013; Naumova et al., 2005, 2007). Some have focused on the disease outbreak (Nichols et al., 2009; Thomas et al., 2006). As a result, some statistical models, such as time-series regression models, have been developed to estimate the effect of climate parameters and explained the potential transmission mechanisms. Available evidence of the association, at different levels, comes from different high-income countries such as Australia (Hu, Mengersen, Fu, et al., 2010; Hu, Mengersen, & Tong, 2010; Hu et al., 2007; Kent et al., 2015), Canada (Thomas et al., 2006), England and Wales (Lake et al., 2005; Naumova et al., 2005; Nichols et al., 2009), New Zealand (Britton et al., 2010; Lake et al., 2008; Lal, Ikeda, et al., 2013), Scotland (Eze et al., 2014) and the United States (Curriero et al., 2001; Naumova et al., 2007).

However, such studies are lacking in low- and middle-income countries where the risk might be higher despite available evidence on the association. No prior published studies report the association between climate variability and cryptosporidiosis incidence. The comprehensive analysis of the association reveals there is a significant research gap between low- and middle-income countries and high-income countries. Moreover, the findings from high-income countries cannot merely be applied to low- and middle-income countries to identify periods at greater risk of exposure; therefore, local knowledge of the association is vital. Much of the robust evidence is focused on either a single city or country and does not represent a wide range of climatic effects in other countries given that weather changes too quickly and affects local regions differently (Polgreen & Polgreen, 2017).

Moreover, variation in the observed association between high-income countries and trends over time within countries highlights the complex disease transmission mechanism. Also, varying and contradictory findings have created many uncertainties about the relationship and warrant further studies in other countries where such an association is still lacking or yet to be reported. Table 1 summarizes the findings obtained from studies conducted in high-income countries. It would be appropriate to provide a better understanding of climate variability on the disease incidence, since the global burden falls principally on low- and middle-income countries, accounting for 0.5%–10% prevalence rates compared with 0.1%–2% prevalence rates in high-income countries (Jagai et al., 2012). Besides, the tremendous burden of cryptosporidiosis occurs among children (Shirley et al., 2012) and 20% of all childhood diarrhoea cases are *Cryptosporidium* spp. (Hofstra et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) predicts that although there will be a difference in the extent and direction of the effects, average global temperatures will increase between 1.8°C and 4°C.

Furthermore, extreme weather events, as well as shifting patterns of the disease, will have significant effects on global disease burden, water and food security, and social conflict over the next century (Solomon et al., 2007). Temperature, rainfall and humidity are especially important. However, others such as run-off, wind speed, diurnal temperature range and El Niño/Southern Oscillation (ENSO) can be significant in the disease transmission process. In general, temperature and rainfall are strong modifiers of cryptosporidiosis transmission, as they play a crucial role in the survival and distribution of the oocysts in the environment. Complicating any assessment of cryptosporidiosis incidence in many countries is the lack of record and systematic surveillance. Research on this zoonosis (transmissible from animals to humans) has been neglected in many low- and middle-income countries and high-income countries. In the case of the impacts of climate change and climate variability, this situation is even more critical.

Only a few data are currently available to understand and support such associations. Therefore, more research on the relationship between epidemiological variables, from humans and animals, as well as ecological, environmental and climatic factors, is needed and justified for cryptosporidiosis. From an environmental point of view, it is essential to understand that other species of *Cryptosporidium*, hosted by different animal reservoirs can also cause cryptosporidiosis in humans, for example immunocompromised individuals and children under five years (Abubakar et al., 2007). The risk factors and routes of transmission for infection are not well defined in low- and middle-income countries. The complex biological, social and environmental transmission pathways, associated with a host of human activities, often accelerate and amplify the natural phenomena that modify waterborne disease patterns like cryptosporidiosis in humans. This process poses unprecedented challenges to global public health. It requires further investigation to determine potential risk factors of cryptosporidiosis to prevent this disease transmission and formulate sound public health policy decisions to evaluate adaptation and mitigation measures. These measures may include enhanced public awareness through public health education and prevention strategies, planning of risk reduction and communication, and promoted integrated disease surveillance, vaccination programmes, information sharing, investment into protective technologies, weather forecasting and early warning systems, emergency management and disaster preparedness. Awareness and evaluation of the associated factors can aid our understanding of how broader socio-environmental interactions may mediate cryptosporidiosis spread and account for disparities in the disease risk. In turn, this can also contribute to the development of practical, evidence-based climate-responsive management strategies under different weather conditions at the local or regional level.

Climate change and variability is a multi-factorial issue. It is vital to note that understanding and managing the impact of climate on disease incidence is a global challenge. A positive association between the prevalence of cryptosporidiosis and rainfall was reported in a global meta-analysis study (Jagai et al., 2009). In a recent Canadian study, extreme precipitation led to a significant increase in cryptosporidiosis after prolonged dry periods (Chhetri et al., 2017). Dry periods could lead to the build-up of oocysts on land, and in combination with more extreme precipitation after these dry periods, higher levels than usual of the oocysts could be transported with run-off to source waters (King & Monis, 2007; Lake et al., 2005). The impact of global climate change and variability on cryptosporidiosis is likely to affect global, regional and local heath. Therefore, further investigation of the influence of weather and climate is necessary.

Moreover, because of the substantial burden of disease along with growing concerns about climate change in low- and middle-income countries, it is of utmost relevance to incorporate climate variability studies into public health control and prevention interventions. Such a practice can provide important information about the disease trend and associated risk factors. Therefore, formulating public health policies to plan and implement preventive measures effectively is crucial (Eisenberg et al., 2002; Robertson et al., 2013).

3 | METHODS

3.1 | Search strategy

A structured electronic search of peer-reviewed epidemiologic publications from 1998 to 2018 was conducted using a variety of databases and indices. The main keywords selected for the review were waterborne diseases, water-related diseases, *Cryptosporidium*, cryptosporidiosis and their determinants. Databases included ISI Web of Knowledge, Medscape, PubMed, Nature.com, ScienceDirect, Co-Action, Google Scholar, Interdisciplinary Perspectives on

TABLE 1 Published research findings on the relationship between weather and climatic variables and cryptosporidiosis

Ref.	Study period	Location	Population	Analytical method	Association found
Curriero et al. (2001)	1948–1994 (47 years)	United States	NA	Monte Carlo version of the Fisher exact test	A positive association between extreme precipitation and outbreaks of cryptosporidiosis.
Naumova et al. (2005)	1990–2000 (10 years)	North West England	8,094 cases	Generalized linear model (GLM) with Poisson distribution	A positive association between precipitation and weekly cryptosporidiosis incidence. Higher weekly rate of cryptosporidiosis when total precipitation during the previous week was above a certain threshold.
Lake et al. (2005)	1986–1996 (10 years)	England and Wales	52,001 cases	Ordinary least-squares (OLS) regression analysis	During the period April–July: no association with neither temperature nor precipitation, but a positive association between maximum river flow and cryptosporidiosis incidence. During the period August–November: a positive association between both mean temperature and maximum river flow and cryptosporidiosis incidence, but a negative association with precipitation at a 1-month lag.
Thomas et al. (2006)	1975–2001 (27 years)	Canada	NA	Time-stratified matched case-crossover analysis Conditional logistic regression analysis	A positive association between both maximum temperature and rainfall and the risk of cryptosporidiosis outbreak. Also, increased risk of cryptosporidiosis outbreak after heavy rainfall
Naumova et al. (2007)	1992–2001 (10 years)	Massachusetts, United States	45,816 cases	Generalized linear model (GLM) with Gaussian distribution	A positive association between temperature and cryptosporidiosis cases.
Hu et al. (2007)	1996–2004 (9 years)	Brisbane, Australia	NA	Poisson regression Seasonal auto-regression integrated moving average (SARIMA)	A positive association between maximum temperature and cryptosporidiosis incidence at lags up to 3 months and relative humidity at a 1-month lag.
Lake et al. (2008)	1997–2005 (8 years)	New Zealand	NA	Ordinary least-squares (OLS) regression analysis	A positive association between mean temperature and cryptosporidiosis rates one month later in the summer and autumn
Nichols et al. (2009)	1910–1999 (90 years)	England and Wales	NA	Time-stratified matched case-crossover analysis Conditional logistic regression analysis	For 10% of cryptosporidiosis outbreaks, positive association with heavy rainfall and for 20% of outbreaks positive association with low rainfall.
Hu, Mengersen, and Tong (2010)	1996–2004 (8 years)	Brisbane, Australia	NA	Zero-inflate Poisson (ZIP) Classification and regression tree (CART) models	A positive association between maximum temperature at a lag of up to 8 weeks, relative humidity at a lag of up to 1 week, wind speed at a 4-week lag and cryptosporidiosis cases, respectively. A negative association between rainfall and cryptosporidiosis cases at a lag of up to 1 week.
Hu, Mengersen, Fu, et al. (2010)	2001 (1 year)	Queensland, Australia	NA	Three-stage spatiotemporal classification and regression tree (CART) models	A positive association between maximum temperature and cryptosporidiosis incidence
Britton et al. (2010)	1997–2006 (10 years)	New Zealand	NA	Negative binomial regression	A positive association between rainfall and cryptosporidiosis rates, but a negative association with mean temperature.

(Continues)

TABLE 1 (Continued)

Ref.	Study period	Location	Population	Analytical method	Association found
Lal, Baker, et al. (2013)	1997–2008 (11 years)	New Zealand	8,092 cases	Multivariate seasonal auto-regressive integrated moving average (SARIMA)	A positive association between mean temperature and cryptosporidiosis incidence at a 1-month lag. El Niño-related cooler and drier conditions were negatively associated with cryptosporidiosis incidence at a 2-month lag.
Eze et al. (2014)	1998–2008 (10 years)	AA and GC, Scotland	NA	Generalized additive models (GAM)	A positive association between temperature and cryptosporidiosis cases. A positive association between relative humidity and cryptosporidiosis cases.
Kent et al. (2015)	2001–2009 (8 years)	Victoria, Australia	NA	Negative binomial regression	A positive association between minimum temperature and cryptosporidiosis incidence during the same month, but a negative association with minimum temperature at a 3-month lag.

Infectious Diseases and PLoS, Cochrane and TRIP. The search also involved published reports provided by IPCC, Centre for Disease Control (CDC), European Centre for Disease Control (ECDC) and World Health Organization (WHO). An additional search was also conducted on the following climate terminologies: weather, climate, climate change, climate variability, temperature, relative humidity, wind speed, rain, precipitation, run-off and extreme weather events. The search was also conducted for other keywords such as waterborne and foodborne diseases, infectious diseases, global disease burden, pathogens, protozoan infection, zoonosis, epidemiology, spatial epidemiology, projection/forecast, public health, environmental and social factors, human behaviour, zoonotic, zoonosis, prevalence, incidence, control, ecology, prevention, and surveillance, low-and middle-income and high-income countries.

The disease keywords were combined the other searched words grouped by the Boolean operators AND and OR. The following search strings were used: waterborne diseases OR water-related diseases OR infectious diseases OR *Cryptosporidium* OR cryptosporidiosis AND (climate change* OR climate variability OR weather OR climate OR projection/forecast OR control OR prevention OR surveillance). These strings were limited to peer-reviewed publications written in English. Firstly, the suitability of the titles and abstracts of articles identified in the search process was performed. Secondly, the studies listed in the references of the articles were reviewed. The full texts of articles that met the selection criteria were extracted for a detailed text review after evaluating the titles and abstracts. In addition to selecting specific articles, a reference list of the identified studies was searched for further evidence and citations to ensure that all relevant articles were included (Figure 1).

3.2 | Selection criteria

Articles were included in the review if they met the following selection criteria: peer-reviewed study or journal articles; and reviews or books on relevant topics, such as infectious diseases and waterborne zoonotic diseases. Studies had to be relevant to the ecology and life cycle, the transmission pathway, epidemiology, environmental and social factors, climate parameters and statistical analysis methods. The search strings also included articles on the disease control and prevention, surveillance strategies and management. Finally, articles had to be either empirical, qualitative or quantitative and were considered eligible if:

1. they were observational studies, including cohort, case–control and cross-sectional studies;
2. they examined the risk of *Cryptosporidium*/cryptosporidiosis specifically;
3. assessed the role of weather/climate on cryptosporidiosis incidence;
4. type of data (monitoring and surveillance data);
5. conducted appropriate statistical analysis (time-series regression analysis); and

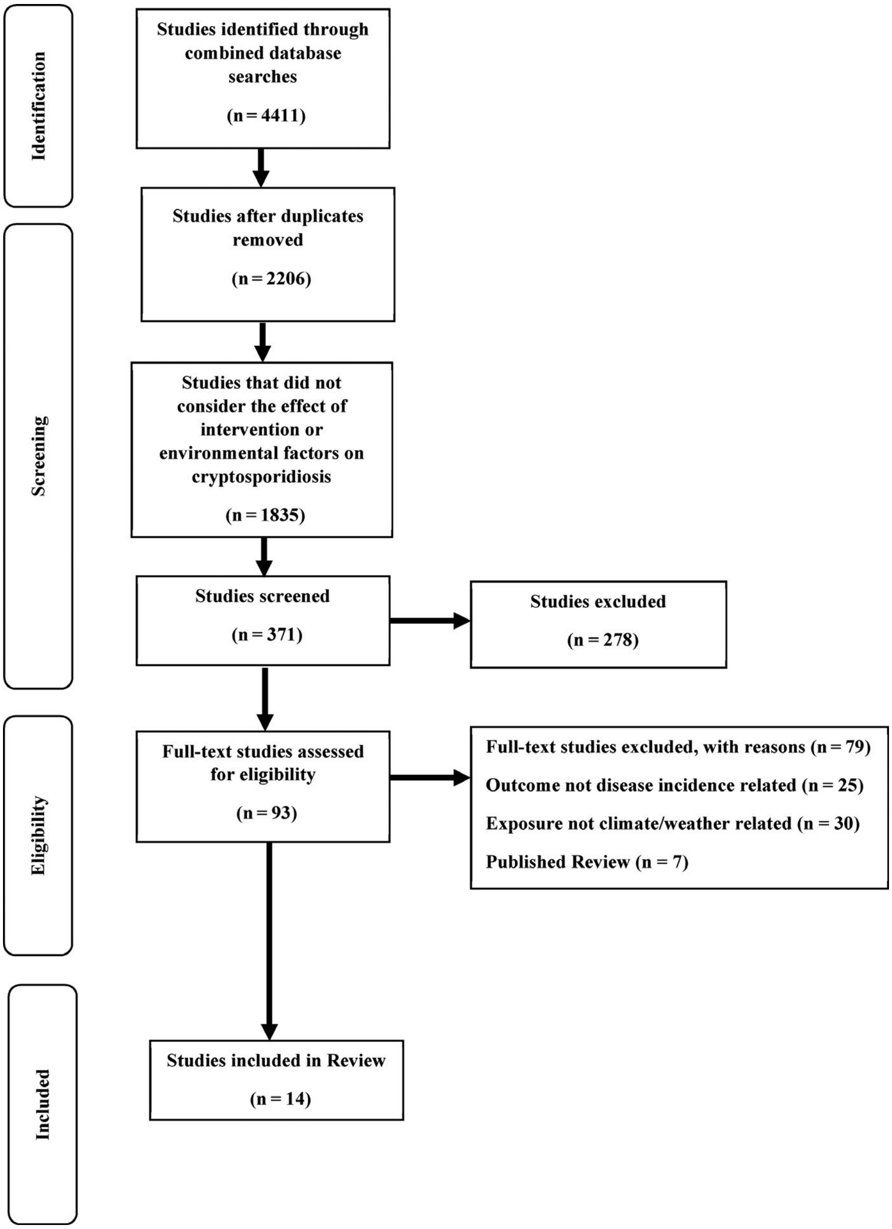

FIGURE 1 The process of investigation and selection of the studies used for the review

6. calculated the precision of statistical estimates, that is odds ratio (OR) and confidence interval (95% CI)/standard error (*SE*)/ probability values (*p* values).

4 | RESULTS

4.1 | Study characteristics

From the search, 371 potentially relevant articles were identified for the systematic review after duplicate citations and studies that did not consider the effect of environmental factors were removed (Figure 1). After the abstract review, 278 articles were selected. Additional 186 articles were further removed because they either did not consider the effect of weather and climates on cryptosporidiosis or they did not consider these determinants in the study. Fourteen studies out of 371 that met inclusion criteria were identified for this review. All the research was conducted in high-income countries. The dynamics of the disease and its seasonal cycle appear to differ across the studies and may be responsible for the observed association with the climatic variables. Six of the articles provided effect estimates at the national level (Curriero et al., 2001; Lake et al., 2005, 2008; Lal, Ikeda, et al., 2013; Nichols et al., 2009; Thomas et al., 2006). Five studies were at the state level (Hu, Mengersen, Fu, et al., 2010; Hu, Mengersen, & Tong, 2010; Hu et al., 2007; Kent et al., 2015; Naumova et al., 2007), one at regional level (Naumova et al., 2005), one at both national and district levels (Britton et al., 2010) and one at health board level (Eze et al., 2014). All articles were published between 2001 and 2015.

4.2 | Association between weather and climate and cryptosporidiosis

The results from the statistical models in the literature provide empirical evidence that climatic variables such as temperature (e.g. mean, maximum and minimum temperatures) and precipitation (e.g. rainfall) are significantly associated with an increased odds of cryptosporidiosis incidence. Table 1 shows a summary of the results of the reviewed studies. Although there is controversy in the association in the literature, there is evidence that cryptosporidiosis transmission is to some extent driven by climate variability. Long-term data sets and several statistical models were adopted to quantify the association between climatic variables and cryptosporidiosis at different levels. The results from the statistical models also confirm visible seasonal patterns in the association between the identified climatic variables and cryptosporidiosis.

A statistically significant relationship was found between monthly mean temperature and the incidence rates of cryptosporidiosis in England and Wales (Lake et al., 2005). In New Zealand, monthly mean temperature was associated with cryptosporidiosis (Lake et al., 2008); similarly, Lal, Ikeda, et al. (2013) reported an association at a time lag of 1–2 months. In contrast, Britton et al. (2010) did not find an association between temperature and cryptosporidiosis in New Zealand. There is also evidence in the pattern of association between maximum temperature and the incidence of cryptosporidiosis. A statistically significant relationship between daily maximum temperature and cryptosporidiosis cases has been shown in Massachusetts, United States (Naumova et al., 2007). Cryptosporidiosis increased about six weeks after ambient temperature reached its annual maximum. Researchers in Australia have also reported similar findings in different studies. Hu, Mengersen, Fu, et al. (2010) found a statistically significant relationship between maximum temperature and the incidence of cryptosporidiosis at a lag of up to eight weeks. Hu et al. (2007) found a significant association between maximum temperature and the incidence of cryptosporidiosis at a lag of up to 3 months in Brisbane. Their result suggests that weather variability (particularly maximum temperature) plays a significant role in the transmission of cryptosporidiosis. It can be either directly or through other unmeasured variables. In another study, Hu, Mengersen, and Tong (2010) also found a significant relationship between monthly maximum temperature and the incidence of cryptosporidiosis in Queensland. A similar association was found with the number of cryptosporidiosis outbreaks in Canada (Thomas et al., 2006). The result revealed that for each degree-day unit increase in total maximum temperature, the relative odds of an outbreak increased by a factor of 1.007 (95% confidence interval [CI] = 1.002–1.012).

Furthermore, in the State of Victoria in Australia, Kent et al. (2015) found that monthly minimum temperature was related to notifications of cryptosporidiosis. In the metropolitan area, a 1°C increase in monthly average minimum temperature of the current month was associated with a 22% increase in cryptosporidiosis notifications (incident rate ratio (IRR) 1.22; 95% confidence interval (CI) 1.13–1.31). In the rural area, a 1°C increase in monthly average minimum temperature, lagged by three months, was associated with a 9% decrease in cryptosporidiosis notifications (IRR 0.91; 95% CI 0.86–0.97). In Scotland, average levels of non-viral gastrointestinal infections, including cryptosporidiosis, increased as temperature and relative humidity increased. In the same study, at the ecological level, increasing levels of faecal indicator organisms in bathing waters were also associated with an increase in the average number of non-viral gastrointestinal infections (Eze et al., 2014). In Australia, two studies analysed the association between relative humidity and wind speed and cryptosporidiosis. The result revealed that these variables were statistically associated with an increased risk of cryptosporidiosis (Hu, Mengersen, & Tong, 2010; Hu et al., 2007).

Changes in precipitation were also related to a higher incidence of cryptosporidiosis. A statistically significant relationship between rainfall and cryptosporidiosis rates was found in the North West region of England (Naumova et al., 2005). The study revealed that there would be a 27% (95% CI 21%–33%) increase in the overall weekly rate of cryptosporidiosis in the region if the cumulative rainfall for the prior week was at its 75th percentile or 22 mm. The findings suggest that different environmental processes may underlie the temporal and spatial variations in microbial contamination of drinking water supply. The large spring peak observed may be related to lambing and calving that occurs in the late spring near the region's water supplies.

In contrast, the autumn peak is thought to be primarily due to infections in people returning from foreign travels. Similarly, there was a positive association between rainfall and cryptosporidiosis in New Zealand, and the effect of rainfall was modified by the quality of the domestic water supply (Britton et al., 2010). In contrast, Lake et al. (2005) did not find a positive relationship between rainfall and the incidence rates of cryptosporidiosis; however, a statistically significant positive relationship was found with river flow in England and Wales. Similarly, Hu et al., (2007) and Kent et al. (2015) did not find any association between rainfall and cryptosporidiosis in Australia, respectively. Heavy rainfall has also been associated with outbreaks of cryptosporidiosis in Canada (Thomas et al., 2006), England and Wales (Nichols et al., 2009) and the United States (Curriero et al., 2001), respectively. Curriero et al. (2001) revealed that heavy rainfall associated with surface water contamination increased cryptosporidiosis outbreak at a lag of 2 months in the United States. In England and Wales, Nichols et al. (2009) showed that heavy rainfall increased cryptosporidiosis cases (up by 40%) during the week preceding the outbreak and up to four weeks preceding the outbreaks, even when the rain had stopped. In Canada, for rainfall events higher than the 93rd percentile there was a greater than twofold increase in the odds of an outbreak compared with rainfall events less than the 93rd percentile (Thomas et al., 2006). The literature also highlighted the significance of relative humidity and wind speed in the incidence of cryptosporidiosis. While there was a statistically significant relationship between relative humidity and the incidence of cryptosporidiosis at a lag of up to one week (Hu, Mengersen, Fu, et al., 2010) and a lag of one month (Hu et al., 2007), a statistically significant relationship with wind speed at a lag of four weeks was found in Brisbane, Australia (Hu, Mengersen, Fu, et al., 2010).

5 | DISCUSSION

Previous studies have shown that weather and climate exert a critical influence on the spatial and temporal range of cryptosporidiosis and several notable points were concluded from the literature. Most importantly, the results suggest that climate variability (temperature and rainfall) may have played a significant role in the transmission of *Cryptosporidium* spp. Also, the transmission could be either through a direct effect or other unmeasured variables. Although the findings across countries showed mixed outcomes for temperature and rainfall, that is the association was either positive or negative, in general, these variables were more often associated with increased risk of cryptosporidiosis. It is important to note that several factors could have influenced the study findings, and inter-country comparison is related to many issues including bias, laboratory ascertainment and depth of environmental investigation. Furthermore, several factors could have influenced the study findings. The transmission of *Cryptosporidium spp*. is a complex process with multiple hosts and routes and varies widely within and across countries. Evidence for this is that the micro-epidemiological variation of *Cryptosporidium* oocysts is related to fine-scale heterogeneity in biological, environmental, genetic, social and other contextual factors (Al Mawly et al., 2015; Shrivastava et al., 2017). However, the literature does not imply a single main transmission route that would explain the observed association. Variability in the association between the climatic factors and cryptosporidiosis may also be explained, in part, by differences in pathogen distribution and regional climate pattern. Therefore, different interaction processes may underlie the temporal and spatial variations in *Cryptosporidium* transmission. Also, the seasonal effect of temperature and rainfall may explain some differences in the variation of cryptosporidiosis incidence within studies and between countries.

The peaks in the incidence of cryptosporidiosis fluctuate with the seasons and are usually associated with warm and moist weather. It is suggested that in England, the spring peaks in cryptosporidiosis incidence may be related to contaminated water supplies as a result of heavy rainfall events (Naumova et al., 2005). Moreover, increased seasonal oocysts load following livestock shedding coupled with heavy rainfall could result in seasonally high cryptosporidiosis rates (Lake et al., 2005). Besides, high rainfall may facilitate oocyst run-off, contaminating surface and drinking water sources (Gertler et al., 2015; Lal et al., 2012). Although increased run-off is an inevitable consequence of increased rainfall, increased run-off may also follow extended dry periods which may lead to a higher oocysts load, resulting in increased disease (Lal, 2016). During the cool and warm conditions of spring, when the oocysts remain viable people become more frequently engaged in several outdoor activities. The spring peak observed in England and Wales, New Zealand, Scotland and the United States could be related to seasonal agricultural activities such as calving, lambing and farm visits (especially during Easter holidays) (Eze et al., 2014; Lake et al., 2005, 2008; McGuigan et al., 2010; Naumova et al., 2005; Nichols et al., 2009; Thomas et al., 2006). Besides, seasonal patterns of high oocysts shedding into the environment generally increases during spring months, and this can lead to a significant increase in human infections (Strachan et al., 2003; Lake et al., 2007; Pollock et al., 2010; Lal, Ikeda, et al., 2013).

Although rainfall plays a role in cryptosporidiosis incidence, temperature affects transmission in several ways. The studies emphasized that as a result of changing climate, temperature is likely to increase cryptosporidiosis incidence (Eze et al., 2014; Hu, Mengersen, Fu, et al., 2010; Hu, Mengersen, & Tong, 2010; Hu et al., 2007; Kent et al., 2015; Lake et al., 2005, 2008; Lal, Ikeda, et al., 2013; Naumova et al., 2007; Thomas et al., 2006). A possible underlying mechanism for the positive association between temperature and cryptosporidiosis is that temperature may have increased the viability of the oocysts and increased the rate of the disease transmission in different regions (King & Monis, 2007). For example, milder winter temperatures may favour some transmission routes, as well as enhance the survival and viability of *Cryptosporidium* oocysts in the environment, change human activities and increase the rate of the disease transmission in different regions. The study by King and Monis (2007) indicated that *Cryptosporidium* oocysts could maintain high levels of infectivity for periods of at least 24 weeks at temperatures between 1 and 15°C. In water, the persistence of oocysts was not affected by temperatures 40°C. Warmer temperatures may also have increased the survival of oocysts in soil subsurface freezing, or lake ice covers prone areas. In turn, this results in significant numbers of oocysts remaining infective after the winter period (King & Monis, 2007).

Moreover, warm temperatures often bring about changes in human activities such as greater use of swimming pools and beaches, increased outdoor activities, demand for water and less conscientious hygienic practice which influence *Cryptosporidium* transmission rates (Hu, Mengersen, & Tong, 2010; Onozuka et al., 2010). Also, *C. parvum* thrives in warm waters of moderate salinity and has a close association with aquatic invertebrates (Hu et al., 2007). Therefore, based on results in the literature and the findings in this study, it can be suggested that temperature and rainfall are significant in the incidence of cryptosporidiosis. However, the association may vary among and within different regions.

Given the variability of these factors across countries and the different characteristics of the data sources used in the analysed studies, it is challenging to synthesize further the results, and the range of statistical techniques and methods employed does not allow us to draw definitive conclusions. However, the findings confirm that there is a direct and indirect relationship between climatic variables and cryptosporidiosis transmission. Therefore, to draw definitive conclusions, we must rely on the precision of the estimates. Doing this allows epidemiologists and public health practitioners to offer useful recommendations for policymakers to plan and coordinate strategic public health prevention actions adequately. Therefore, a key suggestion from the literature review is the adoption of cross-disciplinary research explicitly designed to address the strategic analysis of climate-infection hypotheses. There is a substantial body of evidence that regular short-term climate variability will continue to cause problems for water and water-related health effects (Phung et al., 2015). Thus, our changing climate based on warmer temperatures and increasingly variable rainfall patterns can increase oocysts abundance and distribution in the environment, based on the assumption that climate acts as an essential factor in determining the levels of other risk factors to influence the likelihood of oocysts ending up in the environment and increasing cryptosporidiosis infection, for example animal husbandry involving cattle and possibly goats and sheep, wildlife, improper disposal of manure, sewage sludge or wastewater, leaking septic tanks, cesspools, sewers or landfills, failure of water treatment systems, inadequate attention to sanitation in wells, poor maintenance and treatment practices (Collinet-Adler & Ward, 2010; Daniels et al., 2016; Hrudey, 2004; Miller et al., 2008; Pedley & Howard, 1997; Rizak & Hrudey, 2008; Robertson, 2009; Rose, 1997; Schuster et al., 2005; Young et al., 2015; Zahedi et al., 2016).

Additionally, periods of heavy rainfall can result in re-mobilization and redistribution of oocyst in sewage/wastewater into the environment. Consequently, it remains a significant independent risk factor that should be examined with the incidence of cryptosporidiosis. Assuming that the predicted climate change occurs, it is suggested that rising temperatures might boost the number of cryptosporidiosis cases. Based on the fact that higher summer temperatures may allow the growth of *Cryptosporidium* oocysts, more extreme precipitation events might increase oocyst survival through the saturation of soil profiles and mobilization of the oocysts more often (King & Monis, 2007), thus, significantly increasing the risk of contamination in drinking water and the transmission of *Cryptosporidium*. Although the underlying mechanism remains unclear, it is imperative to note that several other factors such as socio-economic factors and changes in land use are equally significant. These factors add to the difficulty in identifying the nature of the association of climate and predicting exactly how much the change in climate might impact the disease incidence.

Moreover, the impact of climate variability at temporal and spatial scales is predicted to be worse in low- and middle-income countries where challenging socio-economic and political contexts exacerbates lack of epidemiological studies on the disease incidence (Hlahla & Hill, 2018; Olsson et al., 2014). Because of the anticipated increase in the cryptosporidiosis incidence as a result of climate variability, further research to characterize how the impact of changing temperature and rainfall pattern on the disease is necessary. This approach could improve our ability to identify high-risk populations and public health decision-making. The use of mechanistic models that combines epidemiological, experimental and environmental data can also be used to evaluate the climate-attributable risk of cryptosporidiosis and can provide information valuable for the decision-making process (Eisenberg et al., 2002). Besides, examining the determinants of cryptosporidiosis should include interventions, environmental factors and socio-demographics. Evidence of these would allow a better understanding of the epidemiology of cryptosporidiosis and identification of significant predictors to consider for the disease forecasting. Several environmental and population settings should also be examined to improve the understanding of contextual contributions to cryptosporidiosis risk. Environmental variables that are the most related or the most consistently related to cryptosporidiosis risk should be systematically used in future studies assessing the effects of weather and climate. Doing this will allow for the pooling of data across studies and provide a better understanding of the disease transmission process. Further studies should also include clear categorization and description of variables, considerations of timescale, units of measurement and lagged effects. Moreover, the One Health Initiative that emphasizes the interdependency between human, animal and environmental health and the significance of interdisciplinary effort could provide a pragmatic coordinated and collaborative approach to attaining optimal prevention and risk management opportunity to be implemented across countries (Kahn, 2011; Karesh et al., 2012; Rabinowitz et al., 2013).

The limitation of this review is acknowledged. There is evidence of reporting and publication bias. These studies have used secondary data which may have resulted in under-reporting of cryptosporidiosis cases. However, the use of long-term data sets and study designs bolsters confidence in the significant findings revealed in these studies. Moreover, the inclusion of multiple terminologies in the database searches and detailed inclusion/exclusion criteria used in this study aimed to mitigate against publication bias. This review offers a step towards understanding the influence of climate variability on cryptosporidiosis. Several environmental factors and host factors (animal and human) all influence *Cryptosporidium* populations, as well as the degree of contact between human beings and this pathogen. An epidemiological investigation using retrospective data offers insights into the pathways of disease transmission. This concept provides an understanding of the impact of climate on the disease incidence, which is significant for decision-making and resource allocation for disease control and prevention.

6 | CONCLUSION AND RECOMMENDATIONS

Although there is significant debate on the link between weather and climate and cryptosporidiosis occurrence, this review summarizes the evidence of the association. The findings in these studies demonstrate the significant role of weather and climate in the transmission of cryptosporidiosis. There seems to be an increasing incidence of cryptosporidiosis, and it is plausible that the changing pattern of climate will lead to a significant increase in the number of cases. While an increase has been reported in Ireland (HSE, 2018), a decrease has been reported in Scotland (HPS, 2018) showing the difficulty of confirming an association between countries. It is therefore essential to note that the relative contribution of each climatic parameter appears to vary between the regions and countries and is determinant on the prevailing ecological determinants of *Cryptosporidium* transmission. As an emerging global zoonosis that is still neglected and poorly understood further investigation in the context of a changing environment is needed, particularly in high-risk countries. This review has highlighted the need for further epidemiologic research and long-term surveillance in both low- and middle-income countries and high-income countries.

Moreover, the evidence of association in one country is not sufficient to evaluate the influence of variation in weather and climate on cryptosporidiosis incidence in other countries. As climate change threatens to increase global temperature and intensify the frequency of rain and extreme weather events, there might be a significant increase in the disease incidence and in the frequency and duration of outbreaks. Therefore, predicting what may happen in the future can help countries make sure they are prepared and target public health interventions effectively.

Although it may be challenging to determine what approach works well in terms of cryptosporidiosis prevention, the researchers make the following recommendations on managing the potential impact of weather and climate on the disease transmission:

- Strengthen epidemiological surveillance through regular recording historical information on disease incidence and related factors.
- Develop improved models that incorporate the several drivers associated with the disease incidence (such as climate and land use) to assess the risks posed by climatic and ecological changes.
- The need for further research on the link between climate and cryptosporidiosis at different temporal and spatial scales to improve understanding of the effect of climate change and develop effective public health interventions to deal with changing disease pattern.
- Collaboration with environmental organizations to develop management plans to prepare effectively during outbreak resulting from an extreme event (such as flooding and drought).

ACKNOWLEDGEMENTS

The authors acknowledge the contribution of the reviewers whose constructive criticism was of guidance in revision of this review.

CONFLICT OF INTEREST

There are no conflicts of interest.

AUTHORS' CONTRIBUTION

Both authors contributed equally to this review and approved the version to be published.

ETHICAL STATEMENT

This review does not contain any studies involving human participants performed by any of the authors.

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How to cite this article: Ikiroma IA, Pollock KG. Influence of weather and climate on cryptosporidiosis—A review. *Zoonoses Public Health*. 2021;68:285–298. https://doi.org/10.1111/zph.12785