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Waterborne transmission of protozoan parasites: a review of worldwide outbreaks – an update 2017–2022

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ABSTRACT

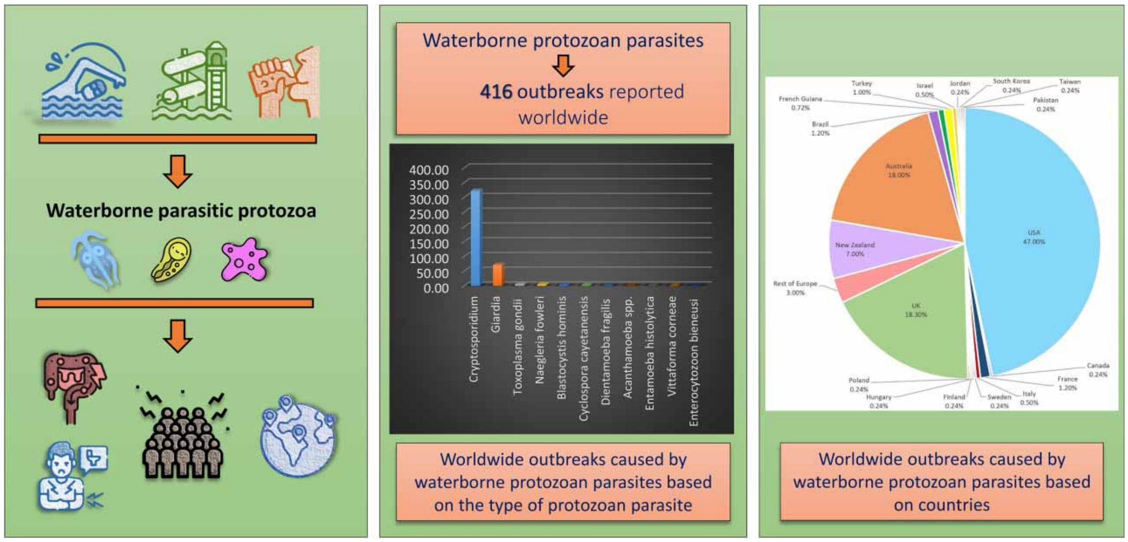
The current study presents a comprehensive review of worldwide waterborne parasitic protozoan outbreaks reported between 2017 and 2022. In total, 416 outbreaks were attributed to the waterborne transmission of parasitic protozoa. *Cryptosporidium* accounted for 77.4% (322) of outbreaks, while *Giardia* was identified as the etiological agent in 17.1% (71). *Toxoplasma gondii* and *Naegleria fowleri* were the primary causes in 1.4% (6) and 1% (4) of outbreaks, respectively. *Blastocystis hominis*, *Cyclospora cayetanensis*, and *Dientamoeba fragilis* were independently identified in 0.72% (3) of outbreaks. Moreover, *Acanthamoeba spp.*, *Entamoeba histolytica*, *Vittaforma corneae*, and *Enterocytozoon bieneusi* were independently the causal agents in 0.24% (1) of the total outbreaks. The majority of the outbreaks (195, 47%) were reported in North America. The suspected sources for 313 (75.2%) waterborne parasitic outbreaks were recreational water and/or swimming pools, accounting for 92% of the total *Cryptosporidium* outbreaks. Furthermore, 25.3% of the outbreaks caused by *Giardia* were associated with recreational water and/or swimming pools. Developing countries are most likely to be impacted by such outbreaks due to the lack of reliable monitoring strategies and water treatment processes. There is still a need for international surveillance and reporting systems concerning both waterborne diseases and water contamination with parasitic protozoa.

Key words: *Cryptosporidium*, *Giardia*, outbreaks, protozoan parasites, water

HIGHLIGHTS

- 416 waterborne protozoan outbreaks were identified between 2017 and 2022, globally.
- *Cryptosporidium* was the most common etiological agent.
- The majority of the outbreaks were reported in North America.
- The number of reported waterborne outbreaks in developed countries were higher than developing countries.
- Recreational water and/or swimming pools were the suspected source of infection in most of the reports.

GRAPHICAL ABSTRACT



INTRODUCTION

Waterborne diseases occur via ingesting contaminated drinking water and bathing water as vehicles for exposure to infectious pathogens (Leclerc *et al.* 2002; Plutzer & Karanis 2016). According to the World Health Organization (WHO), waterborne infections of gastro-enteric origin are among the leading causes of morbidity and mortality worldwide (Angelici & Karanis 2019).

Diarrhoeal illnesses are one of the common causes of mortality in low-income countries. They are among the top five causes of death and pose significant risks to humans and animals (www.who.int). Protozoan parasites are causal agents for 1.7 billion diarrheal diseases and 842,000 deaths annually (Arslan *et al.* 2022). They are the second largest cause of mortality in children under five, with more than 525,000 deaths per year (www.who.int). Waterborne diseases caused by protozoan parasites are regarded as a public health concern in both developed and developing nations and are responsible for many outbreaks worldwide (Plutzer & Karanis 2016).

Cryptosporidium and *Giardia* are the most common pathogens in the reported outbreaks over the last decades in comparison to other parasitic protozoa such as *Entamoeba*, *Toxoplasma*, *Balantidium*, *Isospora*, *Blastocystis*, *Acanthamoeba*, *Microsporidia*, *Sarcocystis*, *Naegleria*, and *Cyclospora* (Karanis *et al.* 2007; Baldursson & Karanis 2011; Efstratiou *et al.* 2017). *Cryptosporidium* oocysts and *Giardia* cysts have been found to contaminate surface waters and groundwater resources around the world (Omarova *et al.* 2018). Also, parasitic protozoa in facilities, such as pools, hot tubs, water playgrounds, or other artificially constructed water structures used for recreational purposes can lead to a waterborne outbreak (Hlavsa 2021). Since most of these protozoa spread via feces, they can also infect humans through sewage, land, or rivers contaminated with animal or human feces (Lanata 2003).

Given the high number of human infectious diseases associated with water, determining the waterborne transmission of less frequent etiological agents is complicated, and the role of different water environments in the transmission of protozoan infections, especially those connected with zoonotic protozoa, is under-recognized (Plutzer & Karanis 2016).

Reliable prediction of waterborne diseases requires global health statistics and effective surveillance systems across all countries. Many countries have developed surveillance systems that report data on national outbreaks. The United States established the Centers for Disease Control and Prevention (CDC), the US Environmental Protection Agency (USEPA), and the USA Waterborne Disease and Outbreak Surveillance System (WBDOSS), which have been monitoring waterborne diseases since 1971. Moreover, the national epidemiological surveillance of infectious illnesses (NESID) in Japan, 'The National Notifiable Diseases Surveillance System (NNDSS)' in Australia, 'Public Health England (PHE)' in the United Kingdom, 'Public Health Agency of Canada (PHAC)' in Canada, and the 'European Center for Disease Control and Prevention

(ECDC)' as a European institution for public health (http://ecdc.europa.eu/). However, in developing countries, monitoring systems still need to indicate and report outbreaks of waterborne protozoan parasites.

Waterborne outbreaks highlight the ability of pathogens to penetrate various water barriers and their potential to infect humans and animals. Moreover, they indicate the incidence and severity of the disease caused by these pathogens and the difficulty of their control via water treatment procedures. Even though the outbreak data do not reveal the accurate incidence of waterborne diseases, the outbreak surveillance provides information regarding the significant waterborne pathogens, relative grades of hazard associated with water resources and water treatment procedures, and the appropriateness of relevant assessments. The outbreak reports are indicators of pathogens of public health importance and hygiene deficiencies in water systems that may also be the leading causes of endemic waterborne diseases. Therefore, the present review aims to update worldwide waterborne parasitic outbreaks reported during 2017–2022.

METHODS

Data from advanced search engines of scholarly databases, including PubMed and Scopus, and data from global surveillance systems, such as the CDC and the ECDC, were searched for literature and reports on waterborne parasitic protozoan outbreaks. Moreover, online sources including Euro Surveillance (published by ECDC), The Institute of Environmental Science and Research Ltd (ESR), Canada Communicable Disease Report (CCDR by PHAC), Health Protection Surveillance Centre (HPSC), Morbidity and Mortality Weekly Report (MMWR by CDC), and outbreak surveillance for gastrointestinal disease (eFOSS by PHE) were used to collect data for the current review.

Keywords used in this study were as follows: 'outbreak (and) *Cryptosporidium*', 'outbreak (and) cryptosporidiosis', 'outbreak (and) *Giardia*', 'outbreak (and) giardiasis', 'outbreak (and) *Cyclospora*', 'outbreak (and) *Blastocystis*', 'outbreak (and) *Entamoeba*', 'outbreak (and) *Acanthamoeba*', 'outbreak (and) Amoebiasis', 'outbreak (and) *Toxoplasma*', 'outbreak (and) toxoplasmosis', 'outbreak (and) microsporidia', 'outbreak (and) microsporidiosis', 'outbreak (and) *Sarcocystis*', 'outbreak (and) sarcocystosis', 'outbreak (and) *Naegleria*', 'outbreak (and) *Balantidium coli*', 'outbreak (and) balantidiosis', 'outbreak (and) *Dientamoeba fragilis*', and 'outbreak (and) *Isospora*'.

The titles and abstracts of the listed papers were critically evaluated and reviewed by two independent authors as part of the screening process. After the screening, duplicates and irrelevant papers were removed. The full texts of the remaining papers were obtained and assessed. Selected articles were checked for relevant references that needed to be identified through the database search. The following criteria were used to determine eligibility:

1. Articles published from January 2017 to December 2022
2. Availability of full-text and abstract in English.
3. All published studies reported waterborne parasitic protozoan outbreaks.
4. Availability of data regarding the source of the waterborne infection and the type of protozoan parasite that caused the outbreak.

Studies were excluded if they did not meet the above criteria. Disagreements were resolved through discussion. Figure 1 shows the study selection process using the PRISMA flow diagram.

RESULTS

The current study identified 1,426 articles. After excluding duplicates, screening titles and abstracts, and completing text evaluation, 45 articles from scholarly databases and 153 reports from online surveillance systems were included in the study (Figure 1).

In the 5 years between 2017 and 2022, 416 waterborne outbreaks of parasitic protozoan diseases were reported worldwide. Tables 1–3 present a summary of the documented outbreaks and also represent a few waterborne outbreaks prior to 2017 that were not included in the 2007, 2011, and 2017 reviews (Karanis *et al.* 2007; Baldursson & Karanis 2011; Efstratiou *et al.* 2017) since these outbreaks have been reported and published later.

Regarding the type of protozoan parasite, *Cryptosporidium* spp. was the etiological agent in most reported outbreaks (77.4% or 322). There were two *Cryptosporidium* species identified, with *C. hominis* and *C. parvum* being etiological agents in 123 (30%) and 100 (24.03%) outbreaks, respectively (Table 1).

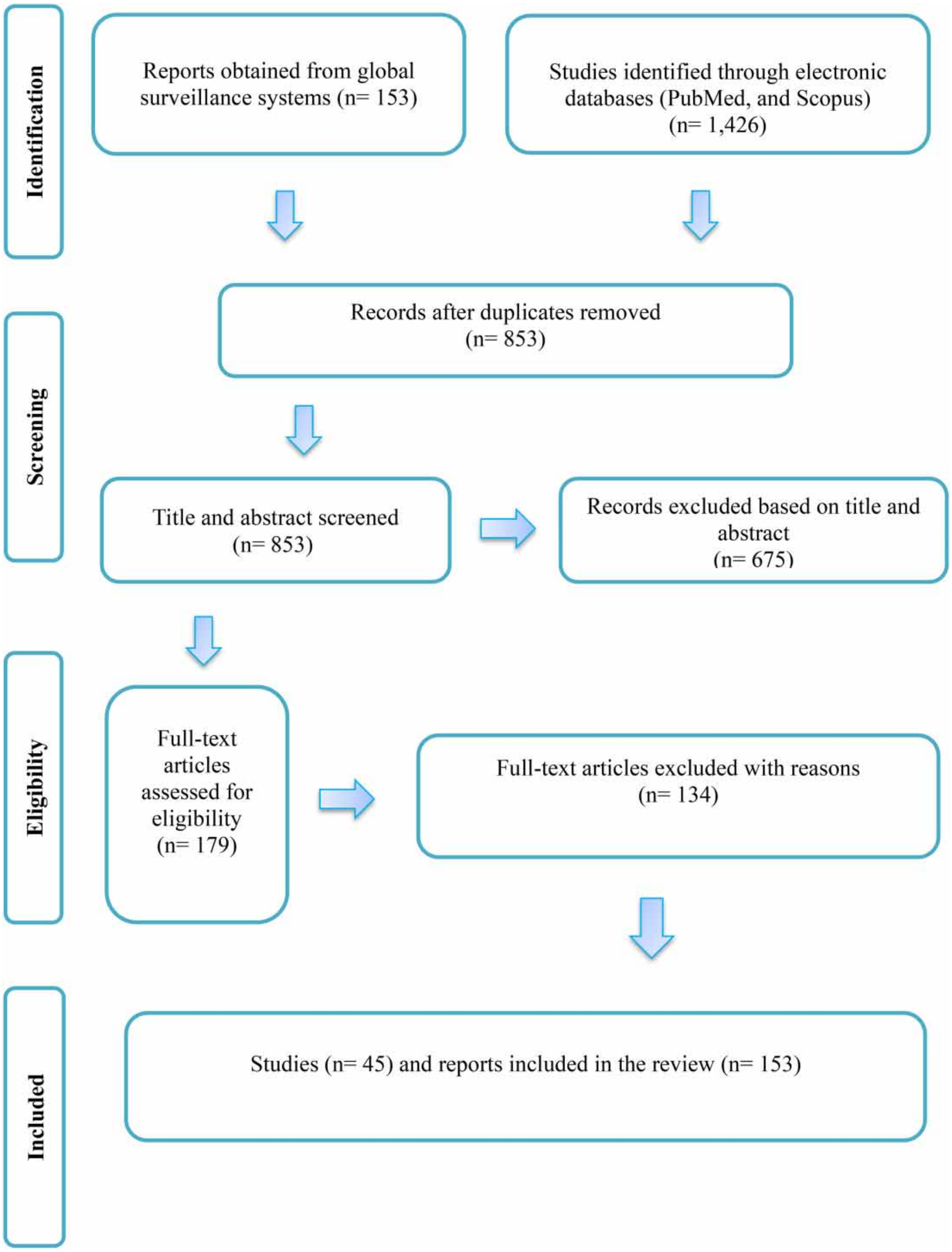


Figure 1 | Flow diagram of the study selection process.

Giardia spp. was detected in 71 outbreaks (17.1%), of which 27 (6.5%) were caused by *G. duodenalis* (Table 2).

Moreover, other protozoa were reported as the causative agents in 5.5% (23) of the outbreaks. In this regard, the type of the protozoan parasite, as well as the number and percentage of outbreaks were as follows: *T. gondii* (6 outbreaks, 1.4%), *N. fowleri* (4 outbreaks, 1%), *B. hominis* (3 outbreaks, 0.72%), *C. cayetanensis* (3 outbreaks, 0.72%), *D. fragilis* (3 outbreaks, 0.72%), *Acanthamoeba* spp. (1 outbreak, 0.24%), *E. histolytica* (1 outbreak, 0.24%), *V. corneae* (1 outbreak, 0.24%), and *E. bieneusi* (1 outbreak, 0.24%) (Table 3).

In terms of the continent, the reports revealed that the majority (47% or 195 outbreaks) of the reported worldwide waterborne outbreaks were reported in North America, following Oceania (103 outbreaks), and Europe (100 outbreaks). Furthermore, 10 outbreaks were documented in Asia, and 8 in South America (Tables 1–3).

Table 1 | List of worldwide waterborne outbreaks caused by *Cryptosporidium* spp.

Month/year	**Location/country**	**Etiological agent species/ genotypes**	**Suspected source**	**Est. cases/ (laboratory-confirmed)**	**[c]Outbreak**	**Key reference**
December 2002–June 2003[a]	Perth, Australia	*Cryptosporidium* spp.	Multiple possible exposures/swimming pools/recreational water activities/water catchments & natural water holes	(404)	1	Ng-Hublin *et al.* (2018)
November 2006–August 2007[a]	Perth, Australia	*C. hominis* IbA10G2, IdA15G1, IdA16, IdA17, IeA11G3T3, IfA12G1, IbA10G2 & *C. parvum* IaA18G3R1	Swimming pools/ recreational water activities/water catchments & natural water holes	(607)	1	Ng-Hublin *et al.* (2018)
Summer 2008[a]	Haifa, Israel	*Cryptosporidium* spp.	Treated recreational water/ Swimming pool	177 (153)	1	Flugelman *et al.* (2019)
August 2009[a]	Wales, UK	*C. hominis*	Swimming pool/oocysts have been found in filter sand	106 (46)	1	Chalmers *et al.* (2019), eFOSS
November 2009[a]	South-East UK	*C. hominis*	Swimming pool/oocysts in strainer basket and sand from two filters	15 (11)	1	Chalmers *et al.* (2019), eFOSS
January – March 2011[a]	Perth, Australia	*C. hominis* IdA15G1, IbA10G2 & *C. parvum* IIaA18G3R1, IIaA15G2R1	Swimming pool/ recreational water activities/water catchments and natural water holes	(355)	1	Ng-Hublin *et al.* (2018)
Spring 2012[a]	South East of Ireland	*C. parvum* IIaA20G3R1, *Cryptosporidium* spp.	Public water supply	(12)	1	Mahon & Doyle (2017)
February 2013[a]	Kentucky, USA	*C. parvum*	Undetermined water related	(8)	1	https://wwwn.cdc.gov/norsdashboard/
April 2013[a]	South West, UK	*C. hominis* IbA10G2 and IdA18	Drinking water/in source waters and in treated waters	(23)	1	Chalmers *et al.* (2019), eFOSS
June 2013[a]	South Carolina, USA	*Cryptosporidium* spp.	Recreational water-untreated/lake–reservoir–impoundment	5	1	https://wwwn.cdc.gov/norsdashboard/
June 2013[a]	Virginia, USA	*C. parvum*	Drinking water/farm-agricultural setting	19	1	Benedict (2017), MMWR, https://wwwn.cdc.gov/norsdashboard/
June 2013[a]	Iowa, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–kiddie/wading	10	1	https://wwwn.cdc.gov/norsdashboard/
June 2013[a]	Oregon, USA	*C. parvum* IIaA15G2R1	Drinking water/lake–reservoir–impoundment/ community–municipality	119	1	Benedict (2017), MMWR, https://wwwn.cdc.gov/norsdashboard/
June 2013[a]	Louisiana, USA	*Cryptosporidium* spp.	Recreational water-treated	141	1	https://wwwn.cdc.gov/norsdashboard/

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
June 2013[a]	Wyoming, USA	*Cryptosporidium* spp.	Environmental water/lake–reservoir–impoundment	121	1	https://wwwn.cdc.gov/norsdashboard/
June 2013[a]	Illinois, USA	*Cryptosporidium* spp.	Suspected recreational water-treated/pool–swimming pool	3	1	https://wwwn.cdc.gov/norsdashboard/
June 2013[a]	Iowa, USA	*Cryptosporidium* spp. – *C. parvum*	Recreational water-treated/ Pool–kiddie–swimming pool	13	**2**	https://wwwn.cdc.gov/norsdashboard/
July 2013[a]	Tennessee, USA	*C. parvum*	Drinking water/camp/ cabin setting/Spring water	34	1	Benedict (2017), MMWR, https://wwwn.cdc.gov/norsdashboard/
July 2013[a]	Louisiana, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–kiddie–wading	3	1	https://wwwn.cdc.gov/norsdashboard/
July 2013[a]	Georgia, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–waterpark	5	1	https://wwwn.cdc.gov/norsdashboard/
July 2013[a]	Indiana, USA	*Cryptosporidium* spp.	Drinking water/mobile home park in a community	7	1	Benedict (2017), MMWR, https://wwwn.cdc.gov/norsdashboard/
August 2013[a]	Pennsylvania, USA	*C. parvum*	Recreational water-treated/ fountains	2	1	https://wwwn.cdc.gov/norsdashboard/
August 2013[a]	Montana, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–waterpark–swimming pool	18	1	https://wwwn.cdc.gov/norsdashboard/
August 2013[a]	Minnesota, USA	*C. hominis,* IaA28R4	recreational water-treated/ pool–swimming pool	10	1	https://wwwn.cdc.gov/norsdashboard/
August 2013[a]	Wisconsin, USA	*Cryptosporidium* spp., *C. hominis,* IfA12G1	Recreational water – treated/pool–swimming pool–waterpark	37	1	https://wwwn.cdc.gov/norsdashboard/
September 2013[a]	Florida, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool	15	1	https://wwwn.cdc.gov/norsdashboard/
October 2013[a]	Wisconsin, USA	*Cryptosporidium* spp., *C. hominis,* IfA12G1	Recreational water-treated/ pool–waterpark	2	1	https://wwwn.cdc.gov/norsdashboard/
July 2013–October 2013	Ontario, Canada	*Cryptosporidium* spp.	Tap water	58 (2)	1	Leung *et al.* (2019)
January 2014–June 2015[a]	French Guiana	*Cryptosporidium* spp., *C. hominis* with IbA10G2, IbA15G1, IbA9G2	Waterborne – playing and bathing in a river/ drinking or animals	(14)	1	Mosnier *et al.* (2018)
March 2014[a]	South-East UK	*C. hominis* IbA10G2	Swimming pool	20 (14)	1	Chalmers *et al.* (2019), eFOSS

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
June 2014[a]	Florida, USA	*Cryptosporidium* spp., *C. hominis*	Recreational water-treated/ pool–swimming pool–waterpark–fountain	96	**4**	https://wwwn.cdc.gov/norsdashboard/
June–July–August 2014[a]	Louisiana, USA	*Cryptosporidium* spp.,	Recreational water-treated/ pool–kiddie	54	**3**	https://wwwn.cdc.gov/norsdashboard/
July 2014[a]	Montana, USA	*Cryptosporidium* spp.	Waterborne outbreak/ undetermined water	11	1	McClung *et al.* (2017), MMWR, https://wwwn.cdc.gov/norsdashboard/
July 2014[a]	North Dakota, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–waterpark	11	1	https://wwwn.cdc.gov/norsdashboard/
August 2014[a]	Wisconsin, USA	*C. hominis,* IdA17	Recreational water-treated/ pool–swimming pool	3	1	https://wwwn.cdc.gov/norsdashboard/
August 2014[a]	Georgia, USA	*C. hominis,* IfA12G1	Recreational water-treated/ pool-swimming pool/ fountain	81	**2**	https://wwwn.cdc.gov/norsdashboard/
August–September 2014[a]	Florida, USA	*Cryptosporidium* spp.	Recreational water-treated/ temporary water slide	31	**2**	https://wwwn.cdc.gov/norsdashboard/
September, 2014[a]	South-East UK	*C. hominis* IaA14R3	Recreational water-treated/ swimming pool/oocysts in filter sand and backwash	(15)	1	Chalmers *et al.* (2019), eFOSS
September, 2014[a]	Minnesota, USA	*C. hominis,* IdA17	Recreational water-treated/ pool–swimming pool	3	1	https://wwwn.cdc.gov/norsdashboard/
October 2014[a]	Ohio, USA	*Cryptosporidium* spp.	Suspected recreational water-untreated/drinking water/river–stream/farm – agricultural setting	100	1	Benedict (2017), MMWR, https://wwwn.cdc.gov/norsdashboard/
October 2014[a]	Wisconsin, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool	3	1	https://wwwn.cdc.gov/norsdashboard/
2014[a]	UK	*C. hominis* IaA14R3, IaA20R3, IbA10G2, IdA25, *C. parvum* IIaA15G2R1 IIdA17G1	Swimming pool (leisure pool, school pool, holiday park, and waterpark), and hydrotherapy pool party at a special needs school	74	**9**[d]	Chalmers *et al.* (2019), Zahedi & Ryan (2020)
August 2014[a]	West Midlands, UK	*C. parvum* IIaA15G2R1	Drinking water (contaminated water supply)	24 (12)	1	Chalmers *et al.* (2019), Zahedi & Ryan (2020)
February–March 2015[a]	Victoria, Australia	*Cryptosporidium* spp.	Waterparks – swimming or paddling – spa	(30)	1	de Gooyer *et al.* (2017)
2015[a]	New Zealand	*Cryptosporidium* spp.	Drinking water	6	**2**	ESR (2016)

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
2015[a]	Haifa and West Galilee, Israel	*C. hominis* IeA11G3T3	Unknown suspected recreational water-swimming pools & other reasons	(146)	1	Grossman *et al.* (2019)
June & July 2015[a]	Tennessee, USA	*Cryptosporidium* spp. & *C. hominis* IfA12G1	Recreational water-treated & untreated/pool & lake	67	**2**	https://wwwn.cdc.gov/norsdashboard/
June & July 2015[a]	Virginia, USA	*C. hominis*, IfA12G1 & *Cryptosporidium* spp.	Recreational water-treated/pool–swimming pool & fountain, respectively	89	**2**	https://wwwn.cdc.gov/norsdashboard/
July 2015[a]	Missouri, USA	*Cryptosporidium* spp. & *C. parvum*	Recreational water-treated & untreated/pool & lake, respectively	45	**2**	https://wwwn.cdc.gov/norsdashboard/
July & August 2015[a]	Florida, USA	*Cryptosporidium* spp. & *C. parvum* & *C. hominis* IfA12G1	Recreational water-treated/pool–waterpark–slide–fountain	57	**5**	https://wwwn.cdc.gov/norsdashboard/
July & November 2015[a]	North Carolina, USA	*Cryptosporidium* spp.	Recreational water-treated/pool–swimming pool–waterpark	10	**2**	https://wwwn.cdc.gov/norsdashboard/
July 2015[a]	Southaven, Mississippi, USA	*C. hominis* IfA12G1	Swimming pool exposure associated	55	1	Fill *et al.* (2017)
July 2015[a]	Kentucky, USA	*C. hominis*	Recreational water-treated/pool–waterpark	11	1	https://wwwn.cdc.gov/norsdashboard/
July 2015[a]	Hawaii, USA	*C. hominis* IgA20	Recreational water-treated/pool–waterpark	7	1	https://wwwn.cdc.gov/norsdashboard/
August 2015[a]	Ohio, USA	*Cryptosporidium* spp.	Recreational water-treated/pool–other	30	**2**	https://wwwn.cdc.gov/norsdashboard/
January & June 2015[a]	Alabama, USA	*Cryptosporidium* spp.	Recreational water-treated/pool–swimming pool–waterpark	10	**2**	https://wwwn.cdc.gov/norsdashboard/
June 2015[a]	Somogy, Hungary	*Cryptosporidium* spp.	Treated recreational water/swimming pool	35 (12)	1	Plutzer *et al.* (2018)
July 2015[a]	North-West, UK	*C. parvum* IIaA15G2R1	Swimming pool	18 (4)	1	Chalmers *et al.* (2019)
August 2015[a]	Wisconsin, USA	*Cryptosporidium* spp.	Recreational water-treated/pool/undetermined water/river–stream	11	**2**	https://wwwn.cdc.gov/norsdashboard/
August 2015[a]	Nebraska, USA	*Cryptosporidium* spp.	Recreational water-treated	23	1	https://wwwn.cdc.gov/norsdashboard/
December 2015[a]	Kansas, USA	*Cryptosporidium* spp.	Recreational water-treated/pool–waterpark	2	1	https://wwwn.cdc.gov/norsdashboard/
2015[a]	UK	*C. hominis* IbA10G2 IaA14R3, *C. parvum*	Swimming pool (leisure pool, holiday park, and	65	**10**[d]	Chalmers *et al.* (2019), Zahedi & Ryan (2020)

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
		IIaA15G2R1 IIaA26G1R1	private club) and hydrotherapy pool			
2015[a]	Ireland	*Cryptosporidium* spp.	Private house (two outbreaks)/community (one outbreak)/ swimming pool (one outbreak)	16	**4**	HPSC (2016a)
2016[a]	Ireland	*Cryptosporidium* spp.	Private house	6	**2**	HPSC (2017)
2016[a]	England and Wales, UK	*C. hominis* IBA10G2, *C. parvum*, *Cryptosporidium* spp. IBA10G2	Swimming pool	(44)	**7**	eFOSS
January & August 2016[a]	Colorado, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool/ park–community/ municipal	9	**2**	https://wwwn.cdc.gov/norsdashboard/
February, April & August 2016[a]	Wisconsin, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool–waterpark/hotel/motel/ lodge/inn	22	**3**	https://wwwn.cdc.gov/norsdashboard/
May & September 2016[a]	Hawaii, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool–waterpark/hotel/motel/ lodge/inn	16	**2**	https://wwwn.cdc.gov/norsdashboard/
May –August 2016[a]	Ohio, USA	*Cryptosporidium* spp., *C. hominis*, *C. parvum*	Recreational water-treated & untreated/pool–swimming pool–waterpark/hotel/motel/ lodge/inn/camp/cabin setting/lake/well/pond/ park–community/ municipal/beach – public/subdivision/ neighborhood/school/ college/university	914	**12**	https://wwwn.cdc.gov/norsdashboard/
May, 2016[a]	West Midlands, UK	*C. hominis* IbA10G2	Swimming pool	10 (9)	1	Chalmers *et al.* (2019), eFOSS
May, 2016[a]	South West, UK	*C. hominis* IbA10G2	Swimming pool–oocyst in filter sand	25 (25)	1	Chalmers *et al.* (2019), eFOSS
March 2016[a]	South East, UK	*Cryptosporidium* spp.	Treated recreational water/ swimming pool	4 (4)	1	Chalmers *et al.* (2019)
May 2016[a]	East Midlands, UK	*Cryptosporidium* spp.	Treated recreational water/ swimming pool	3 (3)	1	Chalmers *et al.* (2019)
July 2016[a]	South West, UK	*C. hominis* IbA10G2	Treated recreational water/ swimming pool in a holiday park	9 (9)	1	Chalmers *et al.* (2019)
August 2016[a]	Yorks & Humber, UK	*C. hominis* & *C. parvum*	Treated recreational water/ swimming pool in a holiday park	8 (8)	1	Chalmers *et al.* (2019)
August 2016[a]	North East, UK	*C. hominis*		5 (5)	1	

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
			Treated recreational water/ swimming pool in a holiday park			Chalmers *et al.* (2019)
August 2016[a]	South West, UK	*C. hominis* IbA10G2	Treated recreational water/ swimming pool	13	1	Chalmers *et al.* (2019)
2016[a]	UK	*C. hominis* IbA10G2 & IdA16, and *C. parvum*	Swimming pool (leisure pool, school pools, and holiday park)	86	**9**[d]	Chalmers *et al.* (2019), Zahedi & Ryan (2020)
June––August 2016[a]	Minnesota, USA	*C. parvum, C. hominis, Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool–waterpark	77	**6**	https://wwwn.cdc.gov/norsdashboard/
June, August, September 2016[a]	North Carolina, USA	*Cryptosporidium* spp., *C. parvum*	Recreational water-treated/ pool–swimming pool	70	**3**	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	Arizona, USA	*C. hominis* IfA12G1, *Cryptosporidium* spp.	Recreational water-treated/ interactive pool–waterpark/community/ municipality; club, private residence, subdivision/public outdoor area	469	**3**	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	Pennsylvania, USA	*C. parvum, Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool	17	**2**	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	Iowa, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool	141	1	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	Illinois, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool	3	1	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	West Virginia, USA	*Cryptosporidium* spp.	Suspected recreational water-treated	9	1	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	California, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool	4	1	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	Alabama, USA	*Cryptosporidium* spp., *C. hominis* IfA12G1R5	Recreational water-treated/ pool–waterpark	23 (3)	1	Hlavsa *et al.* (2017), https://wwwn.cdc.gov/norsdashboard/
August–September 2016[a]	Oregon, USA	*C. hominis,* IfA12G1	Recreational water-treated/ pool–swimming pool–hot spring	91	**2**	https://wwwn.cdc.gov/norsdashboard/
August 2016[a]	Missouri, USA	*Cryptosporidium* spp.	Recreational water-treated/ community/municipality/ pool–swimming pool, water slide, pool–kiddie	24	1	https://wwwn.cdc.gov/norsdashboard/
August 2016[a]	Utah, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–waterpark, water slide	15	**2**	https://wwwn.cdc.gov/norsdashboard/

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
August 2016[a]	Michigan, USA	*Cryptosporidium* spp.	Recreational water-untreated/river stream	40	1	https://wwwn.cdc.gov/norsdashboard/
September 2016[a]	Texas, USA	*Cryptosporidium* spp.	Recreational water-treated/ private residence, pool–swimming pool	7	1	https://wwwn.cdc.gov/norsdashboard/
October 2016[a]	Idaho, USA	*Cryptosporidium* spp.	Recreational water-untreated/public outdoor area, hot spring	7	1	https://wwwn.cdc.gov/norsdashboard/
2016[a,b]	Amman, Jordan	*C. parvum* (IIaA16G2R1, IIaA16G2R1)	Unknown/consumption of contaminated food or water was probable source	160 (23)	1	Hijjawi *et al.* (2017)
2016[a]	New Zealand	*Cryptosporidium* spp.	Drinking water	9	**3**	ESR (2018a)
August 2016[a]	Luleå, Sweden	*C. parvum* IIdA24G1	Contaminated vegetable (romaine lettuce)/sewage water as a possible source of the contamination	50	1	Ahlinder *et al.* (2022)
June,July & August 2017	Texas, USA	*Cryptosporidium* spp.	Recreational water-treated & untreated/pool–swimming pool/lake	53	**4**	https://wwwn.cdc.gov/norsdashboard/
July 2017	Minnesota, USA	*C. hominis* IfA12G1	Recreational water-treated/ pool–swimming pool	28	**2**	https://wwwn.cdc.gov/norsdashboard/
July 2017	Georgia, USA	*C. hominis* IaA15R3	Recreational water-treated/ pool–swimming pool	13	1	McAteer *et al.* (2020), https://wwwn.cdc.gov/norsdashboard/
July–August 2017	North Carolina, USA	*Cryptosporidium* spp.	Recreational water-treated & untreated/pool–swimming pool–river–stream	17	**2**	https://wwwn.cdc.gov/norsdashboard/
October 2017	California, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool/ school/college/university	14	1	https://wwwn.cdc.gov/norsdashboard/
2017	UK	*C. hominis* IbA10G2 and IbA12G3	Swimming pool (leisure pool and holiday park)	43	**2**	Chalmers *et al.* (2019), Zahedi & Ryan (2020)
2013–2017	Victoria, Australia	*Cryptosporidium* spp.	Aquatic facilities (public recreational swimming pools and splash parks, and hotel and motel pools)	(391)	**69**[d]	Cullinan *et al.* (2020)
2017	New Zealand	*Cryptosporidium* spp.	Drinking water	10	**3**	ESR (2018b)
June 2017	Blenheim, New Zealand	*C. hominis* subtype IbA10G2, *C. parvum* subtype IIdA24G1	Swimming pool	3	1	Garcia-R & Hayman (2023)
June 2017		*C. hominis* IbA10G2		100 (13)	**2**	

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
	Occitanie, France		Tap water/military training camp			Watier-Grillot *et al.* (2022)
2017	Ireland	*Cryptosporidium* spp.	Private house/unknown water type	3	1	HPSC (2018a)
2017	England, and Wales, UK	*Cryptosporidium* spp., *C. hominis* IbA12G3	Swimming pool	14 (8)	**3**	eFOSS
2018	Ireland	*Cryptosporidium* spp.	Swimming pool at hotel (one outbreak)/private house (two outbreaks)	9	**3**	HPSC (2019a)
2018	Europe	*Cryptosporidium* spp.	Waterborne	-	**3**	EFSA & ECDC (2019)
February 2018	New Zealand	*Cryptosporidium* spp.	Exposure to a splash pad (water play area)	-	1	https://surv.esr.cri.nz/surveillance/annual_surveillance.php
January-May 2018	Maripasoula, French Guiana	*C. hominis* IbA10G2	Tap water (the water network was contaminated with *C. parvum* IIdA19G2)/ civilian and military	51 (16)	1	Menu *et al.* (2022)
July 2018	Alabama, USA	*Cryptosporidium* spp.	Recreational water-treated/ temporary water slide/ child care/daycare center	3	1	https://wwwn.cdc.gov/norsdashboard/
June 2018	Colorado, USA	*Cryptosporidium* spp.	Environmental water/ pond/park–waterpark/	101	1	https://wwwn.cdc.gov/norsdashboard/
May & July 2018	Florida, USA	*C. parvum*, *Cryptosporidium* spp.	Recreational water-treated & untreated/fountain(s)–interactive/spring/zoo/ park – state park	9	**2**	https://wwwn.cdc.gov/norsdashboard/
August & September 2018	Illinois, USA	*C. hominis*, *Cryptosporidium* spp.	Recreational water-treated, pool–waterpark–swimming pool/school/ college/university	8	**3**	https://wwwn.cdc.gov/norsdashboard/
July & September 2018	Michigan, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool/ hotel/motel/lodge/inn/ private residence	34	**2**	https://wwwn.cdc.gov/norsdashboard/
July & August 2018	Minnesota, USA	*C. parvum* IIaA15G2R1, IIaA15G2R2, *C. hominis* IaA15R3	Recreational water-treated & untreated/fountain(s)–interactive/pool–swimming pool–waterpark/pond/camp/ cabin setting/ community/municipality	108	**5**	https://wwwn.cdc.gov/norsdashboard/
August 2018	Nevada, USA	*Cryptosporidium* spp.	Recreational water-treated/ pool–waterpark	38	1	https://wwwn.cdc.gov/norsdashboard/
June & July 2018	Tennessee, USA	*Cryptosporidium* spp.	Drinking water/individual/ private/recreational	704	**2**	

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	^{c}Outbreak	Key reference
			water-untreated/lake/ reservoir/impoundment			https://wwwn.cdc.gov/norsdashboard/
July 2018	Texas, USA	*Cryptosporidium* spp.	Recreational water-untreated/ocean	3	1	https://wwwn.cdc.gov/norsdashboard/
May & August 2018	Utah, USA	*Cryptosporidium* spp.	Recreational water-treated & untreated/pool–kiddie/wading, public/ river/stream	13	**2**	https://wwwn.cdc.gov/norsdashboard/
June 2018	Wisconsin, USA	*C. parvum* IIaA15G2R2, *Cryptosporidium* spp.	Recreational water-treated/ pool–swimming pool	4	1	https://wwwn.cdc.gov/norsdashboard/
2019	Europe	*Cryptosporidium* spp., *C. parvum*	Waterborne	–	**3**	EFSA & ECDC (2021a)
July 2019	Illinois, USA	*Cryptosporidium* spp.	Recreational water – treated/pool–swimming pool/community/ municipality	15	1	https://wwwn.cdc.gov/norsdashboard/
September 2019	Michigan, USA	*Cryptosporidium* spp.	Recreational water – treated/pool–swimming pool/school/college/ university	32	1	https://wwwn.cdc.gov/norsdashboard/
August 2019	Minnesota, USA	*C. hominis* IfA12G1	Recreational water–treated/ pool–swimming pool/ club	124	1	https://wwwn.cdc.gov/norsdashboard/
August 2019	Ohio, USA	*Cryptosporidium* spp.	Recreational water-treated/ fountain(s)–interactive/ pool–waterpark/park-community/municipal	34	**2**	https://wwwn.cdc.gov/norsdashboard/
July-August 2019	Rhode Island, USA	*C. hominis*, *Cryptosporidium* spp.	Recreational water-untreated/undetermined water/lake–reservoir–impoundment/pond/ camp/cabin setting/ waterpark/	21	**2**	https://wwwn.cdc.gov/norsdashboard/
June-August 2019	Texas, USA	*Cryptosporidium* spp.	Drinking water/recreational water-treated/ undetermined water/ pool–waterpark/ unknown/park–amusement	13	**3**	https://wwwn.cdc.gov/norsdashboard/
July 2019	Virginia, USA	*C. hominis* IfA12G1, *C. parvum*, *Cryptosporidium* spp.	Drinking water/recreational water –treated/ community/fountain(s)–interactive/pool–swimming pool/pool–water slide/military facility	131	**2**	https://wwwn.cdc.gov/norsdashboard/
August 2019	Tuscan-Emilian Apennines, Italy	*C. parvum* IIdA25G1	Drinking water	80	1	Franceschelli *et al.* (2022)

(*Continued.*)

Table 1 | Continued

Month/year	Location/country	Etiological agent species/ genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
September 2019	Nouvelle Aquitaine, France	*Cryptosporidium* spp.	Recreational water, lake/ vacationers/sediment positive to *Cryptosporidium* sp.	4	1	Costa *et al.* (2022)
November 2019–2020	Provence-Alpes-Côte d'Azur, France	*C. parvum* IIdA22G1	Tap water	137	1	Costa *et al.* (2022)
2020	Western Australia	*C. hominis* IbA12G3, *C. parvum* IIaA18G3R1, IIaA16G3R1	Swimming pool point sources	83	1	Braima *et al.* (2021)
October 2020	Wisconsin, USA	*C. parvum* IIaA15G2R1	Recreational water-treated/ pool–waterpark/hotel/ motel/lodge/inn	10	1	https://wwwn.cdc.gov/norsdashboard/
,2020	Europe	*C. parvum, Cryptosporidium* spp.	Waterborne	2	1	EFSA & ECDC (2021b)
July 2020[b]	Dublin, Ireland	*C. parvum* IIaA18G3R1	Waterborne (swimming)/ foodborne (consumption of contaminated salad at restaurants with common supplier farm)	40 (33)	1	Naughton *et al.* (2021)
	Total to this review		**322 total outbreaks reported**		8,480 total cases reported	

Notes: ND, no data.

(), number of laboratory-confirmed cases.

[a] Outbreaks occurred before 2017, but were published after 2010 and are not included in the review of Efstratiou *et al.* (2017).

[b] For some waterborne outbreaks, more than one contributing factor was recorded.

[c] Numbers in bold indicate more than a single outbreak.

[d] Some cases subtracted – conflicted with others and corrected.

A total of 194 (47%) outbreaks were reported in the USA, and only one (0.24%) outbreak was recorded in Canada. The reports from the Oceania continent showed that 74 (18%) outbreaks were documented in Australia, while 29 (7%) occurred in New Zealand (Figure 2).

European countries contributed 24% (100) of the total outbreaks. The distribution within the European countries was as follows: United Kingdom (18.3% or 76 outbreaks), unspecified European countries (3% or 13 outbreaks), France (1.2% or five outbreaks), and Italy (0.5% or two outbreaks). Moreover, Hungary, Poland, Finland, and Sweden independently accounted for one outbreak (0.24%).

South American countries contributed to eight outbreaks, including five (1.2%) outbreaks in Brazil and three (0.72%) in French Guiana (Figure 2).

Concerning the Asian countries, four (1.0%) outbreaks were reported in Turkey and two (0.5%) in Israel. Additionally, Taiwan, South Korea, Jordan, and Pakistan were independently accounted for one (0.24%) outbreak (Figure 2).

Concerning the suspected source of infection, recreational waters/swimming pools were the most suspected source of infection, contributing to 75.2% (313) of the total waterborne outbreaks. These outbreaks were primarily due to contamination with *Cryptosporidium* (92%). *Giardia* was responsible for 25.3% of the outbreaks related to recreational water and/ or swimming pools. In 22% of the outbreaks with swimming pools as sources of infection, other protozoan parasites were the etiological agents. Among the documented outbreaks, swimming pools were the source of infection in 278 (67%) outbreaks. Finally, 154 (37%) and 52 (12.5%) outbreaks were connected to treated and untreated waters, respectively. In comparison, 71 (17.06%) outbreaks were found to be connected to contaminated water supplies, tap water, and drinking water (Tables 1–3).

Table 2 | List of worldwide waterborne outbreaks caused by *Giardia* spp.

Month/Year	Location/Country	Etiological agent Species/genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
July 2012[a]	North Dakota, USA	*Giardia* spp.	Recreational water-untreated/ lake/reservoir/impoundment	(3)	1	https://wwwn.cdc.gov/norsdashboard/
July 2013[a]	New Mexico, USA	*G. duodenalis*	River–stream/camp-camping	3	1	McClung *et al.* (2017), MMWR
July 2013[a]	Louisiana, USA	*Cryptosporidium* spp. & *Giardia* spp.	Recreational water-treated & untreated/pool–kiddie	3	1	https://wwwn.cdc.gov/norsdashboard/
July–August 2013[a]	Idaho, USA	*Giardia* spp.	Environmental contamination or consumption of inadequately treated water/ undetermined water or drinking water	(8)	1	Rosenthal *et al.* (2017)
September 2013[a]	Illinois, USA	*G. duodenalis*	River–stream/park	69	1	McClung *et al.* (2017), MMWR
October 2013[a]	New York, USA	*G. duodenalis*	Spring water	5	1	McClung *et al.* (2017), MMWR
July 2014[a]	Minnesota, USA	*G. duodenalis*	Environmental water/river–stream	6	1	McClung *et al.* (2017), MMWR, https://wwwn.cdc.gov/norsdashboard/
July 2014[a]	Louisiana, USA	*Cryptosporidium* spp. & *Giardia* spp.	Recreational water-treated/ pool–swimming pool	9	**2**	https://wwwn.cdc.gov/norsdashboard/
August 2014[a]	Wisconsin, USA	*G. duodenalis*	Associated with drinking water/national forest	3	1	Benedict (2017), MMWR
August 2014[a]	Alaska, USA	*G. duodenalis*	Associated with drinking water/river stream	5	1	Benedict (2017), MMWR
September 2014[a]	Idaho, USA	*G. duodenalis*	Associated with drinking water	2	1	Benedict (2017), MMWR
October 2014[a]	Colorado, USA	*G. duodenalis*	Recreational water-untreated/ river stream/park	9	1	McClung *et al.* (2017), MMWR
October 2014[a]	Michigan, USA	*G. duodenalis*	Environmental water/sewage/ private residence	6	1	McClung *et al.* (2017), MMWR
October 2014[a]	Utah, USA	*G. duodenalis*	Environmental water/river stream/backcountry	4	1	McClung *et al.* (2017), MMWR
June 2015[a]	Louisiana, USA	*Giardia* spp.	Recreational water-treated	3	1	https://wwwn.cdc.gov/norsdashboard/
June 2015[a]	Utah, USA	*Giardia* spp.	Suspected drinking water	9	1	https://wwwn.cdc.gov/norsdashboard/
July 2015[a]	New Mexico, USA	*G. duodenalis*	Environmental water/river–stream	4	1	https://wwwn.cdc.gov/norsdashboard/
2015[a]	New Zealand	*Giardia* spp.	Drinking water/one of the outbreaks was due to a school trip to Nepal	50	**8**	ESR (2016)
September 2015[a]	Şırnak, Turkey	*G. duodenalis*	Contamination of drinking water with sewage water/ lack of adequate water purification	24	1	Maçin *et al.* (2017)

(*Continued.*)

Table 2 | Continued

Month/Year	**Location/Country**	**Etiological agent Species/genotypes**	**Suspected source**	**Est. cases/ (laboratory-confirmed)**	**^{c}Outbreak**	**Key reference**
2015[a]	Ireland	*Giardia* spp.	Waterborne/private houses	–	**3**	HPSC (2016b)
June 2016[a]	Missouri, USA	*G. duodenalis*	Suspected drinking water	13	1	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	Minnesota, USA	*Giardia* spp.	Environmental water/river–stream	4	1	https://wwwn.cdc.gov/norsdashboard/
July 2016[a]	Michigan, USA	*G. duodenalis*	Recreational water-untreated/lake–reservoir	3	1	https://wwwn.cdc.gov/norsdashboard/
2016[a]	New Zealand	*Giardia* spp.	Waterborne/drinking water	16	**5**	ESR (2018a)
June 2017	Alaska, USA	*G. duodenalis*	Environmental water/river–stream	5	1	https://wwwn.cdc.gov/norsdashboard/
July 2017	Idaho, USA	*G. duodenalis*	Recreational water-treated/pool–swimming pool	4	1	https://wwwn.cdc.gov/norsdashboard/
September 2017	Minnesota, USA	*Giardia* spp.	Environmental water/river–stream	7	1	https://wwwn.cdc.gov/norsdashboard/
September 2017	Wisconsin, USA	*G. duodenalis*	Drinking water/individual–private	6	1	https://wwwn.cdc.gov/norsdashboard/
2017[b]	Ireland	*Giardia* spp.	Waterborne/foodborne	–	1	HPSC (2018b)
2017	New Zealand	*Giardia* spp.	Drinking water	13	**4**	ESR (2018b)
2017	England and Wales	*G. duodenalis*	Treated recreational water/swimming pool	(7)	**2**	PHE (2019)
2018	Europe	*Giardia* spp.	Waterborne	–	1	EFSA & ECDC (2019)
2018	Ireland	*Giardia* spp.	Waterborne	–	**2**	HPSC (2019b)
June 2018	Colorado, USA	*Cryptosporidium* spp. & *Giardia* spp.	Environmental water/river/stream/pond/national forest/park–waterpark	104	**2**	https://wwwn.cdc.gov/norsdashboard/
May & August 2018	Minnesota, USA	*G. duodenalis*	Recreational water-untreated/river/stream/lake/reservoir/impoundment	7	**2**	https://wwwn.cdc.gov/norsdashboard/
March 2018	Pennsylvania, USA	*Giardia* spp.	Recreational water-treated/pool–swimming pool; spa/whirlpool/hot tub/hotel/motel/lodge/inn	2	1	https://wwwn.cdc.gov/norsdashboard/
June 2018	Tennessee, USA	*Cryptosporidium* spp. & *Giardia* spp.	Drinking water/individual/private/park–amusement	693	1	https://wwwn.cdc.gov/norsdashboard/
August & September 2018	Utah, USA	*Giardia* spp.	Recreational water-treated & untreated/ocean; lake/reservoir/impoundment; other/pool–swimming pool/beach – public; private residence	13	**3**	https://wwwn.cdc.gov/norsdashboard/
July & August 2018	Wisconsin, USA	*G. duodenalis*	Environmental water/river/stream/park/public outdoor area	17	**2**	https://wwwn.cdc.gov/norsdashboard/
November 2018 – April 2019	Bologna, Italy	*G. duodenalis* assemblage B	Tap water	228 (199)	1	Resi *et al.* (2021)

(*Continued.*)

Table 2 | Continued

Month/Year	Location/Country	Etiological agent Species/genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
April 2019	New Zealand	*Giardia* spp.	Swimming pool	10	1	https://surv.esr.cri.nz/surveillance/annual_surveillance.php
2019	Europe	*G. duodenalis*	Waterborne	–	**3**	EFSA & ECDC (2021a)
February 2020	Pennsylvania, USA	*Giardia* spp.	Recreational water-untreated/pond/private residence	13	1	https://wwwn.cdc.gov/norsdashboard/
March 2020	Hawaii, USA	*Giardia* spp.	Drinking water/community	2	1	https://wwwn.cdc.gov/norsdashboard/
2020	Europe	*Giardia* spp.	Waterborne	2	1	EFSA & ECDC (2021b)
	Total to this review		**71 total outbreaks reported**		1,394 total cases reported	

Notes: ND, no data.

(), number of laboratory-confirmed cases.

[a]Outbreaks occurred before 2017, but were published after 2010 and are not included in the review of Efstratiou *et al.* (2017).

[b]For some waterborne outbreaks more than one contributing factor was recorded.

[c]Numbers in bold indicate more than a single outbreak.

DISCUSSION

In the last three decades, many reports of waterborne outbreaks were linked to protozoan parasites. WHO has classified *Cryptosporidium* as one of the leading causal agents in both food and waterborne diseases (Gururajan *et al.* 2021). During the past few years, scientific articles have provided accurate and ongoing records of global outbreaks. The first global review (Karanis *et al.* 2007) in this regard showed a large number of outbreaks (325), with the subsequent ones (Baldursson & Karanis 2011; Efstratiou *et al.* 2017; Ma *et al.* 2022) recording 199, 381, and 251 outbreaks in 2011, 2017, and 2022, respectively.

The present review identified 416 outbreaks reported during the past 5 years globally and continues the previous studies of 2007, 2011, and 2017. We found that the highest number of parasitic waterborne outbreaks were reported in developed countries. The review of 2007 indicated that most of the outbreaks were reported in the USA (52.6%) with nearly two-thirds of them having occurred in North America. The review of 2011 showed that the highest number of reports appeared in New Zealand (40.2% or 80 outbreaks), and 30.1% of the total outbreaks were recorded in the United States (60 outbreaks). Based on the review of 2017, 48% were observed in New Zealand, following 41% of the total numbers in North America.

Similarly, in the present review, the highest number of outbreaks (195, 46.8%) were reported on the North American continent, most of which occurred in the United States. The increased trend in reports of waterborne protozoan parasite outbreaks in developed countries is in accordance with prior studies (Yang *et al.* 2012). The significant improvements in reporting and surveillance systems, improved public health policies, precise detection approaches, and advanced socioeconomic status established in developed countries contributed to the rise in reported parasitic protozoan outbreaks. In the United States, the local, territorial, and state public health departments are predominantly responsible for the detection and investigation of waterborne disease outbreaks, and they voluntarily report the cases to the CDC via the National Outbreak Reporting System (NORS), which is a web-based platform (Hlavsa *et al.* 2011). There are also improved notification and reporting systems in the United Kingdom (PHE) and Australia (NNDSS), which have the highest number of waterborne outbreak reports after the United States.

Although the United States has achieved considerable progress in preventing of waterborne infections over the last century, the CDC's estimates showed that approximately 7.2 million Americans are infected (Gharpure *et al.* 2019). *Cryptosporidium* oocysts and *Giardia* cysts have been broadly detected in water samples throughout the United States (Ongerth 2013, 2017). Moreover, *Cryptosporidium* is the most frequently reported cause of waterborne outbreaks and the third leading cause of intestinal infections attributed to animal contact in the United States (Gharpure *et al.* 2019).

Table 3 | Other parasites

Month/Year	Location/Country	Etiological agent Species/genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
October 2002[a]	Arizona, USA	*N. fowleri*	Drinking water	(2)	1	https://wwwn.cdc.gov/norsdashboard/
July 2005[a]	Oklahoma, USA	*N. fowleri*	Recreational water-untreated	2 (1)	1	https://wwwn.cdc.gov/norsdashboard/
2009[a]	Oklahoma, USA	*B. hominis*	Untreated recreational water/ river–stream	45	1	https://wwwn.cdc.gov/norsdashboard/
2011[a]	Ouro Preto do Oeste, Brazil	*T. gondii*	Contaminated water supply	78	1	Almeria & Dubey (2021), Santana *et al.* (2015)
July 2008-November 2009[a]	Karachi, Pakistan	*N. fowleri*	Infection likely occurred through ablution with domestic tap water/*N. fowleri* was found in tap water from two patient's homes/only one patient had a history of swimming	13 (3)	1	Shakoor *et al.* (2011)
2012[a]	Alaska, USA	*B. hominis*	Drinking water	21	1	https://wwwn.cdc.gov/norsdashboard/
2013[a,b]	Ponte de Pedra, Brazil	*T. gondii*	Acai juice/unfiltered water (not confirmed, everyone consumed juice in the area)	73	1	Almeria & Dubey (2021)
2013[a]	Poland	*C. cayetanensis*	Drinking water suspected/ travelers from Indonesia	(3)	1	Almeria *et al.* (2019), Bednarska *et al.* (2015)
April 2013[a]	South Korea	*C. cayetanensis*	Drinking water/travelers consume water in a church of Nepal	8 (3)	1	Ma *et al.* (2020)
2015[a]	Gouveia, Brazil	*T. gondii*	Waterborne	(52)	1	Brandão-de-Resende *et al.* (2020)
September 2015[a]	Şırnak, Turkey	*D. fragilis*	Contamination of drinking water with sewage water/lack of adequate water purification	440 (6)	1	Maçin *et al.* (2017)
September 2015[a]	Şırnak, Turkey	*B. hominis*	Contamination of drinking water with sewage water/lack of adequate water purification	44	1	Maçin *et al.* (2017)
September 2015[a]	Şırnak, Turkey	*E. histolytica*	Contamination of drinking water with sewage water/lack of adequate water purification	96	1	Maçin *et al.* (2017)
Summer 2015[a]	Alpes-Maritimes, France	*Naegleria* spp.	Participants in an obstacle race/ environmental water samples from muddy water ponds	–	1	Six *et al.* (2016)
November 2015[a]	South Carolina, USA	*Acanthamoeba* spp.	Recreational water-treated/ swimming pool	2	1	https://wwwn.cdc.gov/norsdashboard/
2015[a]	New Zealand	*D. fragilis*	Drinking water	3	1	ESR (2016)
2015–2016[a,b]		*T. gondii*		14	1	

(*Continued.*)

Table 3 | Continued

Month/Year	Location/Country	Etiological agent Species/genotypes	Suspected source	Est. cases/ (laboratory-confirmed)	[c]Outbreak	Key reference
	Montes Claros de Goias, Brazil		Contaminated irrigation water/or Artisan fresh cheese from raw cow's milk			Almeria & Dubey (2021), da Costa *et al.* (2020)
June–September 2015[a,b]	England, Scotland, and Wales, UK	*Cyclosporiasis*	Travellers returning from Mexico/ consumption of fruit or berries, salad or vegetables, fresh herbs, bottled water, and ice	(79)	1	Nichols *et al.* (2015)
October 2016[a]	Finland	*D. fragilis*	Intrusion of wastewater into a drinking water distribution system	458 (2)	1	Kauppinen *et al.* (2019)
June 2017	New Taipei, Taiwan	*V. corneae*	Swimming pool associated	(13)	1	Chen *et al.* (2019), Wang *et al.* (2018)
May–July 2017	Camopi, French Guiana	*T. gondii*	Drinking water/consumption of unfiltered water/sharing traditional drink/floods/river flood in Amerindian community	(20)	1	Blaizot *et al.* (2020)
April 2018	Santa Maria, Brazil	*T. gondii*	Treated water/drinking water	1,162 (902)	1	Dal Ponte *et al.* (2019), Minuzzi *et al.* (2021)
2020	Europe	*E. bieneusi*	Waterborne	–	1	EFSA & ECDC (2021b)
	Total to this review		**23 total outbreaks reported**		2,627 total cases reported	

Notes: ND, no data.

(), number of laboratory-confirmed cases.

[a] Outbreaks occurred before 2017, but were published after 2010 and are not included in the review of Efstratiou *et al.* (2017).

[b] For some waterborne outbreaks more than one contributing factor was recorded.

[c] Numbers in bold indicate more than a single outbreak.

In addition to the advanced surveillance system, which can serve as a contributing factor, there are other factors, such as a large number of livestock living and grazing around surface water resources, mass farming, and manure distribution in fields, leading to the high prevalence of waterborne giardiasis and cryptosporidiosis in developed countries. The environmental distribution of *Cryptosporidium* and *Giardia* depends on human, wildlife, and agricultural sources, which have a potential role in the contamination of surface waters. The anthropogenic disturbance also leads to increasing numbers of zoonotic diseases and spillovers of zoonotic pathogens.

This review found that most waterborne outbreaks are caused by *Cryptosporidium*, with *C. hominis* being more frequent than *C. parvum*. It is demonstrated that many of the microbial pathogens of public health concern in recreational waters are derived from fecal contamination sources, including surface runoff, sewage, wildlife, and domestic animals (Fewtrell & Kay 2015). Waterborne cryptosporidiosis outbreaks that involve *C. hominis* as the primary cause attract attention toward sewage contamination rather than runoff from agricultural sources (Robertson *et al.* 2020). Previous experimental research proved that increased human recreation in water bodies is a risk factor strongly associated with the increased *Cryptosporidium* contamination levels at these sources, as only *C. hominis* was identified. It implies that recreational access to drinking water catchments poses a potential public health risk and that government policies restricting activities to the outskirts of the catchments should be facilitated (Loganthan *et al.* 2012).

The global data on waterborne disease outbreaks may underestimate the true incidence of these diseases, as not all of them are recognized, investigated, and reported in developing countries which are probably most affected by waterborne infections due to poor hygiene and inadequate water treatment standards (Baldursson & Karanis 2011). For instance, many households in these countries utilize raw water for other purposes, such as cooking, bathing, and recreational activities (Young *et al.*

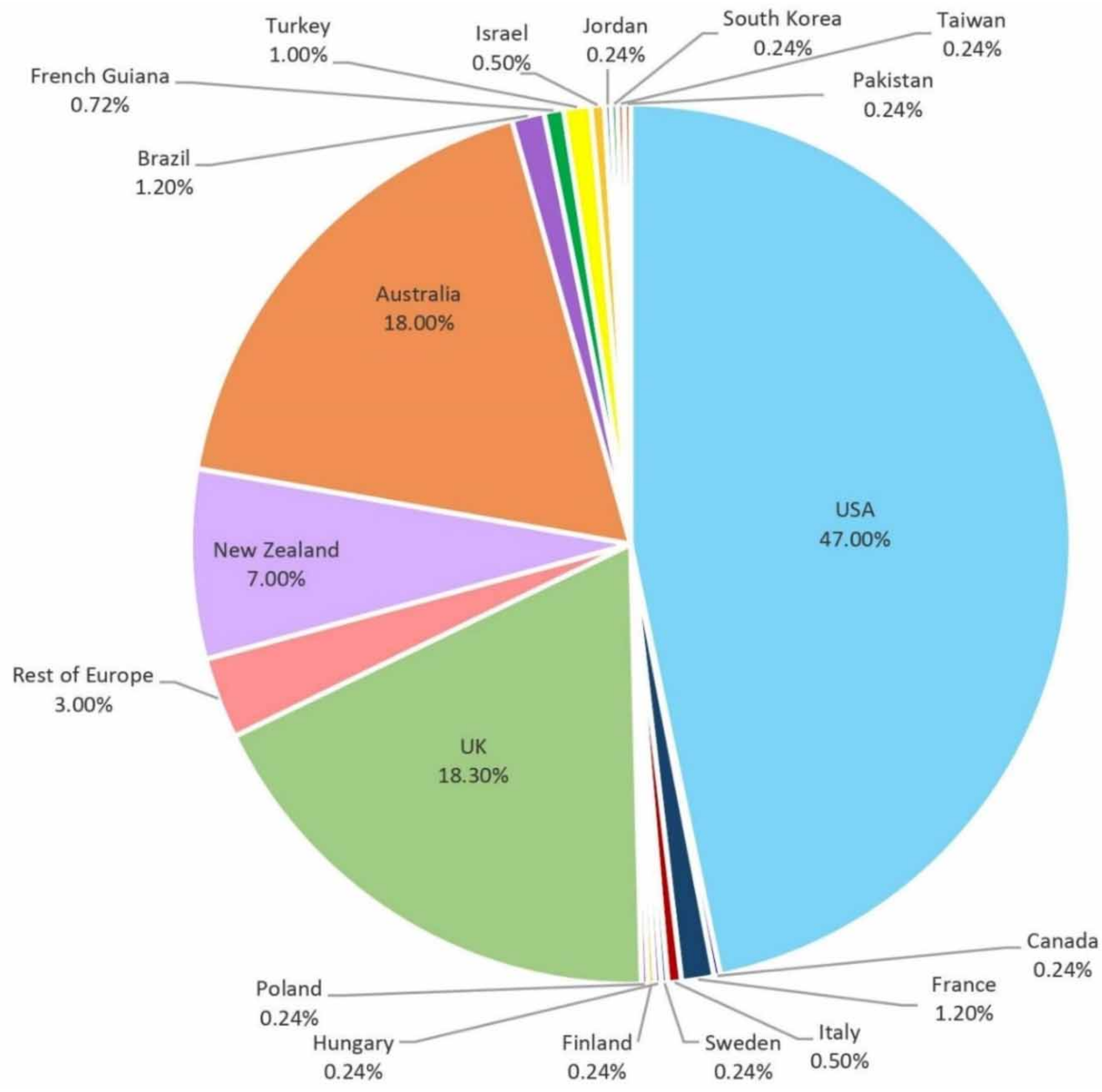


Figure 2 | Distribution of worldwide waterborne outbreaks reported between 2017 and 2022 by country.

2012; Siwila *et al.* 2020). Hence, to prevent misrepresenting the worldwide status of waterborne outbreaks, public health organizations in these regions require strategies for establishing an accurate diagnosis and reliable surveillance and notification system.

Waterborne pathogens infect people not only via drinking water but also when they breathe in contaminated water or get water in their ears or nose. The recent estimates by the CDC revealed a shift in the types of waterborne infections and routes of exposure in the United States during the past decades. Once the world's population grew, the need for using water on a broader scale and in new and creative ways arose. To accommodate these demands, high-rise structures, water parks, and other facilities have been built, which all need complex water systems. Water circulates further in these complicated structures, including many pipes, drains, and other plumbing equipment. Therefore it is more difficult to control water quality and apply enough disinfectant in the system (https://www.cdc.gov).

The substantial role of recreational water as a source of waterborne infections has been frequently discussed in recent decades. In parallel, we found that parasitic protozoan outbreaks are more associated with recreational water and/or swimming pools than other sources (e.g., drinking water and community water). Global cryptosporidiosis outbreaks via recreational water sources are reported more frequently than drinking water-associated outbreaks (Chalmers 2012). A review of 2011 (Baldursson & Karanis 2011) indicated that in 7 years (between 2004 and 2010), of 120 waterborne *Cryptosporidium* outbreaks, 54% were related to recreational waters and 46% were linked to drinking water sources. Untreated recreational waters (e.g., lakes and dams) may be contaminated via animal, sewage, and agricultural sources. Swimming in these environments is a public health hazard (Karanis *et al.* 2007).

The current review found that recreational water and/or swimming pools were the infection sources in 313 (75.2%) waterborne parasitic outbreaks, 92% related to cryptosporidiosis outbreaks. These findings are consistent with the advanced monitoring systems and research on cases linked to water supply systems and recreational waters. In recent years, parasitic infection outbreaks connected to swimming pools have escalated in the United States (Hlavsa *et al.* 2017). *Cryptosporidium* is the primary cause of outbreaks in recreational water sources and swimming pools, given its chlorine resistance and the challenges of eliminating it through filtration (Gururajan *et al.* 2021). Thus, bathers and swimmers may be at risk of infection with participation in recreational activities in pools infected with chlorine-resistant protozoa (Pineda *et al.* 2020). A preliminary record published by the CDC's MMWR stated that in the United States, the number of *Cryptosporidium* outbreaks (at least 32) associated with swimming pools and water playgrounds was higher in 2016 compared to 2014, with 16 outbreaks (https://www.cdc.gov).

In the United States and the United Kingdom, swimming pools are the most common sources of infection for cryptosporidiosis outbreaks (Chalmers & Johnston 2018). Based on a previous study, 444 cryptosporidiosis outbreaks were reported to the CDC between 2009 and 2017. According to these reports, 156 (35.1%) outbreaks were connected with treated recreational water, with pools (100 outbreaks), kiddie/wading pools (11 outbreaks), and water playgrounds (10 outbreaks) being the most frequently involved recreational water facilities (Gharpure *et al.* 2019). Recent advancements in our knowledge of the potential risks of recreational waters and swimming pools and our ability to investigate waterborne infections have played a part in the apparent increase in outbreaks at these locations (Chalmers 2012).

The efficacy of the treatment strategies in removing microbial pathogens from water is undetermined, and the frequency of reported outbreaks of gastrointestinal infections caused by chlorine-resistant protozoan parasites has been a rising concern (Wood *et al.* 2019). *Cryptosporidium* oocysts which are infectious after excretion and are excreted in numbers significantly larger than the human infectious dosage (10 oocysts) possess high resistance to chlorine disinfection. All of these features should be taken into account while developing successful cryptosporidiosis prevention methods, including improved guidelines for water treatment procedures in pools and efficient filtration systems in recreational centers. Implementing extensive decontamination measures, such as hyperchlorination of public-treated recreational waters in a cryptosporidiosis outbreak is imperative (Gharpure *et al.* 2019).

The concentration of the disinfectant, contact time, temperature, and pH (depending on the disinfectant) are the primary elements that determine disinfection efficiency. In many industrialized and developing countries, chlorine is the most commonly used disinfectant for water purification (Omarova *et al.* 2018). In the United States and Europe, pressure-activated membrane processes (microfiltration, ultrafiltration, nanofiltration, and reverse osmosis) play an essential role in the production of drinking water (Deborde & von Gunten 2008; Lundqvist *et al.* 2019; Mozia *et al.* 2020; Sousi *et al.* 2020). Other water treatment processes are based on alternative disinfectants, such as chlorine dioxide, ozone, and UV radiation, which have yet to prove solely effective. The efficacy of drinking water treatment can be improved by using a combination of disinfectants and filtration technologies, which eliminate and inactivate various microbial pathogens (Omarova *et al.* 2018).

In contrast to drinking water, most treated recreational water sites lack proper regulations (Chalmers 2012). Additionally, surveillance of recreational waters to evaluate the safety of swimmers is only partially possible (Boehm & Soller 2012). The most prevalent cause of swimming pool outbreaks is a failure in policies and procedures, poorly designed sanitation systems, and inadequate maintenance, which are significant barriers to preventing and controlling waterborne outbreaks (Lewis *et al.* 2015).

Climate change and global warming can enhance human exposure to waterborne pathogens, especially parasitic protozoa, by directly impacting the ecosystem and human lifestyles (Lal *et al.* 2019). Ongoing climate change may be closely related to extreme weather events (such as floods and storms with soil runoff) that accelerate the release of fecal-contaminated surface water into groundwater, affecting drinking water resources (Angelici & Karanis 2019). Since the amount and frequency of runoff, rainfall patterns, and temperature can potentially alter the state of microbial contaminations in recreational waters, it is crucial to predict how climate change will affect the burden of recreational water diseases globally (Boehm & Soller 2012).

Seasonality also affects the transmission of waterborne infections due to the higher frequency of fecal contamination of surface waters in rainy seasons. Furthermore, high temperatures lead people to consume more water and bathe more to refresh themselves. It is demonstrated that the incidence of cryptosporidiosis and giardiasis is increased in late summer and autumn, emphasizing the significant association between weather and the transmission of waterborne pathogens (Angelici & Karanis 2019).

Concerning drinking water sources, the WHO published new treatment standards for drinking water quality in 2017, and the second addendum was published in 2022 (www.who.int). The CDC teaches people to adopt safe swimming habits in the United States and preserve their private well water from parasitic contamination. CDC aims to deliver clean and healthy water to people worldwide through various initiatives, projects, and sanitation protocols (www.cdc.gov). Moreover, the CDC launched CryptoNet (https://www.cdc.gov/parasites/crypto/cryptonet.html) in 2010, the first molecularly-based surveillance system for parasitic disease in the United States. The data provided by CryptoNet can further reveal the epidemiology of *Cryptosporidium* and its chains of transmission and help improve evidence-based prevention programs (Hlavsa *et al.* 2017).

Most monitoring and notification systems suffer from underestimating due to similar features of the diseases, absence of manifestations, and self-limiting infections (Efstratiou *et al.* 2017). It is notwithstanding that the efficiency of reporting is different for each country and each pathogen and highly depends on the availability of research and relevant surveillance organizations and the epidemiological feature of the causal agent (Yang *et al.* 2012). Many developed countries prioritize viral and bacterial infectious diseases; consequently, their monitoring systems only include a small number of parasitic protozoa (Fletcher *et al.* 2012). However, *Cryptosporidium* is considered a contaminant of surface water supplies by regulations for public water systems in the United States (Stokdyk *et al.* 2019).

Learning more about the epidemiology of parasitic infections, especially in developing countries, is crucial. This necessitates proper reporting and documentation systems and approaches, including accurate pathogen isolation, speciation, and subtyping. Finally, each country must provide its own surveillance system for monitoring waterborne outbreaks (Baldursson & Karanis 2011; Efstratiou *et al.* 2017), but even in countries with such systems, outbreak investigation activities have repeatedly failed to detect sources of infection and etiologic agents precisely.

CONCLUSIONS

The current review focuses on waterborne parasite outbreaks reported between 2017 and 2022, and it is the fifth overview of its kind globally as a continuation of a series of reviews since 2007. It provides compact information and demonstrates that recorded outbreaks are still high. Not only *Cryptosporidium* and *Giardia* but also other neglected protozoan parasites have been reported in recent years, a fact that foretells a breakthrough in recording systems and scientific research on these subjects. There are undoubtedly unprecedented outbreaks, particularly in developing nations, the documentation of which may shed light on public health surveillance systems regarding parasitic diseases.

The national public health surveillance systems should consider appropriate outbreak reporting systems in each country, which is a fundamental approach to rapidly diagnosing and controlling outbreaks precisely. Safe water for bathing and drinking is critical for the health of a population, especially children.

The status of outbreaks caused by waterborne pathogens indicates the quality of bathing and drinking water. It is recommended that the water purification guidelines and monitoring of waters in each country take into account all parasitic infections of public health importance. Moreover, the recent efforts to improve water and sanitation facilities should be continued, as they are highly linked to outbreaks of diseases. Participants in large-scale sporting events including open-water swimming should be aware of the increased risk of gastrointestinal infection.

The current review underlines the importance of more large-scale and effective surveillance systems, especially in light of climatic events caused by climate change, which are currently on the rise globally and pose the threat of massive waterborne disease outbreaks. Finally, the data provided by our review can help policymakers, public health communities, and related industries (e.g., owners of swimming pools and recreational water facilities) give priority to the next steps for waterborne disease prevention.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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