

A Scoping Review and Thematic Analysis of the Effects of Tropical Cyclones on Diarrheal Diseases

Szu Yu Lin¹, Paul LC Chua¹, Lei Yuan¹, Nasif Hossain¹, Jinyu He³, Lisa Yamasaki^{1,4}, Lina Madaniyazi², Chris Fook Sheng Ng^{1,2}, Aurelio Tobias⁵, Masahiro Hashizume^{1,2}

¹ Department of Global Health Policy, Graduate School of Medicine, The University of Tokyo, Tokyo, Japan.

² School of Tropical Medicine and Global Health, Nagasaki University, Nagasaki, Japan.

³ Center for Climate Change Adaptation, National Institute for Environmental Studies, Tsukuba, Japan.

⁴ Center Hospital of the National Center for Global Health and Medicine, Tokyo, Japan.

⁵ Institute of Environmental Assessment and Water Research (IDAEA), Spanish Council for Scientific Research (CSIS), Barcelona, Spain.

Corresponding author: Szu Yu Lin first and last name (ariellin64@m.u-tokyo.ac.jp)

†7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Key Points:

- Half of the epidemiological studies reported positive associations between tropical cyclone events and diarrheal diseases.
- Tropical cyclone exposure was defined differently across studies such as using timeframes, wind speeds, or rainfall amounts.
- Most studies used a simple pre-post comparison study design without controls and adjustments for temporal confounders.

Abstract

Tropical cyclones bring health risks and can trigger outbreaks of diarrheal diseases in affected populations. There are several reviews that mention the relationship between tropical cyclones and diarrheal diseases. However, there is no dedicated review of the current evidence and extent of research on the association between tropical cyclones and diarrheal diseases. We performed a scoping review to thoroughly examine the available literature. We also thematically analyzed the transmission pathways explained in the literature. A total of 96 studies were included. Twenty-three studies quantitatively measured the tropical cyclone–diarrhea associations, with half reporting positive associations. We found that the studies defined and measured tropical cyclone exposure differently and mostly analyzed a single event. The study designs employed were mostly pre-post comparisons that had several limitations affecting internal validity. These differences also prevent the quantitative pooling of evidence. A standardized approach to measuring the association between tropical cyclones and diarrheal diseases can be devised by suggesting the most appropriate exposure definition and modeling.

Plain Language Summary

Tropical cyclones bring forth strong winds and heavy precipitation in a short period, which could lead to disease outbreaks. This paper aims to explore the extent of research conducted to analyze the impact of tropical cyclones on diarrheal diseases. Numerous studies from the current literature were examined. Half of the epidemiological studies indicated an increasing incidence of diarrheal diseases post-tropical cyclones. Definitions of tropical cyclone exposure and diarrheal disease outcome as well as study designs varied across studies. The most utilized study design for quantification of tropical cyclone impacts on diarrheal diseases came with several limitations that can be overcome using advanced designs. These discrepancies pose challenges in comparing results between studies or synthesizing the overall evidence. Moreover, studies explained broad concepts of transmission pathways between tropical cyclones and diarrheal diseases such as heavy rainfall, flooding, saltwater intrusion, and emergency evacuation. Specific transmission pathways linking tropical cyclones to diarrheal diseases require further investigation, particularly through fieldwork studies. In conclusion, the review underscores the need for a standardized approach to measuring cyclone-disease associations and employing more robust study designs and pathogen-specific analyses for future studies.

1 Introduction

Tropical cyclones are extreme weather events that bring strong winds and heavy rainfall in a short period, causing significant floods and damage to infrastructures. From a public health perspective, investigating tropical cyclones becomes essential due to their profound impact on human health. Tropical cyclones can give rise to various health risks, strain vital infrastructures, and potentially trigger disease outbreaks in affected populations. As tropical cyclones can cause widespread devastation and disruption, understanding their implications on human health is crucial in developing effective strategies to secure communities and mitigate adverse health consequences.

Previous studies have examined the effects of tropical cyclones on a range of health outcomes, including all-cause mortality (Santos-Burgoa et al., 2018; Nethery et al., 2021; Liu et al., 2023), preterm births (Sun et al., 2020), cardiovascular diseases (Yan et al., 2021; Burrows et al., 2023), respiratory health diseases (Yan et al., 2021; Burrows et al., 2023), kidney diseases (Blum et al., 2022), and infectious diseases (Zheng et al., 2017). One of the infectious diseases of crucial concern is diarrheal diseases due to their heightened sensitivity to the ambient environment. To our knowledge, five review articles touch on the topic of tropical cyclones and diarrheal diseases (Levy et al., 2016; Huang et al., 2023; Arpin et al., 2021; Kraay et al., 2020; Ahern et al., 2005). These studies contribute valuable perspectives to understanding the complex interplay between environmental factors and waterborne diseases; however, they do not specifically focus on the association between tropical cyclones and diarrheal diseases. Most of them analyzed the impact of heavy rainfall and floods and plainly connected or mentioned tropical cyclones. Two reviews extracted statistical measures from the literature but did not elaborate on their relationship.

This scoping review aims to comprehensively analyze the available literature on the association between tropical cyclones and diarrheal diseases. The primary objective is to examine various methodological approaches employed in quantifying this association. The second objective is to elucidate the pathways through which exposure to tropical cyclones contributes to the incidence of diarrheal diseases by utilizing a thematic analysis. By identifying gaps in current research on this topic, our goal is to offer valuable insights for guiding future research endeavors and policymaking aimed at enhancing preparedness for tropical cyclone events.

2 Materials and Methods

This scoping review followed the Joanna Briggs Institute guidelines (Pollock et al., 2021). It was conducted following a developed protocol (Lin et al. 2023) in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses for Scoping Review (PRISMA-ScR) reporting guidelines (Tricco et al., 2018).

2.1 Search strategy

We used online databases of PubMed/MEDLINE, Web of Science, Scopus, Google Scholar, and ProQuest to perform the literature search on August 23rd, 2023. The search terms used refer to tropical cyclones (e.g., tropical cyclone, tropical depression, tropical storm, hurricane, typhoon) and diarrheal diseases (e.g., diarrhea, enteric infection, and gastroenteritis).

2.2 Eligibility criteria

We included all types of published research. Review studies, such as narrative, scoping, and systematic reviews, were also included. Gray literature, such as reports, conference abstracts, editorials, and theses, were included. Only articles written in English were included. We excluded presentation slides, newspaper articles, and research articles without accessible full text.

2.2.1 Participants

We included all human-related studies irrespective of age, sex, health status, and geographic location. Studies on animals, plants, and pathogens without the involvement of humans were excluded.

2.2.2 Exposure

We encompass all tropical cyclones occurring in all tropical cyclone basins (Lavender & McBride, 2020). We excluded extra-tropical cyclones (i.e., mid-latitude cyclones that occur outside the tropical locations), monsoons, and tornadoes. We excluded floodings that are not caused by tropical cyclones.

2.2.3 Outcome

We included all kinds of diarrheal disease-related health outcomes, including mortality, hospital admissions, healthcare facility visits, ambulance transport, emergency room visits, and clinically diagnosed or self-reported symptoms cases. Also, we included pathogen-specific diarrheal diseases listed in the 10th revision of the International Statistical Classification of Diseases (ICD10) A00 to A09.

2.2.4 Context

All articles that directly described the association between tropical cyclones and diarrheal diseases were considered in this scoping review.

2.3 Study selection, data extraction, and summary of results

All records from the literature search were imported and deduplicated using EndNote 20. At least two reviewers (SYL, LY, NH, and JH) independently screened the titles and abstracts based on the inclusion and exclusion criteria before full-text review. Two reviewers (SYL and PLCC) independently performed a full-text review. Any disagreements between the evaluations made by the reviewers were resolved through discussion or feedback from a third reviewer (MH). Rayyan, a web and mobile app for systematic and scoping reviews (Ouzzani et al., 2016), was used to perform the screening process. A PRISMA flow diagram was created to show the inclusion process. A data extraction form was created within Notion (a productivity software) and reviewers (SYL and LY) extracted the following data for each included study:

1. Citation details (e.g., first author and affiliation, title, journal, and publication date)
2. Study area and period
3. Characteristics of the study population (e.g., children, elderly, or evacuees)
4. Tropical cyclone definition and data source(s)
5. Diarrheal diseases definition, type of health outcome (e.g., surveillance, hospital admissions, or healthcare facility visits), and data source(s)

- 150 6. Study design and statistical analysis
- 151 7. Direction of association (i.e., positive, negative, or mixed)
- 152 8. Statement of presumed mechanism(s) associating tropical cyclones with diarrheal
- 153 diseases

154 We used the World Bank regions for the categorization of the study area.

156 2.4 Thematic analysis of pathways

157 In the thematic analysis (Gale et al., 2013; Levy et al., 2016), the focus was on extracting
158 pathways from exposures to tropical cyclones to diarrheal diseases. The analysis began with a
159 full-text review of included articles to gain a comprehensive understanding of their content and
160 then extract relevant information about transmission mechanisms or pathways. Initially, an open
161 coding approach was employed, encompassing various perspectives such as human behavior
162 (e.g., unsafe water handling practices), pathogen dispersion, and environmental factors (e.g.,
163 damage to water systems). These codes were then traced back to their underlying environmental
164 exposure causes, and then categorized into major themes.

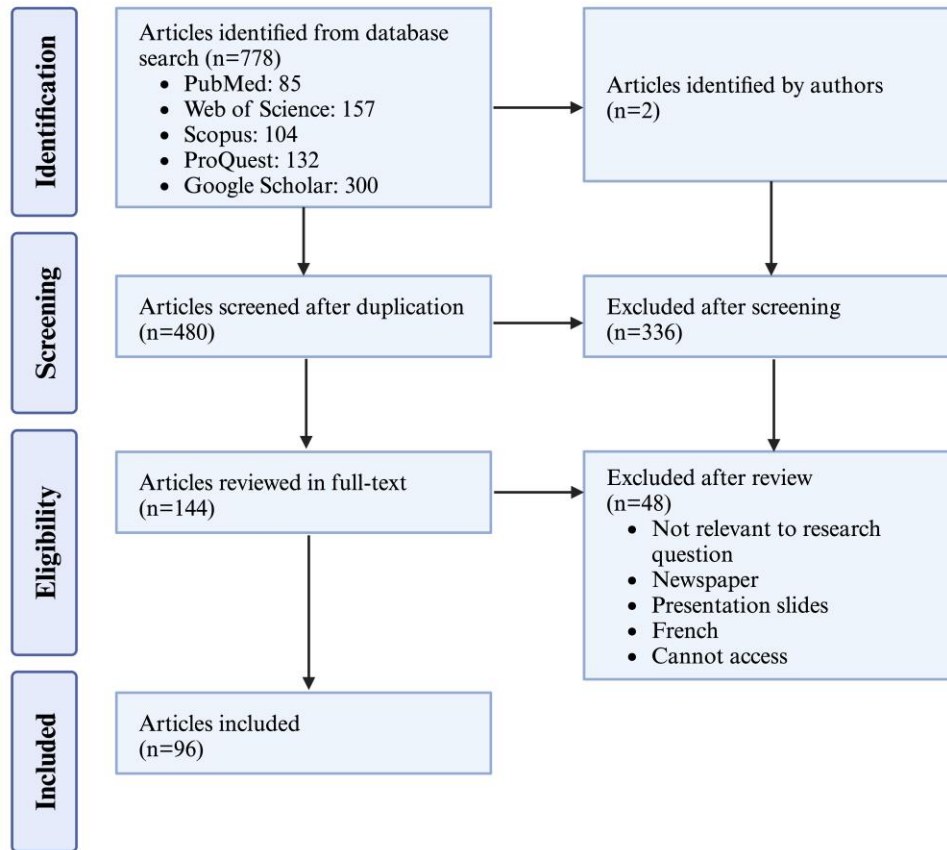
166 2.5 Quality assessment

167 In line with scoping review guidelines, study quality or formal risk of bias was not
168 assessed nor used as a basis for study exclusion (Peters et al., 2015; Tricco et al., 2018).

170 2.6 Ethical approval

171 We did not apply for ethical approval because this scoping review was confined to a
172 descriptive narrative analysis of publicly available studies and gray literature. This scoping
173 review protocol is registered in the Open Science Framework at <https://osf.io/qmnft/>

174 3 Results



175 **Figure 1. Flow chart of selected studies.**

176 3.1 Review of studies

177 A total of 778 records were retrieved through database searches supplemented by two published articles known to the authors. Figure 1 shows the PRISMA flow diagram. After removing duplicates, 480 records underwent title and abstract screening, leading to the exclusion of 336 records. Full-text review was conducted on 144 records, resulting in the exclusion of 48 records. Finally, 96 studies were included. See supplementary table 1–3 in Supporting Information.

185 **Table 1. Descriptive characteristics of selected studies (N=96).**

	Num. of studies	(%)
Publication Type		
Journal publication	81	(84.4)
<i>Research</i>	52	(64.2)
<i>Review</i>	15	(18.5)
<i>Others</i>	14	(17.3)
Gray literature	15	(15.6)

Study Region

East Asia and the Pacific	22	(22.9)
Latin America and the Caribbean	10	(10.4)
Middle East and North Africa	1	(1.0)
North America	26	(27.1)
South Asia	18	(18.8)
Sub-Saharan Africa	5	(5.2)
Not region specific	14	(14.6)

Study Population

All population	73	(76.0)
Children	15	(15.6)
Elderly	4	(4.2)
Evacuee & relief worker	10	(10.4)
Others	6	(6.3)

Most of the studies (84.4%) were published in scientific journals, while others (15.6%) were gray literature, including government reports, conference abstracts, and student theses (Table 1). The published subset further breaks down as original research studies (64.2%), reviews (18.5%), and other publication types (17.3%), such as letters to the editor and technical reports. North America and the East Asia and the Pacific region were the main study areas where the studies were conducted (27.1% and 22.9%, respectively). Most studies examine the entire populations (76%), while others either also examine or solely focus on specific subgroups (24%).

Table 2. Outcome variable in the epidemiological studies (N=23).

	Num. of studies	(%)
TC Event		
Single	14	(60.9)
Multiple	9	(39.1)
Exposure Definition		
Event based	15	(65.2)
Wind speed	4	(17.4)
Flooding	2	(8.7)
Rainfall	1	(4.3)
Health Outcome		
Surveillance	10	(43.5)
Healthcare facility visits	7	(30.4)

Hospital admission	4	(17.4)
Self-report survey	3	(13.0)
Multiple outcomes	1	(4.3)

Pathogen

<i>All-cause (not pathogen-specific)</i>	16	(69.6)
<i>Pathogen-specific (including one or more pathogen)</i>	7	(30.4)

Study Design

Pre-post comparison	14	(60.9)
Interrupted time series /difference-in-difference	5	(21.7)
Case-crossover	4	(17.4)

Direction of Association

Positive	12	(52.2)
Mixed	6	(26.1)
Negative	2	(8.7)
Not significant	3	(13.0)

Among original research studies, we identified 23 epidemiological studies that satisfy the criteria of having a clear study objective of quantifying the association between tropical cyclones and diarrheal diseases for further analysis. Sixty percent of these studies analyzed a single tropical cyclone event, while the rest examined the impact of multiple tropical cyclones (Table 2). In single tropical cyclone studies, three investigations assessed the impact of Typhoon Haiyan on diarrheal diseases in the Philippines. Among the studies examining multiple tropical cyclones, 77.8% analyzed approximately 10 years of data, while 22.2% utilized more than 20 years of data. Most of the epidemiological studies defined tropical cyclone exposure as an event with a fixed timeframe (65.2%), while the others defined it based on maximum wind speed (17.4%), flooding event (8.7%), and amount of rainfall (4.3%). Only one study explored a multi-criteria approach by combining the amount of rainfall, strength of wind speed, distance from tropical cyclones, and proportion of affected population.

Almost half of the epidemiological studies (43.5%) analyzed cases of diarrheal diseases reported from existing surveillance systems, while the others analyzed cases from healthcare facility visits (30.4%), and self-report surveys (13.0%) (Table 2). Sixty-nine percent of studies analyzed all-cause diarrheal diseases. For pathogen-specific studies, *Shigellosis* stands out as the most studied diarrheal disease, with three studies, followed by cholera and typhoid, each having two studies. Other studied diseases were paratyphoid fever, non-typhoidal *Salmonellosis*, *E. coli* infection, *Giardiasis*, and *Cryptosporidiosis*.

The pre-post comparison without controlling for any time-varying factors is the most frequently utilized study design (60.9%). Other study designs included interrupted time series

221 and differences-in-difference (21.7%), which incorporated time-varying factors and control
222 groups, while the remaining 17.4% utilized a case-crossover design. Half of the epidemiological
223 studies (52.2%) showed positive associations, revealing an increase in diarrheal disease risk
224 associated with tropical cyclones. Meanwhile, 8.7% of the studies reported negative outcomes,
225 indicating a decrease in diarrheal diseases following tropical cyclones. Twenty-six percent
226 presented mixed results, suggesting a nuanced relationship involving both positive and negative
227 associations depending on the subgroups or days after the tropical cyclone.

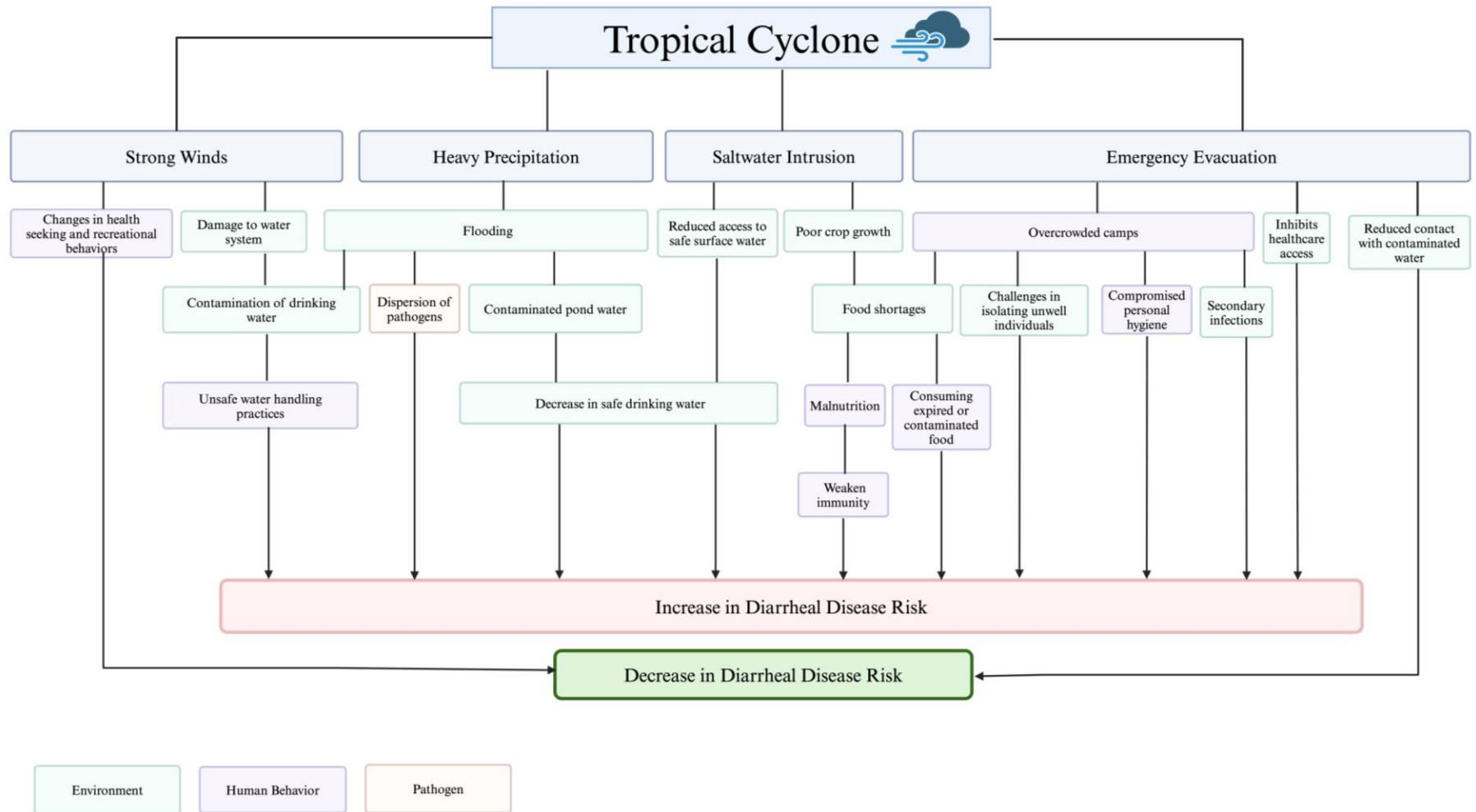


Figure 2. Transmission pathways for tropical cyclone to diarrheal diseases.

3.2 Review of transmission pathways

Figure 2 illustrates all the potential pathways that connect tropical cyclones to the risk of diarrheal diseases mentioned in the articles selected for scoping review. The main themes encompass factors directly induced by a tropical cyclone, including strong winds, heavy precipitation, saltwater intrusion, and emergency evacuation. Saltwater intrusion refers to the infiltration of saline water into freshwater reservoirs, such as estuaries and underground aquifers, resulting in elevated salinity levels that can degrade groundwater quality and impact drinking water sources (Yang et al., 2023). Sub-themes depict the effects generated by the main themes. They are categorized by their causes, environment, human behavior, or pathogen, each represented by a distinct color.

Strong winds and heavy precipitation - Tropical cyclones, characterized by strong winds and heavy precipitation, could cause **damage to water systems** leading to the **contamination of drinking water**. Breaches in water pipelines especially after restoration efforts, have been identified as contributing factors to these challenges. Municipal water systems have been suggested as likely sources of contaminated water. The combination of water contamination and **unsafe water handling practices**, such as the failure to boil or chlorinate drinking water, contributes to the consumption of contaminated water.

Flooding - Heavy precipitation leads to flooding which could cause **contamination of drinking water** pollution and facilitate the **dispersion of pathogens** from excreta in soil to surface. Limited access to tube wells during floods intensifies dependence on **contaminated pond water**, leading to a decrease in safe drinking water contributing to disease transmission.

Saltwater intrusion - Tropical cyclones contribute to saltwater intrusion in coastal regions, contaminating water sources vital for drinking and household use. In coastal Bangladesh, this intrusion significantly **reduces access to safe surface water**. Salinity heavily impacts local water sources like rivers, canals, ponds, and wetlands, causing a decrease in safe drinking water. Consequently, communities must travel long distances in search of relatively safe water alternatives, often finding dirty, turbid, and odorous sources. This situation increases the prevalence of waterborne diseases, particularly diarrhea. Additionally, saltwater intrusion causes **poor crop growth**, leading to food shortages and exacerbating **malnutrition** among affected populations. With **weakened immunity** due to food scarcity, these communities become more vulnerable to diarrheal diseases, compounding their already precarious situation.

Emergency evacuation - Numerous studies have identified emergency evacuation as a significant factor contributing to the rise in diarrheal diseases following tropical cyclones, as it not only **inhibits healthcare access** but also leads to **overcrowded camps**. In these settings, individuals grapple with poor ventilation, insufficiently equipped lavatories, and compromised water supplies, resulting in **compromised personal hygiene**. Additionally, the cramped conditions pose **challenges in isolating unwell individuals** due to space constraints. Even if isolation were possible, maintaining it becomes increasingly tough as time passes, given the emotional strain on displaced family members confronting separation due to illnesses. Moreover, there's a noted risk of **secondary infections** among relief workers, healthcare professionals, police officers, and volunteers who had direct contact with patients. Furthermore, overcrowded camps often experience **food shortages**, prompting individuals to resort to **consuming expired or contaminated food**, which can lead to diarrheal diseases.

Counterarguments – A few studies suggested ways in which tropical cyclones could decrease the risk of diarrheal diseases. For example, the storms causing emergency evacuation could **reduce people's contact with contaminated water**. Additionally, strong storms could prompt **changes in health-seeking and recreational behaviors**. During strong winds, people often refrain from seeking treatment, which could lead to underreporting of diarrheal cases. Similarly, during storm weeks, individuals tend to avoid recreational waters like swimming pools and rivers, thereby decreasing the transmission of *Giardia*.

4 Discussion

This scoping review examined the relationship between tropical cyclones and diarrheal diseases, with a specific emphasis on epidemiological studies and transmission pathways. We found valuable insights into several key aspects, including the region of the study, the definition of exposure and outcomes, and the study design employed to investigate the effect of tropical cyclones on diarrheal diseases.

4.1 Study area and population

East Asia and the Pacific and North America are the most studied regions given that they receive the greatest number of tropical cyclones annually and have considerable populations affected. The United States of America, Bangladesh, and the Philippines are the most studied countries. Some low- and middle-income countries that have considerable diarrheal diseases incidence (Troeger et al., 2020) and are affected by tropical cyclones without any study are Madagascar, Belize, Mexico, and Vietnam. Moreover, only a few studies have considered vulnerable subpopulations like children and displaced individuals/households. Future studies would benefit from expanding to other vulnerable locations and subpopulations for more targeted policies and disaster risk and management efforts.

4.2 Outcome variables

The variability in defining diarrheal diseases across studies is notable, with some relying on self-reported symptoms (Rath et al., 2002; Loebach et al., 2019; Simeon et al., 1993), while others utilize International Classification of Diseases (ICD) codes (Van Loenhout et al., 2018; Quist et al., 2022; Kim et al., 2013), or national definitions (Kang et al., 2015; Deng et al., 2015). Studies that identify cases through self-reported surveys may be subject to recall bias or misinterpretation of symptoms, potentially resulting in less reliable data compared to cases identified through professional examination. Moreover, the lack of specificity in reporting the specific ICD codes used in some studies adds to the variability and vagueness in defining diarrheal diseases, further hindering the direct comparability of findings across studies (Huang et al., 2023).

Among pathogen-specific studies, the majority have focused on bacteria, with a smaller number addressing viral pathogens (Gaither et al., 2015; Morantz, 2005; CDC, 2015), and only one paper specifically examined protozoa such as *Cryptosporidium* and *Giardia* (Setzer et al., 2004). No epidemiological studies have investigated diarrheal disease mortality in relation to tropical cyclones.

Future studies could benefit from the use of surveillance and electronic health records, where available, as cases would have been assessed and diagnosed by medical practitioners.

Conducting pathogen-specific analysis would also be useful to identify which pathogens spread considerably following typhoon cyclones.

4.3 Exposure variables

Our review revealed substantial variability in exposure definitions across multiple cyclone studies, encompassing variables such as wind speed, precipitation, event-based parameters, or a combination of variables. Four studies that used wind speed as an exposure metric relied on weather station data obtained from national meteorological agencies (Kim et al., 2013; Kang et al., 2015; Deng et al., 2015; Chen et al., 2022). However, relying on weather station data instead of satellite data is constrained by the fact that the weather stations may not directly experience the maximum wind speeds generated by tropical cyclones. The winds experienced in a location of interest cannot always be accurately measured by a weather station, especially if it is located far from the cyclone's path. Additionally, the occasional destruction of observational equipment due to extreme wind speeds further poses a limitation in obtaining accurate and complete information (Fang et al., 2022).

Event-based approaches often oversimplify the effects of tropical cyclones experienced by populations across various locations. This is primarily because such approaches fail to account for the diverse impacts of wind and precipitation in different regions. A more effective solution could be a geospatial analysis, which would provide a more comprehensive understanding of the localized impacts of cyclones. Additionally, relying on a single definition, such as solely considering rain or wind, may not capture the full impact of a tropical cyclone on diarrheal diseases. Lynch et al. (2023) addressed this challenge by categorizing exposure levels based on wind intensity, rainfall amount, and affected population, offering a potential solution to better understand the comprehensive impact of tropical cyclones.

4.4 Study design

Most studies utilized a pre-post comparison, which is a rapid and convenient method to evaluate the effect of a major event on an outcome. However, this method typically lacks randomization and a control group, resulting in limitations that affect internal validity. First is the arbitrary selection of pre and post timeframe. For example, three studies (Van Loenhout et al., 2018; Salazar et al., 2017; Chang et al., 2016), which analyzed the impacts of typhoon Haiyan on diarrheal diseases in the same province, selected timeframes lasting one week, six weeks, or two months before and after the date of typhoon landfall. Varying timeframes can yield different findings, as the transmission of diarrheal diseases takes time to establish and peak. It is crucial to consider the health system and socioeconomic conditions of the study location when selecting appropriate timeframes and lag structures. Second is the lack of consideration for interannual trend, seasonality, and other confounders like rainfall and flooding. These temporal and time-varying parameters can affect the results, especially in time series analysis and longer pre-post timeframes.

To address certain limitations, using advanced designs such as difference-in-difference (Rothbard et al., 2023) or controlled interrupted time series (Milojevic et al., 2012) can provide more robust measurements of the association between tropical cyclone events and diarrheal diseases. These designs incorporate control groups, temporal confounders, and lag effects. Our scoping review showed that more recent studies have begun to adopt these designs (Quist et al.,

2022; Ramesh et al., 2022). However, it is important to note that these designs are limited to analysing the effects of individual tropical cyclone event.

In regions prone to frequent tropical cyclones, measuring the health impact of multiple tropical cyclone events would be important. This can be accomplished using the case-crossover design, which functions as a self-controlled study design where each case serves as its own control. Our review identified several studies that applied this approach, utilizing either unidirectional, bidirectional, or time-stratified designs (refer to Supporting Information Table 3). Studies employing the unidirectional design typically select the days before the case period as the control period, but the approach is subject to biases because of non-independent selection of controls, as well as biases associated with trends and seasonal patterns in the exposure (Janes, 2005). The time-stratified design eliminates these biases by allowing the referent control periods from both directions, while restricted to the same day-of-week, month and year, thus, accounting for trends, seasonality, and other time-varying confounders by design (Tobias et al. 2024).

Future studies investigating the relationship between tropical cyclones and diarrheal diseases should carefully consider the selection of study designs, especially when using time series data from surveillance systems or electronic health records. A thorough review of the characteristics of the tropical cyclone exposure, diarrheal diseases, spatiotemporal dimensions, and socioeconomic conditions is essential to guide the selection to the most appropriate study design and analytical approach.

4.5 Transmission pathways

The rise of diarrheal diseases during tropical cyclones is broadly attributed to heavy rainfall and flooding, which lead to serious safety risks and disruptions to water and sanitation services. Specifically, water contamination or drinking water with poor quality from these disruptions lead to diarrheal diseases outbreaks. Also, the intrusion of saltwater to drinking water exacerbates the conditions post-tropical cyclones. Moreover, displacement in shelters with poor conditions like overcrowding and unsafe sanitation facilities could also lead to outbreaks of diarrheal diseases.

However, the suggested transmission pathways generally lack specific explanations regarding the mechanisms through which tropical cyclones impact diarrheal diseases. Fieldwork studies are crucial in enhancing our understanding of the intricate relationship between tropical cyclones and diarrheal diseases, offering valuable insights for policymakers to target interventions more effectively. Specifically, conducting fieldwork in various locations, including both low-income and high-income areas, allows for a deeper exploration of location-specific intricacies and their impact on the relationship between tropical cyclones and diarrheal diseases.

5 Conclusions

Tropical cyclones pose a significant natural disaster, impacting human health by exacerbating climate-sensitive diarrheal diseases. However, existing studies lack a unified definition of outcomes, exposures, and methodologies, hindering the comparability of results. Moreover, dedicated research on the transmission mechanisms is crucial to comprehending the complexity of how tropical cyclones influence the risk of diarrheal diseases.

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