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Comparative Assessment of Environmental Determinants and Seasonal Patterns of Major Infectious Disease Outbreaks in India

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Abstract:

Comparative evidence of the influence of climatic variability and transition seasons on persistence of pathogens, vector ecology, environmental contamination, and exposure of populations is scarce for numerous infectious diseases in India. This study compared the epidemiological characteristics, environmental determinants, and seasonal patterns of major infectious disease outbreaks in India and identified disease-specific associations with outbreak case counts. A retrospective observational analysis was conducted using weekly district-level outbreak records for acute diarrhoeal disease, dengue, chikungunya, cholera, and malaria. Descriptive statistics summarized outbreak burden, geographic coverage, climatic conditions, and seasonality. Kruskal–Wallis tests evaluated differences in temperature, precipitation, and Leaf Area Index across diseases, while disease-specific multivariable negative binomial regression models estimated adjusted incidence rate ratios with 95% confidence intervals. The analysis included 8,679 outbreak records representing 779,693 reported cases across 782 districts. Acute diarrhoeal disease exhibited the largest outbreak burden and widest geographic distribution. Monsoon was the predominant season for all diseases, accounting for 42.0%-61.7% of outbreaks. Significant differences in temperature, precipitation, and Leaf Area Index were observed among diseases ($P<0.001$). Dengue showed a strong positive association with precipitation, whereas higher Leaf Area Index was associated with lower dengue incidence. Acute diarrhoeal disease, chikungunya, and cholera demonstrated distinct seasonal and environmental relationships. The results suggest that different major disease types in India are sensitive to climate, underscoring the need for climate-informed infectious disease surveillance to enhance preparedness for outbreak response, early warning systems and targeted public health interventions.

Keywords: infectious disease outbreaks, climate variability, seasonality, environmental determinants, public health

1.Introduction

Although significant progress has been made in the global prevention, surveillance and health services delivery of infectious diseases, they continue to be one of the major drivers of morbidity, mortality and socio-economic disruption globally. The recurrent and recurring outbreaks have heightened the understanding of the intricate interplay among pathogens, people and environmental shifts. Many infectious diseases have been geographically re-distributed, intensified and altered in their seasonal dynamics by global environmental change, posing new health challenges for the management of health systems and disease control strategies (Baker et al., 2022). The Global Burden of Disease Study (GBD) conducted in recent years shows that infectious diseases remain a major health burden in various populations, especially in low- and middle-income countries where environmental vulnerability and inequities in health services are still high (Murray, 2024). In spite of significant advances during the last few decades in controlling the impact of some communicable diseases, infectious diseases remain a significant source of DALYs and early death around the world. Demographic change, urbanization, environmental degradation and climatic change have affected disease transmission patterns, and these patterns need to be monitored and responded to adaptively in public health practice (Vos et al., 2020). Viral infectious diseases, especially, still continue to be a significant public health problem because of their widespread distribution, repeated outbreaks and increasing environmental sensitivity, which calls for an improvement of their epidemiological assessment in various climatic conditions (Li et al., 2024). Infectious agents, vectors and intermediate hosts are greatly affected by their environment in terms of survival, reproduction and transmission. Pathogen persistence, vector abundance, human exposure and ecological interactions are all influenced by temperature, rainfall, vegetation dynamics, and all contribute to determining outbreak occurrence. Climate variability is growing in intensity, necessitating a greater need to comprehend these environmental determinants to support surveillance systems and public health interventions that are adapted to climate change (Uwishema et al., 2023). A series of infectious diseases have also emerged or re-emerged thanks to climatic changes, which have changed ecological conditions that support the persistence and transmission of pathogens, thereby complicating disease prevention and control (El-Sayed & Kamel, 2020).

There is increasing evidence that climatic variability can affect the dynamics of infectious diseases in a number of biological and ecological ways. The influences of temperature on pathogen replication, vector development, and host susceptibility and of precipitation upon water quality, breeding habitats and environmental contamination are the ones that are worth considering. Along with changes in vegetation cover, changes in vegetation type also affect vector ecology and suitability for habitat, thereby affecting spatial variation in disease transmission. The interplay of these environmental processes has raised interest in incorporating climatic information in infectious disease surveillance and outbreak forecasting (Semenza et al., 2022). The fact that environmental exposure is a key factor in the occurrence of food-borne and water-borne diseases has been identified, especially in areas with high rates of climate change and poor environmental infrastructure. Changes in the rainfall pattern, floods and water availability can significantly affect the transmission dynamics of pathogens, necessitating the need for integrated environmental surveillance systems for supporting timely public health response (Cissé, 2019).

Earlier studies have shown many links between individual infectious diseases and ecological factors. Climatic drivers have been associated with fluctuations in disease vectors (e.g., dengue and Malaria) and disease vectors (e.g. cholera and acute diarrhoeal disease) that transmit these diseases. However, the intensity and direction of these interactions often vary with the biology and ecology of the pathogen, geographic location, and season, and generalizations are not easy to make. Thus, the importance of knowing these responses for each disease cannot be overstated and is a key goal of epidemiological studies (Metcalf et al., 2017). Other factors associated with weather variability have also been identified as playing a significant role in the occurrence of infectious diseases, including effects on vector ecology, environmental contamination and host exposure. These findings highlight the need for environmental factors to be used in disease surveillance along with traditional epidemiological monitoring to enhance the ability to forecast outbreaks and be prepared for them (Polgreen & Polgreen, 2018). More recently, studies on the impact of extreme climatic events have revealed evidence of multiple parallel outbreaks of various infectious diseases, more often than not, rather than single health events, thus emphasizing the need for comparative epidemiological research at the cross-cutting level of various disease groups (Alcayna et al., 2022).

Studies available at present have shown the significance of the role played by environmental and seasonal factors in the spread of an infectious disease, but the majority of investigations have been carried out with respect to individual diseases and have been based upon disease-specific analytical methods. Few efforts have been made to focus on comparative analyses of several major infectious diseases and provide consideration of the common climatic indicators and of seasonal variability in a single analytical framework. As a result, the understanding of common environmental factors and differences between diseases is still limited, which hinders the ability to develop integrated public health surveillance strategies for climate and disease. Filling this gap can enhance the ability to predict outbreaks, allocate resources, and aid in evidence-based preparedness planning in various epidemiological contexts in India.

The present study intended to comparatively analyze the environmental determinants and seasonal trends of major outbreaks of infectious diseases in India by examining the epidemiological characteristics of the outbreaks; to explore the inter-disease climatic differences; and to assess the inter-disease relationships between environmental factors, seasonal variation and outbreak case counts using multivariable statistical modelling.

2. Methodology

2.1 Research Design

A retrospective observational analytical study was conducted, with an aim to study the environmental determinants and the seasonal trend of major outbreaks of infectious diseases in India. The variations in outbreak characteristics between acute diarrhoeal disease, dengue, chikungunya, cholera and malaria were analyzed using a comparative epidemiological framework. Outbreak distributions and climatic parameters were summarized using descriptive statistical methods, and differences in climatic parameters were assessed using inferential statistical methods, with disease-specific associations between climatic variables and outbreak case counts quantified.

2.2 Data Source

This study was conducted on a publicly available climate–health surveillance dataset that was built for GeoHealth research by linking epidemiological data with environmental data in Indian districts. The standardized weekly outbreak data are accompanied by the data for the various climatic indicators, which allows for the assessment of the spatial, temporal and climatic influences on infectious disease occurrence. The data were gathered from the public data repository mentioned by Kaur et al. (2024).

2.3 Study Variables

The primary outcome variable was number of outbreak cases reported for each disease. Diseases covered were Acute diarrhoeal disease, Dengue, Chikungunya, Cholera and Malaria. To test the temporal and seasonal effects, environmental predictor variables were temperature, precipitation, and Leaf Area Index (LAI) along with the seasons (winter, pre-monsoon, monsoon, and post-monsoon) and calendar year. Spatial distribution of outbreaks was characterized by geographic information, namely, district and State/Union Territory.

2.4 Data Preparation

The data set was checked prior to analysis for completeness, consistency, and duplicates. Disease names, seasons and geographic identifiers were standardized to provide consistent classification of the observations. Climatic variables were kept on the same measurement scale as they were originally taken and data that had missing values in some of the variables used for analysis were excluded as appropriate. Records of outbreaks and environmental characteristics were the final analytical dataset selected for the five infectious diseases.

2.5 Statistical Analysis

Outbreak frequency, reported case counts, geographical coverage, climatic characteristics and seasonal distribution were summarized using descriptive statistics. Data for continuous variables were non-normally distributed and presented as medians (IQR). The Kruskal-Wallis test was used to compare differences in temperature, precipitation and Leaf Area Index among the diseases.

The annual occurrence of outbreaks and seasonal outbreak distributions were graphed to assess temporal trends in the distribution of outbreaks over the study period. Disease-specific multivariable negative binomial regression models were fitted with the number of reported outbreak cases as the outcome and temperature, precipitation, Leaf Area Index, season, and calendar year as predictors. For each predictor, the incidence rate ratios (IRRs) were estimated with 95% confidence intervals (CIs). A p-value of <0.05 was considered statistically significant (two-sided).

3. Results

3.1 Epidemiological Characteristics of Infectious Disease Outbreaks

The epidemiological parameters of the five major epidemically active diseases considered in the analysis are given in Table 1. A total of 8,679 outbreak records representing 779,693 reported cases were identified across 782 districts in 36 States and Union Territories. The highest number of outbreaks (5,119) were reported for acute diarrhoeal disease, followed by dengue (1,619), chikungunya (731), cholera (666), and malaria (544). The highest cumulative number was reported with acute diarrhoeal disease (250,748), while chikungunya contributed the least (53,289). There was moderate variation in median outbreak size between diseases (between 23 and 35 cases). The extent of geographical coverage was large for acute diarrhoeal disease and dengue, and was comparatively low for chikungunya, cholera and malaria.

Table 1. Dataset and Epidemiological Characteristics

Disease	Outbreak records (n)	Total reported cases	Median cases per outbreak (IQR)	Geographical coverage
Acute Diarrhoeal Disease	5,119	250,748	28.0 (16.0–52.0)	35 States/UTs; 684 districts
Dengue	1,619	238,044	23.0 (13.0–51.0)	34 States/UTs; 344 districts
Chikungunya	731	53,289	25.0 (15.0–44.0)	21 States/UTs; 195 districts
Cholera	666	126,495	35.0 (15.2–78.8)	25 States/UTs; 208 districts
Malaria	544	111,117	35.0 (14.0–86.2)	24 States/UTs; 199 districts
Overall	8,679	779,693	27.0 (15.0–54.0)	36 States/UTs; 782 districts

The distribution of outbreak-associated temperatures for each disease is shown in Figure 1A. There were variations in the amount of precipitation recorded during outbreaks, as indicated in Figure 1B. The distribution of Leaf Area Index values related to outbreak events is presented in Figure 1C. Climatic distributions showed a distinct variation in diseases. The outbreaks of chikungunya were more common under the highest levels of temperature, while the outbreaks of malaria and cholera were associated with comparatively lower levels of median temperatures. The precipitation variability was highest for cholera, and chikungunya was mostly found under relatively dry conditions. Malaria and dengue had generally higher Leaf Area Index values, indicating that outbreaks were common in areas of denser vegetation, while chikungunya had comparatively lower Leaf Area Index value indicating less vegetation in the places of outbreaks.

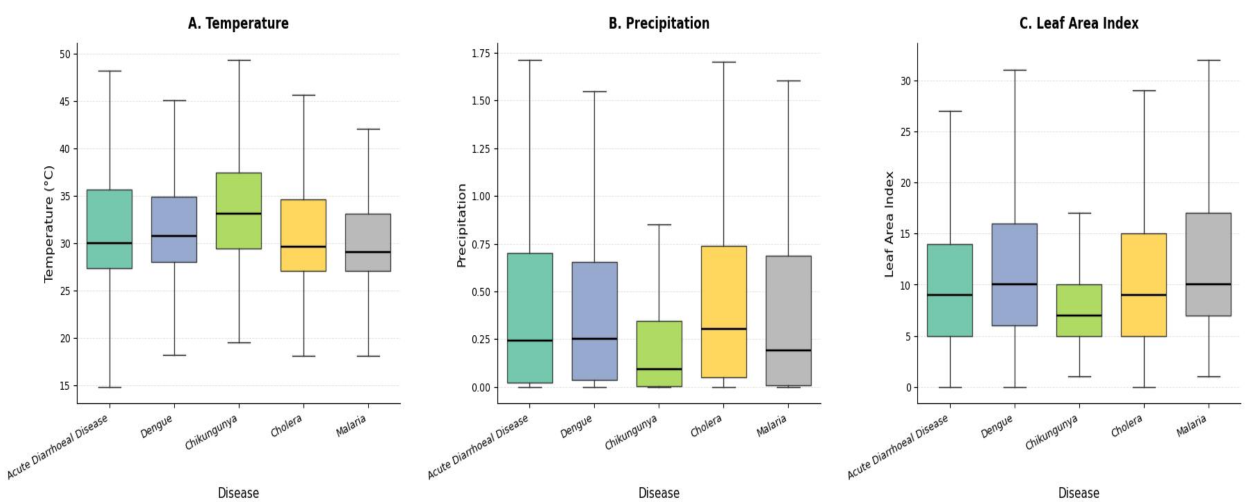

Figure 1. Climate Profiles of Major Infectious Disease Outbreaks. (A) Distribution of temperature across infectious disease outbreaks. (B) Distribution of precipitation across infectious disease outbreaks. (C) Distribution of Leaf Area Index across infectious disease outbreaks

3.2 Climatic and Seasonal Characteristics of Outbreaks

The climatic conditions and seasonality by disease are summarized in Table 2. In all the diseases, the monsoon season was the major season for transmission, as it ranged between 42.0% and 61.7% of the outbreaks recorded. Chikungunya had the highest median temperature of the outbreaks (33.1°C), while the highest median precipitation was for the cholera outbreak (0.30). The results of Kruskal–Wallis testing showed that all the variables (temperature, precipitation and Leaf Area Index (LAI)) differed significantly between diseases (all $P < 0.001$), which supports the hypothesis of different environmental profiles for the different outbreak types.

Table 2. Climatic and Seasonal Profiles of Major Infectious Disease Outbreaks

Disease	Temperature, median (IQR), °C	Precipitation, median (IQR)	Leaf Area Index, median (IQR)	Dominant season
Acute Diarrhoeal Disease	30.0 (27.3–35.7)	0.24 (0.02–0.70)	9.0 (5.0–14.0)	Monsoon (54.6%)
Dengue	30.8 (28.0–34.8)	0.25 (0.04–0.65)	10.0 (6.0–16.0)	Monsoon (51.7%)
Chikungunya	33.1 (29.4–37.4)	0.09 (0.00–0.35)	7.0 (5.0–10.0)	Monsoon (42.0%)
Cholera	29.7 (27.1–34.6)	0.30 (0.05–0.74)	9.0 (5.0–15.0)	Monsoon (61.7%)
Malaria	29.0 (27.0–33.1)	0.19 (0.01–0.69)	10.0 (7.0–17.0)	Monsoon (52.2%)

The annual trends of outbreaks for each disease are illustrated in Figure 2A from 2009 to 2022. The proportional seasonal distribution of the outbreak records by disease is presented in Figure 2B. The timings were very different for each disease. Although the annual burden of acute diarrhoeal disease was found to be generally decreasing throughout the latter part of the study period, it remained the highest burden of any disease. Dengue and chikungunya showed significant variation from one year to the next, while the frequency of outbreaks of cholera and malaria was relatively constant and with very occasional epidemic peaks. Seasonal analysis showed that outbreaks of all five diseases were concentrated predominantly during the monsoon season, although outbreaks were also recorded during winter, pre-monsoon, and post-monsoon periods.

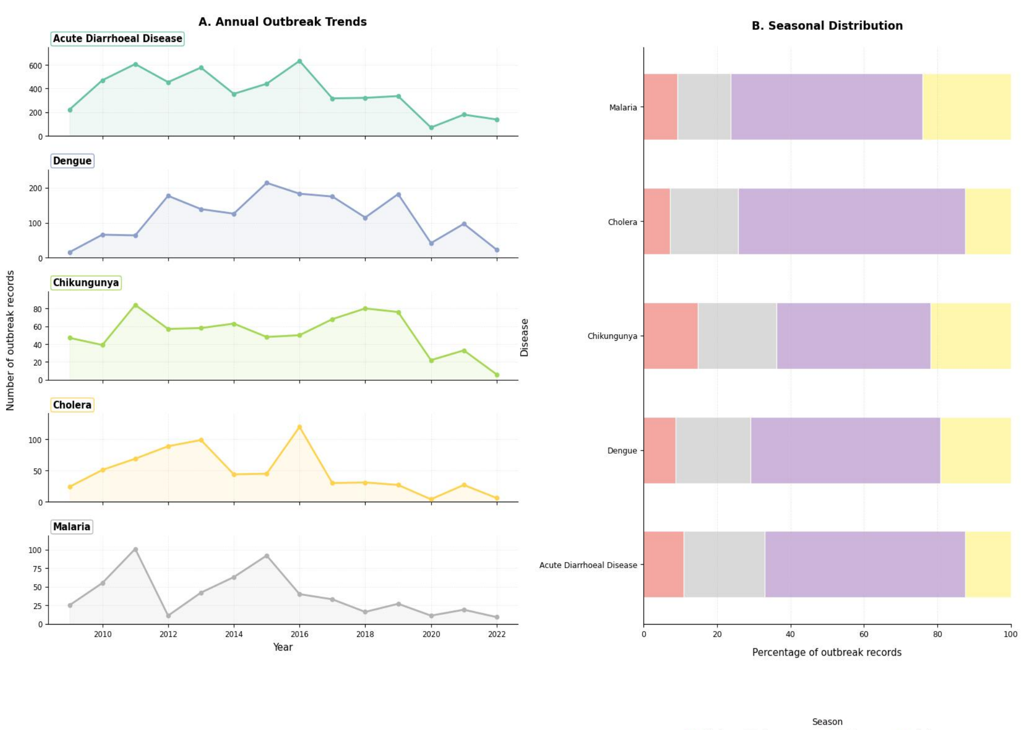

Figure 2. Temporal and Seasonal Epidemiological Patterns. (A) Annual outbreak trends for the five major infectious diseases from 2009–2022. (B) Percentage distribution of outbreak records across winter, pre-monsoon, monsoon, and post-monsoon seasons

3.3 Disease-Specific Environmental Associations

The multivariable negative binomial regression estimates assessing seasonal and environmental predictors of the number of outbreak cases are presented in Table 3. The incidence of acute diarrhoeal disease was significantly lower in the winter (adjusted IRR=0.832) and post-monsoon (adjusted IRR=0.801) seasons, and there was an inverse relationship between temperature and incidence (adjusted IRR=0.984; P=0.001). There was a strong positive association between Dengue and precipitation (adjusted IRR=2.085; P<0.001), with the higher the LAI values, the lower the incidence of Dengue outbreaks (adjusted IRR=0.970; P<0.001). Chikungunya showed significantly lower incidence during winter, whereas temperature and precipitation were not independently associated after adjustment, while cholera had an inverse relationship with these variables in successive calendar years and winter.

Table 3. Disease-Specific Multivariable Negative Binomial Regression

Disease	Significant predictor	Adjusted IRR (95% CI)	P-value
Acute Diarrhoeal Disease	Temperature	0.984 (0.975–0.994)	0.001
Acute Diarrhoeal Disease	Winter vs Monsoon	0.832 (0.697–0.993)	0.041
Acute Diarrhoeal Disease	Post-monsoon vs Monsoon	0.801 (0.669–0.961)	0.017
Dengue	Precipitation	2.085 (1.624–2.676)	<0.001
Dengue	Leaf Area Index	0.970 (0.955–0.985)	<0.001
Dengue	Pre-monsoon vs Monsoon	0.243 (0.135–0.439)	<0.001
Chikungunya	Winter vs Monsoon	0.552 (0.380–0.803)	0.002
Chikungunya	Calendar year	0.866 (0.828–0.906)	<0.001
Cholera	Winter vs Monsoon	0.267 (0.150–0.474)	<0.001
Cholera	Temperature	0.954 (0.913–0.997)	0.037
Cholera	Precipitation	0.486 (0.362–0.651)	<0.001

Adjusted incidence rate ratios and 95% confidence intervals for environmental predictors are presented in Figure 3. The forest plot shows adjusted incidence rate ratios and 95% CIs for each of the disease-specific negative binomial regression models for the three variables: temperature, precipitation, and Leaf Area Index. Associations marked: filled markers indicate statistically significant associations, open markers indicate non-significant associations, and the vertical dashed line indicates the null association (adjusted IRR = 1).

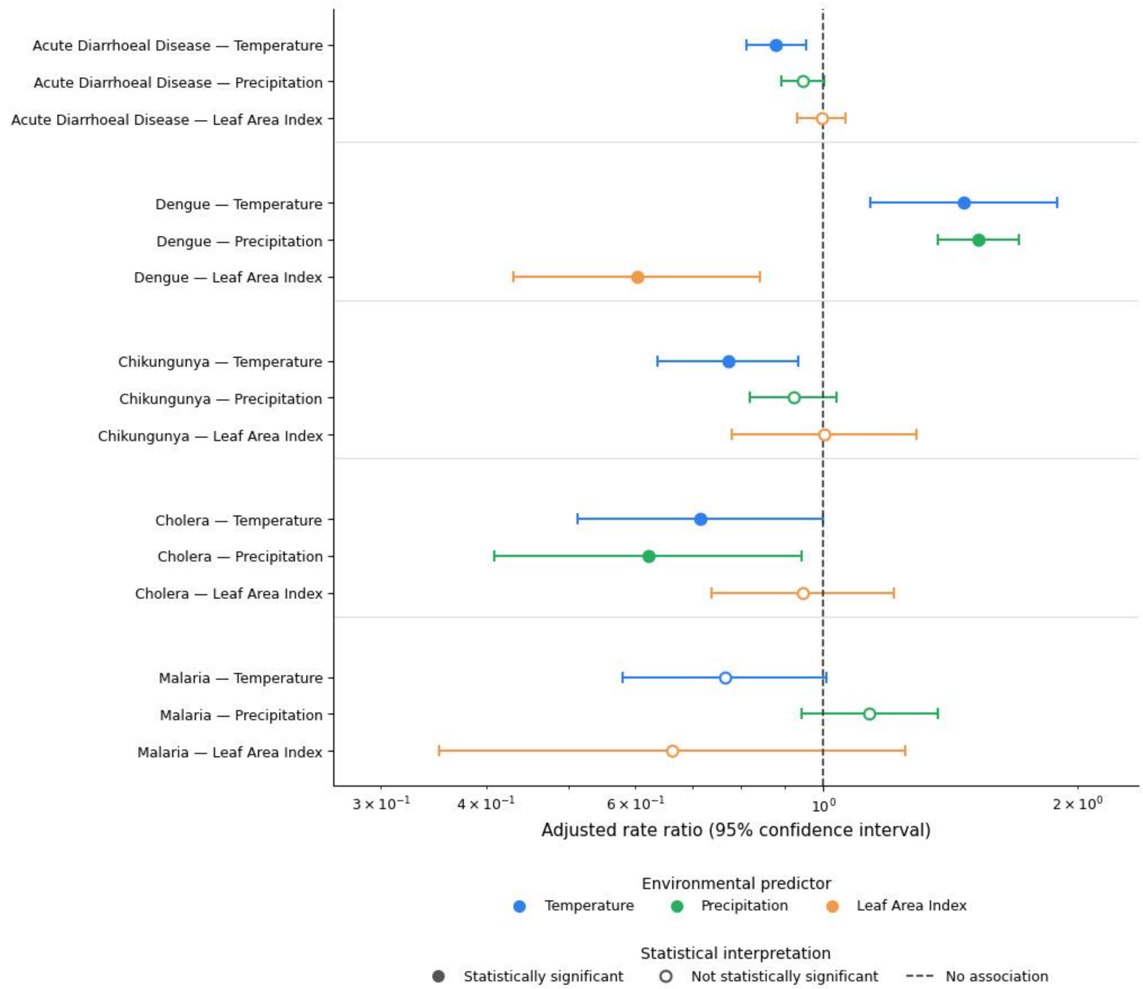

Figure 3. Adjusted Environmental Associations with Outbreak Case Counts.

4. Discussion

The results highlight that there is significant variability in the epidemiologic size, climatic characteristics, temporal clustering, and sensitivity to climate of major epidemics in India. The highest number of outbreak records and geographic distribution was seen with acute diarrhoeal disease, which suggests a high public health burden. Likewise, dengue had a similar number of reported cases, although not many dengue outbreak records were reported, indicating that individual dengue outbreaks may involve substantial numbers of cases and therefore produce considerable population-level effects. The median outbreak size of cholera and malaria was greater than that of dengue and chikungunya, but was geographically more localized. Patterns that are identified suggest that, when prioritizing surveillance and response, the frequency and outbreak size should be treated separately. However, environmental profiles were not the same for the different diseases. The outbreaks of chikungunya were linked to comparatively higher temperatures and drier conditions while outbreaks of malaria and dengue were linked to higher vegetation. The precipitation median was the highest for cholera and the monsoon concentration was the highest for cholera. There are also important differences in response by disease and environment as demonstrated by differences in temperature, precipitation, and Leaf Area Index, which indicate the presence of disease-specific ecological pathways to environmental exposure.

The occurrence of outbreaks was identified as being seasonal. The monsoon season was the most predominant season for all five diseases, with the relative contribution of monsoon varying. In acute diarrhoeal disease and cholera, the monsoon concentration was particularly high, as expected due to the impact of contamination of water and disruption of sanitation facilities. The monsoon predominance was observed for dengue and chikungunya, but their annual pattern was more irregular, which could be attributed to the interplay of vector ecology, climate and local transmission dynamics. A reduction in the number of outbreaks reported for some diseases each year could reflect a shift in surveillance and/or prevention, exposure, or reporting, and should not be interpreted as a consistent epidemiological decrease. Furthermore, the results of the regression analysis revealed that there were environmental associations of different magnitude and direction. The number of dengue outbreaks was significantly correlated with increased precipitation and the reduction of dengue was significantly correlated with increased Leaf Area Index. There were low-level inverse associations of acute diarrhoeal disease with temperature and calendar year, as well as fewer cases of the disease in the winter and post-monsoon seasons compared to the monsoon season. Temporal trends were downward for Chikungunya and it was low during the winter months. Climate patterns that are simple and descriptive, such as cholera being inversely related to winter, temperature and precipitation, were found to be different from patterns involving multivariable conditioning. Because of the lack of convergence, the malaria model could not be interpreted.

The majority of monsoon-associated outbreaks are consistent with studies that have shown that monsoon season in South Asia, associated with an increase in rainfall/humidity, floods, water contamination, and breeding conditions of vectors, is the ideal time for the spread of infectious diseases (Verma et al., 2025). Comparisons of epidemiology between regions have also revealed significant differences in the spread of infectious diseases, due to ecological differences, exposure of the hosts, movement, health infrastructure, and the intensity of surveillance (Sarkar, 2023). The large variation in climatic parameters between the diseases is congruent with the spatiotemporal analysis performed for different diseases at the Indian regional level, which revealed non-uniformity in the effects of environmental variables on various infectious disease categories (Kanagaraj & Vijayan, 2024). The positive correlation found here between precipitation and dengue also supports the findings of the study done in Dhaka, where the variability in the climate conditions affected the abundance of mosquitoes and dengue incidence by affecting the breeding conditions and the persistence of the vector (Islam et al., 2021). Consistent results from Brazil show that rain and temperature can influence the spread of dengue, though the impact and when it occurs vary by place and location (Xavier et al., 2021). The malaria patterns described here are parallel to patterns reported in other studies that have demonstrated that rainfall and temperature modulate the malaria transmission window, with the magnitude of their impacts differing between climatic regions (Yamba et al., 2023). Cross-country evidence has also indicated that malaria-climate associations vary in different regions and could shift based on the context of baseline endemicity, intervention coverage and environmental context (Wang et al., 2023). This is because the comparatively warm temperatures of chikungunya are biologically plausible due to the influence of temperature on mosquito development, viral replication, and transmission potential (Tjaden et al., 2017). Climate and vector ecology are also shown to have an impact on the timing and likelihood of outbreaks of dengue and chikungunya together, highlighting the importance of developing a broadened understanding of the combined role of climate and vector ecology on these disease outbreaks (Farooq et al., 2025). The cholera findings must be taken with a grain of salt. Based on the descriptive concentration during periods of monsoon rains, it's known that aquatic environments, disruptions in sanitation, and persistence of pathogens in response to climate are relevant. However, the modified inverse relationship with precipitation indicates that the temporal occurrence of precipitation, non-linearities, lags, and the presence of other environmental factors might alter this relationship at a local level. In the case of Vibrio, predictive risk is related to multiple interacting water (including salinity), ecosystem (including temperature), and climatic conditions, and not a single climatic variable (Brumfield et al., 2025).

The results indicate that rather than a generic seasonal warning system, disease-specific warning systems for climate should be developed. Diarrhoeal disease, cholera, dengue, and even malaria should be emphasized in monsoon preparation, and warmer and drier seasons may also be important in the preparation for chikungunya. In addition to the usual epidemiological data, indicators of the environment should be integrated into the district-level early warning systems. Disease-specific climate thresholds could be harnessed for vector control, water quality monitoring, diagnostic preparedness, staffing and communicating risk to the public. The marked geographic and seasonal differences also lend a degree of support to the idea of resource allocation in more specific terms than general allocation of intervention.

There are a few limitations to be noted. The analysis was based on consistently reported outbreak data; completeness of the data at each site and each year is uncertain. The ecological design did not attempt to establish causes at an individual level and only selected environmental variables were investigated. Future study should address lagged, non-linear and interaction effects, as well as include other factors like humidity, flooding, sanitation, land use and population density, and validate disease-specific prediction models in different regions and over different time periods.

5. Conclusion

There is a definite difference in the burden of infectious diseases, climatic exposure and seasonality in India when major outbreaks occur. The maximum geographic distribution was observed for acute diarrhoeal disease, and a significant case burden was found for dengue, which was also significantly correlated with precipitation. Chikungunya was seen in a comparatively warmer season while decreasing in the winter season, while cholera was seen to have a pronounced monsoon concentration and had a distinct adjusted relationship with temperature and rainfall. In all five diseases, monsoon came out as the major season of outbreak, highlighting the importance of the seasonality of climatic variability in the transmission dynamics. The results reinforce the move away from a uniform approach to outbreak preparedness to a disease-specific, climate-informed approach. The incorporation of temperature, precipitation, vegetation indicators and seasonal timing into district-level monitoring may enhance early warning, resource targeting, readiness for timely vector control, water-quality surveillance, etc., and risk communication. These relationships should be further developed with lagged and non-linear modelling, more environmental covariates, and external validation in a wider range of areas in the future. Further development and external validation of these models could strengthen preparedness for climate-sensitive infectious diseases and support evidence-based public health decision-making in India.

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