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Research article

Identification of climate-sensitive disease incidences in vietnam: A longitudinal retrospective analysis of infectious disease rates between 2014 and 2022

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A R T I C L E I N F O

Keywords:
Infectious diseases
Climate change
Climate factors
Health policy

A B S T R A C T

Objective: There is a growing correlation between the rise in infectious diseases and climate change; however, little is known about the interactions and mixed effects of climate factors on infectious diseases.
Method: We conducted a retrospective longitudinal study spanning 108 consecutive months from 2014 to 2022 in Can Tho, Vietnam to identify common infectious diseases (excluding tuberculosis, HIV, and COVID-19) and their associations with climate change and determine which common diseases presented concurrently with the COVID-19 period using multivariate linear regression, receiver operating characteristic (ROC) curve analysis, Bayesian kernel machine regression (BKMR) and orthogonal partial least squares discriminant analysis.
Result: The five infectious diseases with the highest average incidence rates per 100,000 people were diarrhea; hand, foot, and mouth disease (HFMD); dengue fever; viral hepatitis; and influenza. Positive associations with humidity were observed for dengue fever and HFMD. Temperature was positively associated with malaria. Negative associations were found between humidity and both chickenpox and tetanus. Diarrhea (AUC = 0.79; 95 % CL = 0.70–0.87) and dengue fever (AUC = 0.74; 95 % CL = 0.62–0.83) emerged as the most influential diseases both before and during the COVID-19 period. In our BKMR analysis, we found a significant association between the combined influence of temperature and humidity and the occurrence of dengue fever and HFMD, especially when all climate factors were at or above their 60th percentile relative to their values at the 50th percentile. Temperature emerged as the primary driver associated with the occurrence of infectious diseases.

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Conclusion: These findings underscore the importance of implementing robust surveillance, prevention, and control measures by public health authorities in Can Tho. Initiatives like vaccination campaigns, vector control programs, public education on hygiene practices, and strengthening healthcare infrastructure are crucial for mitigating the spread of infectious diseases and safeguarding public health in the region.

1. Introduction

Over 30 novel infectious diseases have emerged or resurged in recent decades, posing significant challenges to public health [1]. Among these, the A/H1N1 influenza pandemic stands out for its staggering numbers of cases and fatalities [2]. The recurrent emergence of novel strains of microbial pathogens, including influenza A/H7N9, influenza A/H8N10, Nipah, Hendra, Marburg, Ebola, and MERS-CoV viruses, poses continual risks to global health and healthcare equity [3]. These pathogens serve as alarming indicators of the evolving landscape of infectious diseases, warranting heightened vigilance and preparedness measures on a global scale. The recent reemergence of infectious diseases like mpox, and the emergence of novel pathogens like SARS-CoV-2, further complicate the global health landscape [4–6]. This proliferation of emerging and reemerging infectious diseases drives an urgent need for coordinated efforts among nations and international organizations to address these evolving threats effectively.

Vietnam is currently experiencing a resurgence of multiple infectious diseases, including mpox and H9N2 [4,7], and has emerged as a "hot spot" with a heightened risk of novel zoonotic diseases and major health threats to the region [8]. Climate change poses global challenges in the 21st century, and Vietnam is particularly vulnerable to its effects [9]. Beyond its direct impacts, climate change engenders adverse effects on human health, livelihood, and community well-being, including increased mortality and injuries from natural disasters, warmer weather that facilitates the emergence of new diseases, heightened susceptibility to sudden death among older adults, and economic repercussions from rising sea levels and saltwater intrusion. Changes in rainfall patterns, sunshine duration, storms, and floods increase the cost of home reinforcement and repair and increase the incidence of infectious diseases. We anticipate a global proliferation of diseases closely linked to climate change, predominantly those endemic in tropical and subtropical regions, like malaria, meningitis, and dengue fever [10]. Climate change demands urgent proactive adaptation and mitigation strategies to protect communities, infrastructure, and health.

Can Tho, the largest city in Vietnam's Mekong Delta region, has witnessed the emergence of several infectious diseases in recent years [4]. This trend is unsurprising, given the city's population density, urbanization, and environmental factors that contribute to the transmission of infectious agents. The city's status as a major economic and transportation hub further heightens the risk of disease spread due to the influx of people and goods from diverse regions. Factors such as inadequate sanitation infrastructure, poor waste management, and close human proximity to livestock exacerbate the danger. The impacts of climate change, including shifts in temperature, rainfall patterns, sunshine duration, and humidity, can also create environments conducive to the proliferation of disease vectors, particularly mosquitoes. The global community has faced the most significant public health crisis in over a century with the COVID-19 pandemic [11]. Given the endemic nature of COVID-19, it is crucial to identify infectious diseases that may occur simultaneously with COVID-19 and to understand how climate factors influence their prevalence. In this study, we aim to 1) examine the relationship between climate change and infectious diseases in Can Tho City using cohort data from 2014 to 2022, and 2) analyze the presence of infectious diseases related to climate change both before and during the COVID-19 pandemic. By examining the relationship between climate variables and the incidence of infectious diseases, we can better understand the dynamics of disease transmission and develop strategies for effective infectious disease management, particularly in the context of the ongoing COVID-19 crisis.

2. Methods

2.1. Data collection

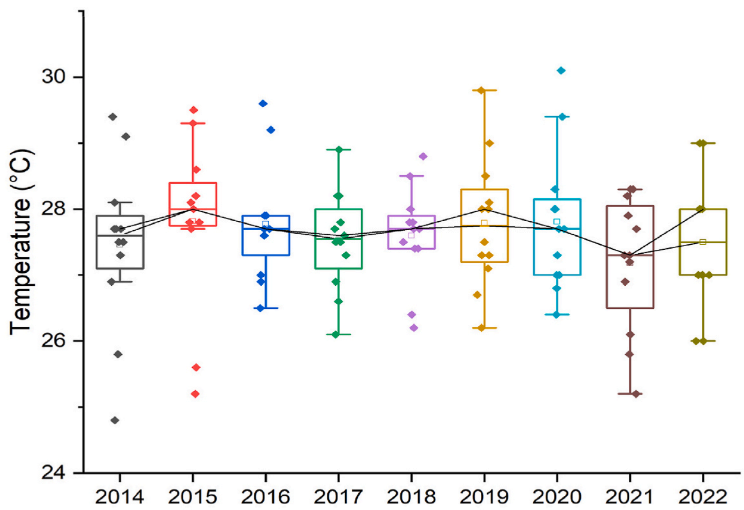
We examined the association between climate change and infectious diseases using a retrospective cohort dataset that included cases of infectious diseases and climatic factors spanning all months from 2014 to 2022 in Can Tho City, Vietnam. For this analysis, only records containing complete data on both infectious diseases and climatic factors throughout the entire period from 2014 to 2022 in Can Tho City were included. Records with missing data for two months or more within a given year were excluded. Months were considered to have missing data if any of the required variables (infectious diseases and climatic factors) were absent.

Meteorological and infectious disease data were obtained from the Can Tho City Statistical Yearbooks covering 2014–2022. Meteorological data primarily originated from the Can Tho Statistics Office and the Vietnam Institute of Meteorology, Hydrology, and Climate Change. The Vietnam Ministry of Health issued Circular 48/2010/TT-BYT on December 31, 2010, outlining the guidelines for the declaration, information, and reporting of infectious diseases. This circular established a comprehensive list of infectious diseases that clinicians were required to report. The Ministry then developed an infectious disease reporting system in accordance with Circular 54/2015/TT-BYT, adhering to guidelines for information reporting and declaration for infectious diseases. Deployed nationwide, the guidelines serve essential functions including statistical reporting, monitoring, and case management of 42 specified infectious diseases (Table S1). The system is critical in monitoring infectious diseases from initial suspicion to outbreak containment, providing timely and accurate reporting data. By facilitating statistical analysis of disease outbreaks, the system reduces manual workload and paperwork. In this study, infectious disease data were primarily sourced from the Vietnam Ministry of Health in accordance with Circular 54/2015/TT-BYT, which outlines guidelines for the reporting and declaration of infectious diseases (Table S1). Diseases were defined following the International Classification of Diseases, 10th Revision (ICD-10). The infectious disease data underwent meticulous collection and investigation by trained personnel and were reported by the Can Tho Centers for Disease Control and Prevention from 2014 to 2022.

2.2. Data analysis

The demographic characteristics of infectious diseases and climate factors were expressed using frequencies and proportions for categorical variables, while continuous variables were represented using means and standard deviations, or medians and interquartile ranges. A Student's t-test was applied to assess differences between groups for normally distributed continuous variables.

A



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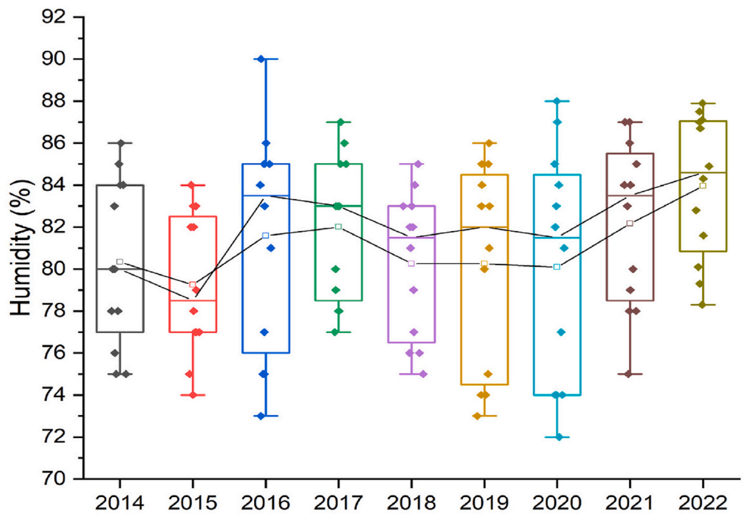
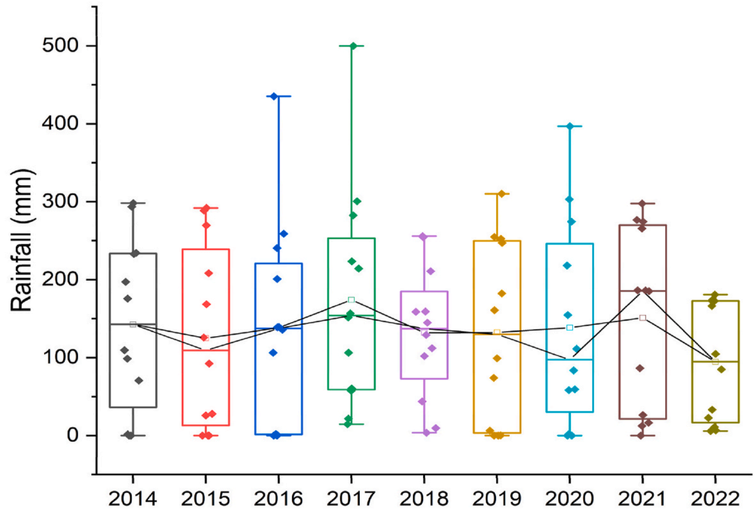


Fig. 1. Climate Characteristics in Can Tho City, Vietnam (2014–2022). This figure illustrates the monthly averages of key climate factors in Can Tho City, Vietnam, from 2014 to 2022. Panels display trends for temperature (A), relative humidity (B), rainfall (C), and sunshine duration (D), highlighting seasonal and inter-annual variations.

C



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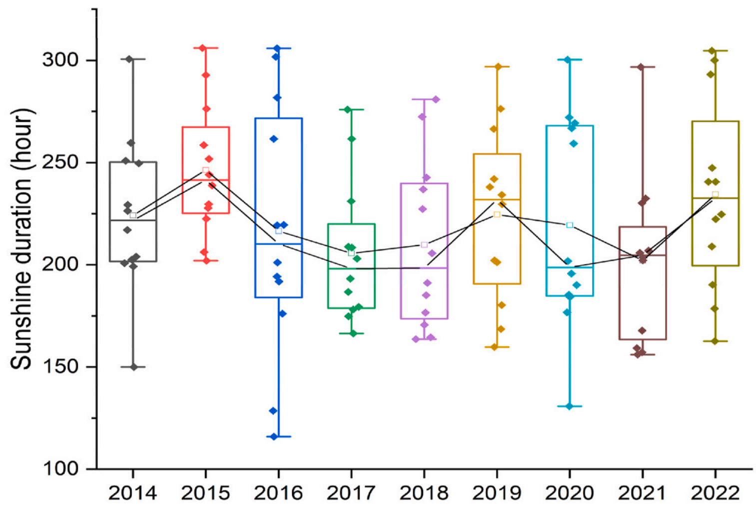


Fig. 1. (*continued*).

We used the Pearson correlation coefficient to examine the association between continuous variables. The association between each climate factor and infectious diseases was then investigated through both univariate and multivariate linear regression analyses. Initially, individual climate factors were independently entered into univariate models, but we incorporated potential climate factors in the full model, informed by existing literature or subjective prior knowledge (e.g., temperature, rainfall, humidity, etc.), along with variables demonstrating p values of $\leq$0.25 in univariate analysis [12,13]. We further analyzed and plotted non-linear and linear region models to visualize the relationship between climate factors and infectious diseases.

To investigate the complex relationships between climate variables and infectious disease incidences, we employed both multivariate linear regression and Bayesian Kernel Machine Regression (BKMR). The multivariate linear regression model served as a baseline to evaluate the linear associations between individual climate variables (e.g., temperature, rainfall, humidity) and disease rates. However, given the potential for non-linear interactions and synergistic effects among climate variables, BKMR was utilized to capture these complex dynamics [14]. BKMR is particularly advantageous in studies involving multiple predictors, as it can simultaneously account for non-linear relationships and interactions without requiring pre-specification of interaction terms [14–16]. While simpler methods like linear regression can provide valuable insights, they may fail to identify non-linear or interactive effects inherent in climate-health relationships. BKMR overcomes these limitations by using kernel functions to flexibly model such interactions, making it an ideal choice for this study, where multiple climate variables likely act in concert to influence disease incidence.

Next, we assessed the interactions and mixed effects of climate factors on infectious diseases using BKMR. BKMR is a supervised method used to assess exposure mixtures via a nonparametric approach, particularly through a kernel function, to model the unknown relationship between exposure and outcome variables [14]. This method accommodates potential interactions and nonlinear associations while also incorporating additional covariates of interest in a parametric manner. In brief, our BKMR model was formulated using the following equation:

$$Y_i = h\left(\text{Humidity}_i, \text{Temperature}_i\right) + \beta qZi + ei \qquad (1)$$

Here, the exposure-response function h in Equation (1) addresses nonlinearity and/or interaction among the different components of climate factors in the mixture. Z = Z1, Z2, …, where Zq represents q potential confounders. In our analysis, we employed a Gaussian kernel function and implemented a component-wise variable selection strategy. Following the fitting of the final model using Markov Chain Monte Carlo (MCMC) sampling with a burn-in of 25,000 iterations out of 20,000, we obtained posterior inclusion probabilities (PIPs) for each climate factor and estimated the exposure-outcome function [17]. Given the significant roles of humidity and temperature observed in previous models, we further examined the combined effects of climate factors on key infectious diseases by comparing outcomes when all factors were set to different percentiles relative to their 50th percentile. We also explored potential pairwise interactions between each pair of climate factors by plotting the exposure-outcome function of one factor while holding the second factor constant at different percentiles, with all other factors set to their median values.

Orthogonal Partial Least Squares Discriminant Analysis (OPLS-DA) was used to assess the presence of infectious diseases influenced by climate factors both before (2014–2019) and during (2020–2022) the COVID-19 pandemic period. Variable Importance in Projection (VIP) analysis was used to assess the loadings, which indicate the impact of each variable on the response. Variables with VIP values > 1 are considered significant and contribute to the classification between groups [18].

We conducted receiver operating characteristic (ROC) analysis to compare differences in abilities between two groups (before

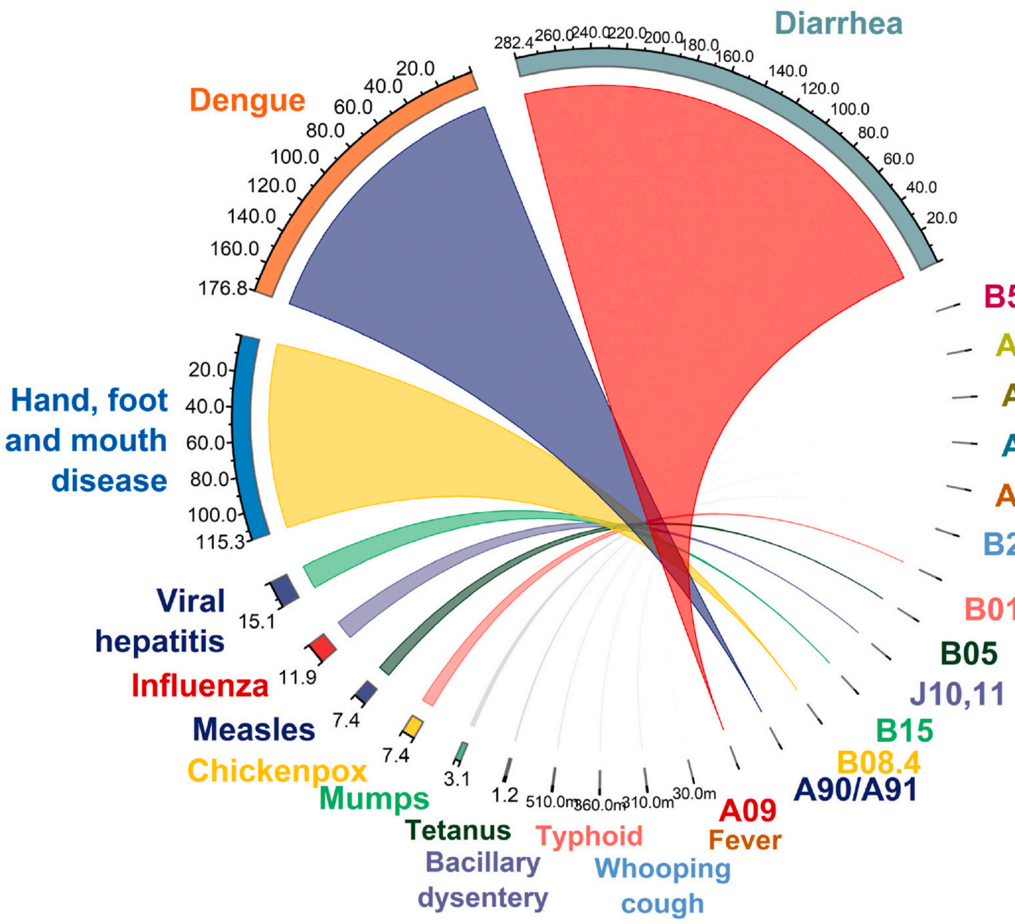


Fig. 2. Infectious Disease Incidence in Can Tho City, Vietnam (2014–2022). This figure shows the average annual incidence rates (per 100,000 population) for infectious diseases classified according to the International Classification of Diseases. The data span the period from 2014 to 2022, illustrating temporal patterns and disease trends.

COVID-19 vs. during COVID-19) and assess the accuracy of the models. The cut-off values for sensitivity and specificity were determined using the maximized Youden index. Parametric tests were employed to compare the areas under the ROC curves (AUC) [19]. The statistical analysis was performed using Stata software (version 1.0; StataCorp, TX, USA) and R (version 4.1.0) ropls, circlize, ggpubr, bkmr, and ggplot2 packages. In two-tailed statistical tests, p-values <0.05 were considered statistically significant.

3. Results

3.1. Characteristics of climate factors in Can Tho City from 2014 to 2022

The climate characteristics of Can Tho City revealed trends in temperature, humidity, and rainfall from 2014 to 2022. Temperature fluctuated over the years, with a discernible upward trend beginning in 2019 and peaking in 2020 with a yearly average of 34.8 °C (Fig. 1A). Humidity levels also fluctuated throughout the period, reaching their highest point in 2022 and their lowest in 2015, with an average humidity level consistently above 79 % (Fig. 1B). As shown in Fig. 1C, average rainfall showed variability with an overall increasing tendency in 2017 and 2021, with peak levels recorded in 2017 (~174 mm) and 2021 (~151 mm). Sunshine duration also fluctuated, with peak levels recorded in 2015 (~246 h), in 2019 (~225 h), and in 2022 (~235 h) (Fig. 1D).

3.2. Characteristics of infectious disease incidence in Can Tho City (2014–2022)

From 2014 to 2022, incidence rates per 100,000 individuals for the top five infectious diseases belonging to group B according to Circular 54/2015/TT-BYT issued by the Vietnam Ministry of Health were diarrhea, dengue fever, HFMD, viral hepatitis, and influenza (Table S1 and Fig. 2). The average number of cases per year and the average incidence rate per 100,000 people during this period were: diarrhea (31,874 cases, 282.38 incidence rate), dengue fever (19,961 cases, 176.84 incidence rate), HFMD (13,019 cases, 115.34 incidence rate), viral hepatitis (1702 cases, 15.08 incidence rate), and influenza (1339 cases, 11.86 incidence rate) (Table 1).

3.3. The relationship between climate factors and infectious diseases in Can Tho City from 2014 to 2022

We next examined the correlations between climate factors and infectious diseases. Strong correlations were observed between climate factors themselves, such as rainfall and humidity ($r > 0.77$) as well as sunshine duration and humidity ($r = -0.83$). Moderate correlations were found between infectious diseases such as dengue and HFMD ($r = 0.59$) and mumps and chickenpox ($r = 0.51$). In our univariate and multivariate analyses, we observed positive associations between humidity and both dengue fever ($\beta = 57.30$; 95% CI = 37.40–77.20) and HFMD ($\beta = 14.17$; 95%CI = 4.56–23.77) (Fig. 3) and found negative associations between humidity and chickenpox ($\beta = -1.02$; 95%CI = −1.83 to −0.21), measles ($\beta = -1.68$; 95%CI = −3.35-0.001), and tetanus ($\beta = -0.0495$%CI = −0.12 to 0.03). Temperature showed a positive association with malaria ($\beta = 0.04$; 95%CI = 0.004–0.083) (Table 2). There was an increasing trend in the incidence of HFMD and a decreasing trend in the incidence of chickenpox according to humidity, as indicated by both linear and non-linear regression models. A U-shaped association was observed between measles and humidity, whereas a slightly inverted U-shaped association was found for malaria and temperature in the nonlinear regression model. A W-shaped association was identified for dengue fever, tetanus, and humidity in the nonlinear regression model (Fig. 4A–F).

Table 1
Characteristics of infectious diseases in can tho city, vietnam, from 2014 to 2022.

Diseases	ICD	Group[a]	Total number of cases in the period 2014–2022	Average number of cases per year	Average incidence rate/100,000 people
Diarrhea	A09	B	31874	3541.56	282.38
Dengue fever	A90/A91	B	19961	2217.89	176.84
Hand. foot and mouth disease	B08.4	B	13019	1446.56	115.34
Viral hepatitis	B15	B	1702	189.11	15.08
Influenza	J10,11	B	1339	148.78	11.86
Measles	B05	B	840	93.33	7.44
Chickenpox	B01	B	832	92.44	7.37
Mumps	B26	B	355	39.44	3.14
Bacillary dysentery	A03	B	138	15.33	1.22
Tetanus	A35	B	58	6.44	0.51
Typhoid	A01	B	41	4.56	0.36
Whooping cough	A37	B	35	3.89	0.31
Malaria	B50	B	3	0.33	0.03

ICD: International Classification of Diseases.
[a] sourced from the Vietnam Ministry of Health in accordance with Circular 54/2015/TT-BYT.

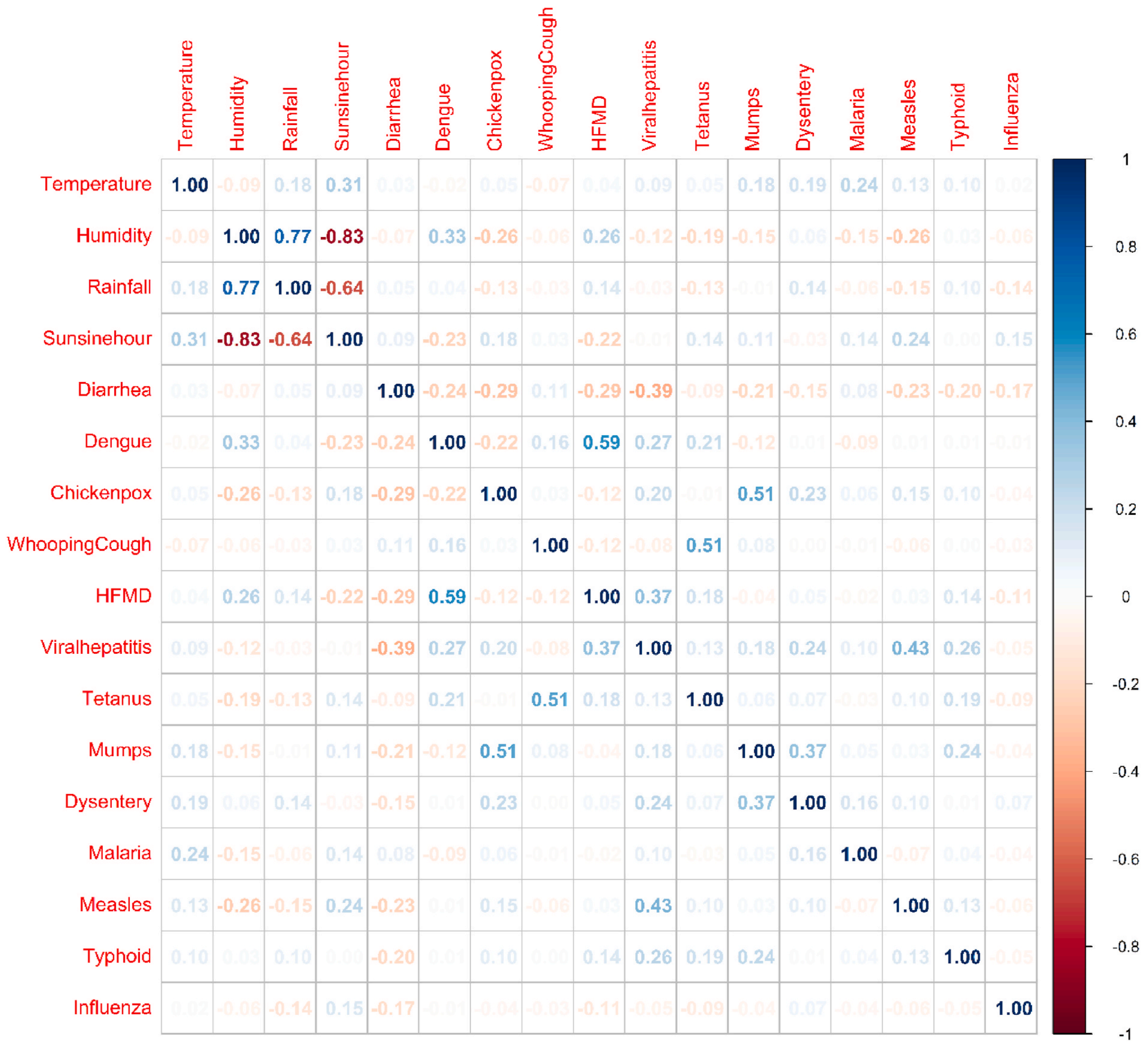
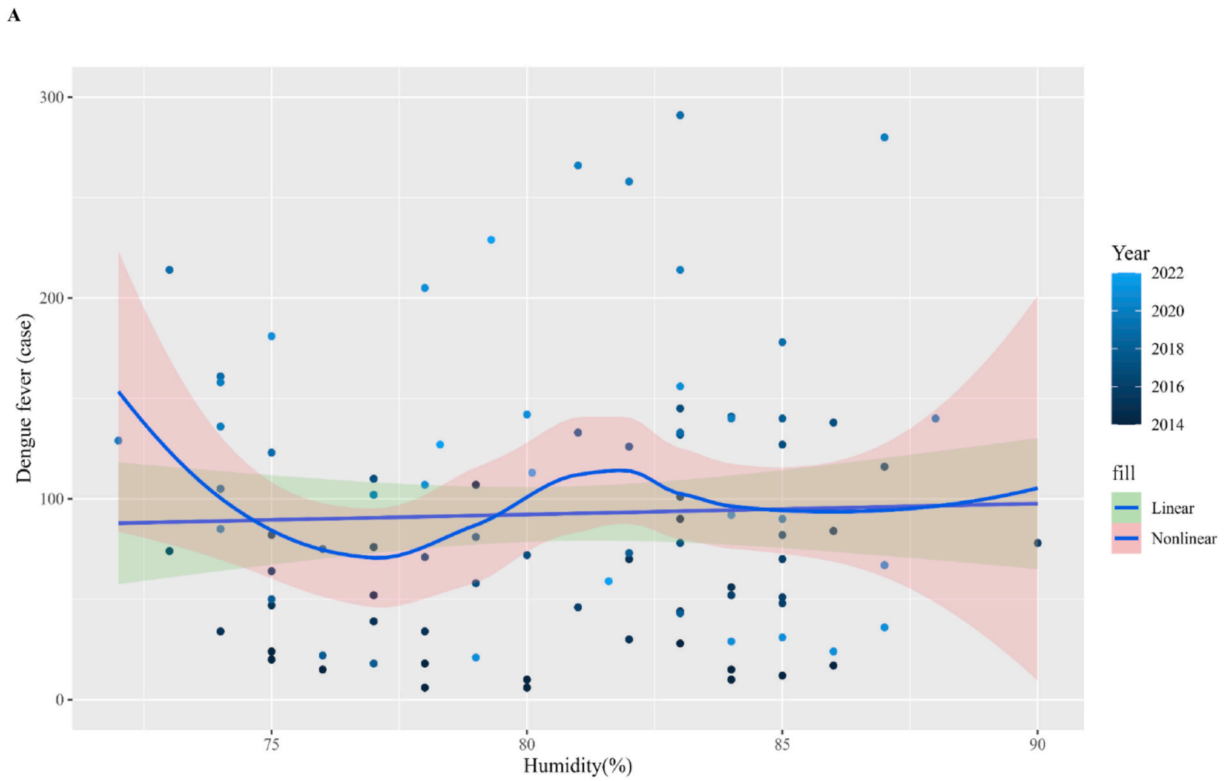


Fig. 3. Correlations Between Climate Factors and Infectious Diseases in Can Tho City, Vietnam (2014–2022). This figure illustrates the correlation matrix between climate factors and infectious disease incidence, including hand, foot, and mouth disease (HFMD). The scale bar indicates correlation coefficients (*r* values), where blue represents positive correlations and red represents negative correlations. A.

Table 2
Associations between climate factors and infectious diseases in can tho city, vietnam, from 2014 to 2022.

Diseases	ICD	Climate factors	β (95%CI)	*p*-values
Dengue fever	B08.4	Humidity	23.13 (10.38–35.88)	<0.001
		Humidity[a]	57.30 (37.40–77.20)	<0.001
Chickenpox	B15	Humidity	−0.53 (−0.90 to −0.16)	0.006
		Humidity[a]	−1.02 (−1.83 to −0.21)	0.014
Hand, foot and mouth disease	A90/A91	Humidity	8.25 (2.43–14.07)	0.006
		Humidity[a]	14.17 (4.56–23.77)	0.004
Tetanus	A35	Humidity	−0.04 (−0.09 to −0.001)	0.048
		Humidity[a]	−0.04 (−0.12 to 0.03)	0.241
Malaria	B50	Temperature	0.05 (0.01–0.08)	0.012
		Temperature[a]	0.04 (0.004–0.083)	0.030
Measles	B05	Humidity	−1.42 (−2.42 to −0.42)	0.001
		Humidity[a]	−1.68 (−3.35-0.001)	0.050

ICD: International Classification of Diseases.
[a] models were adjusted for temperature, humidity, rainfall, year, and sunshine duration.



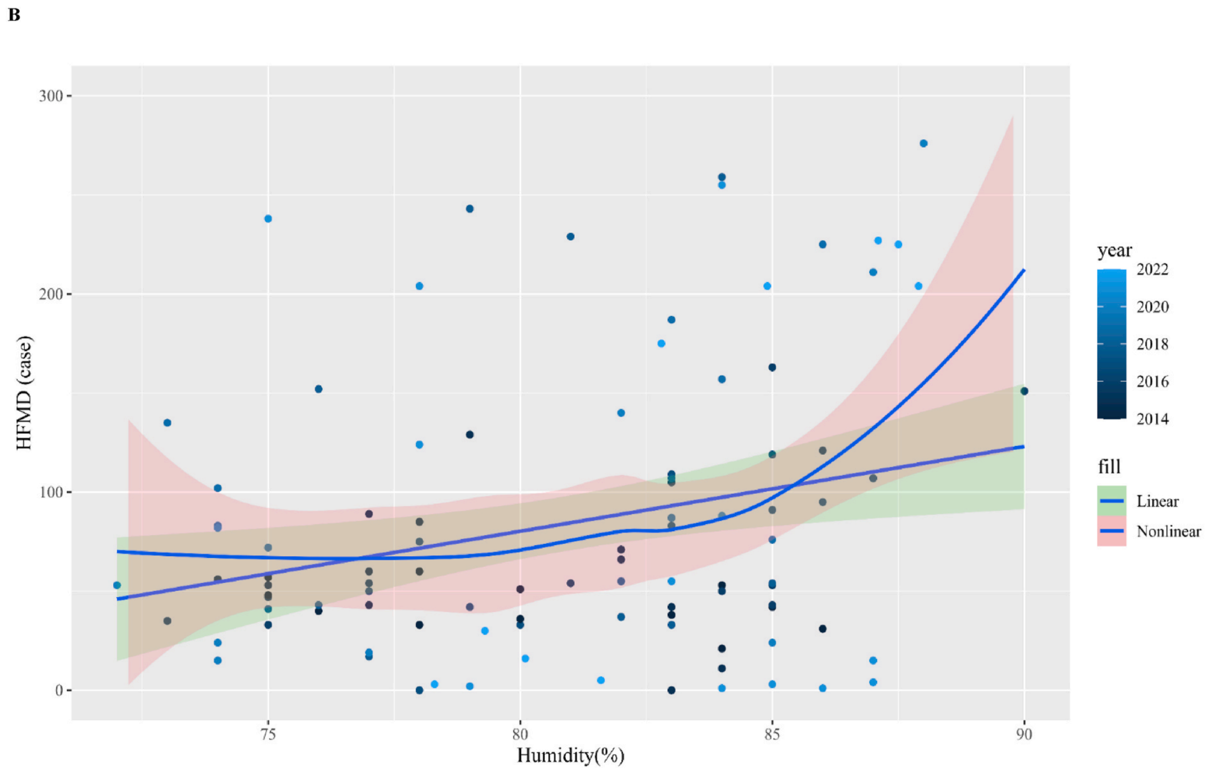
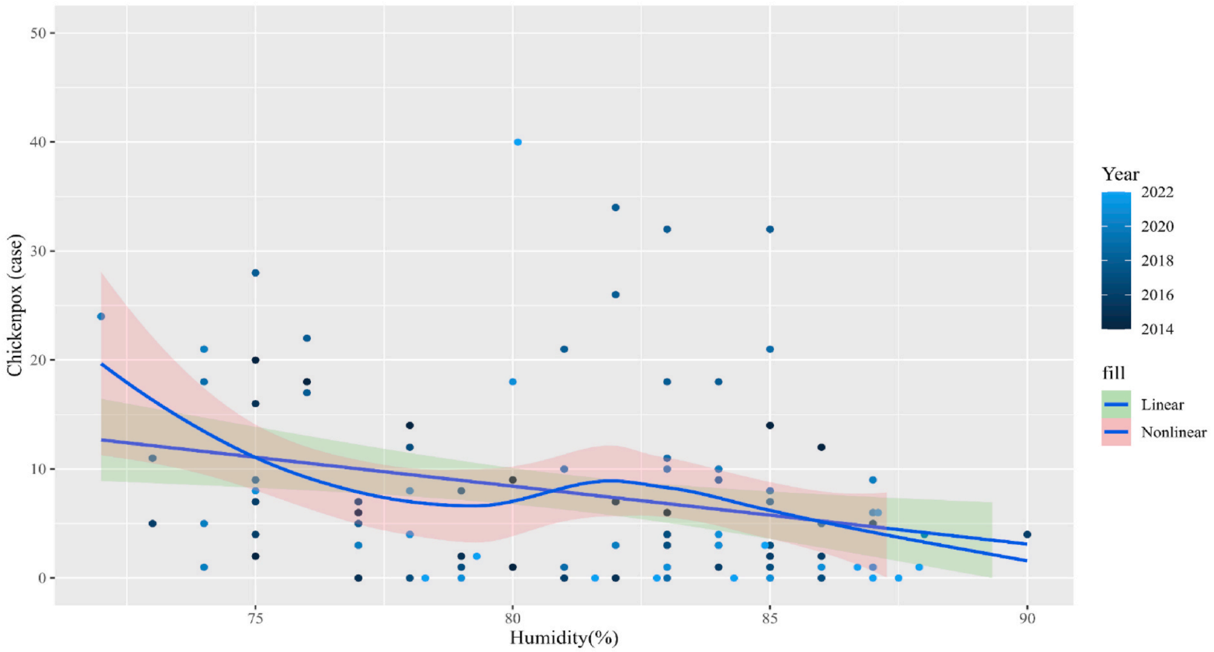


Fig. 4. Predicted Relationships Between Climate Factors and Infectious Disease Incidence in Can Tho City (2014–2022). Predicted curves illustrating linear and non-linear regression models for the relationships between climate factors and the incidence of dengue fever (A), HFMD (B), chickenpox (C), tetanus (D), measles (E), and malaria (F). Shaded areas represent 95 % confidence intervals, and the reference values are set at the 50th percentile of climate factors. A

C



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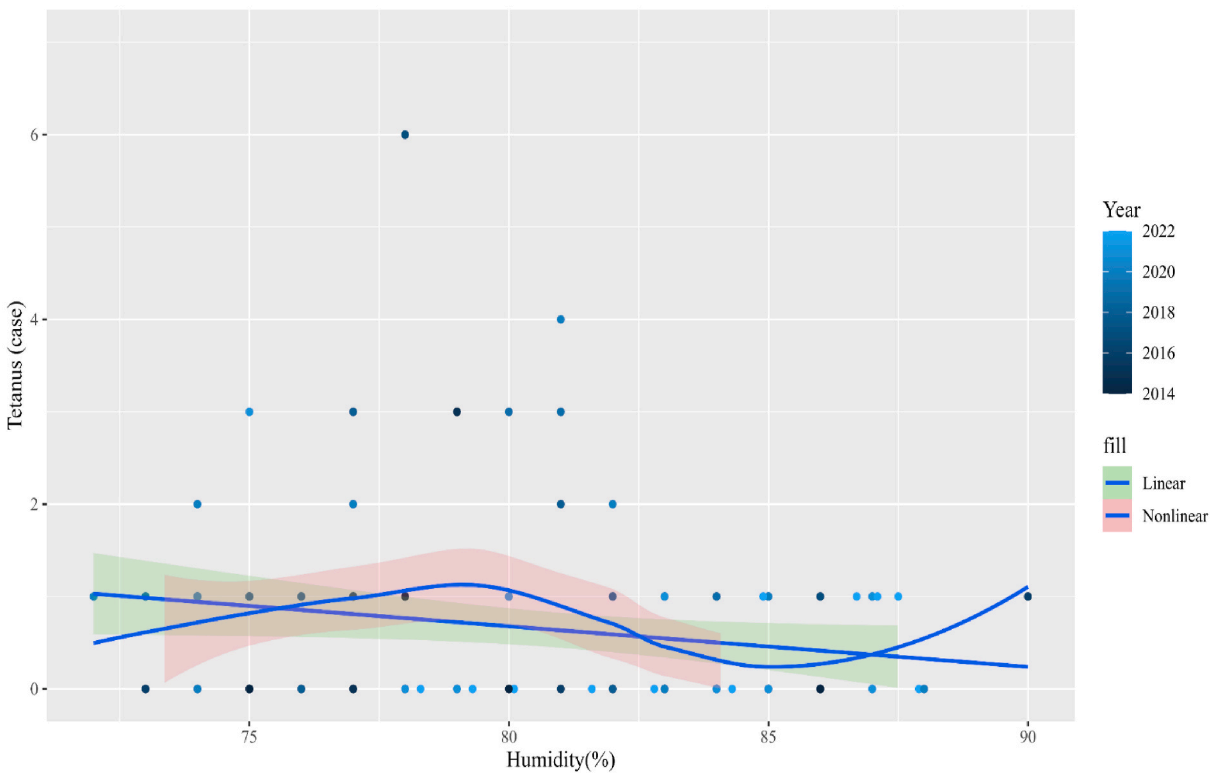

Fig. 4. (*continued*).

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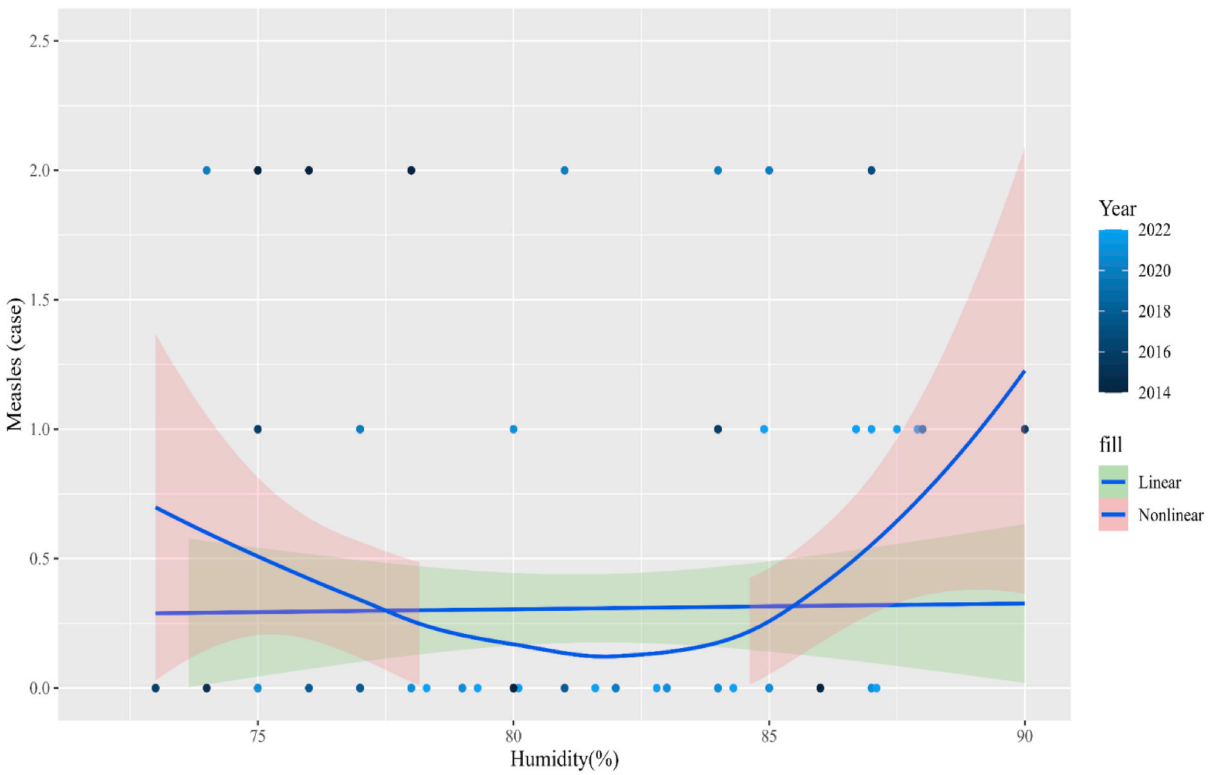

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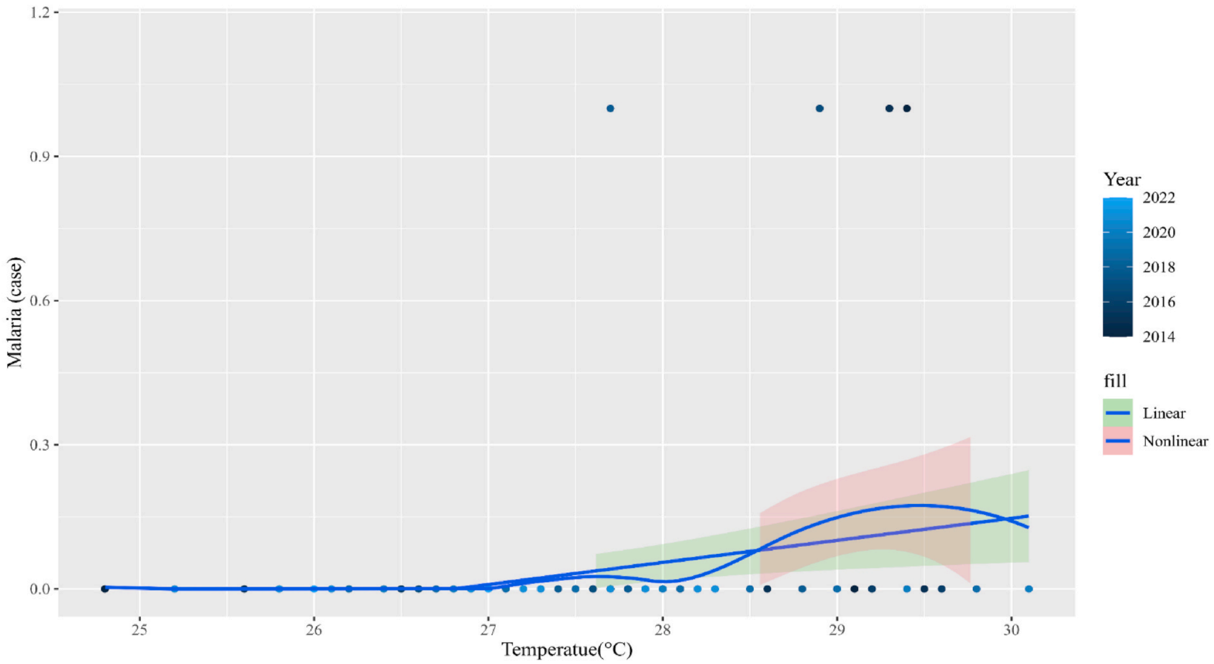

Fig. 4. (*continued*).

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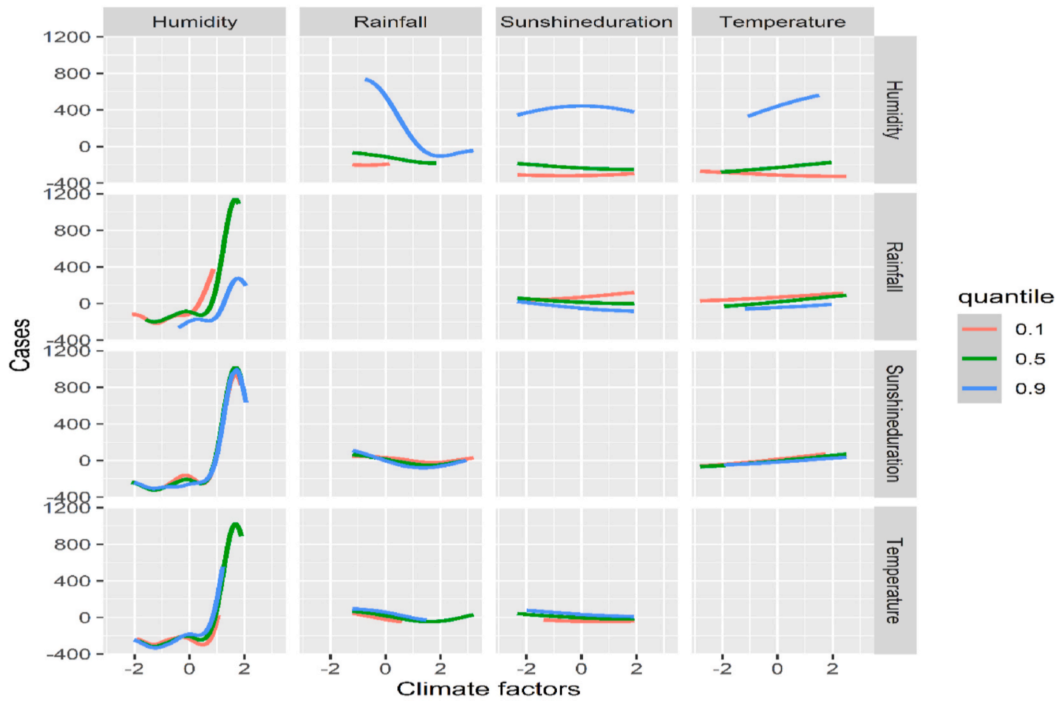

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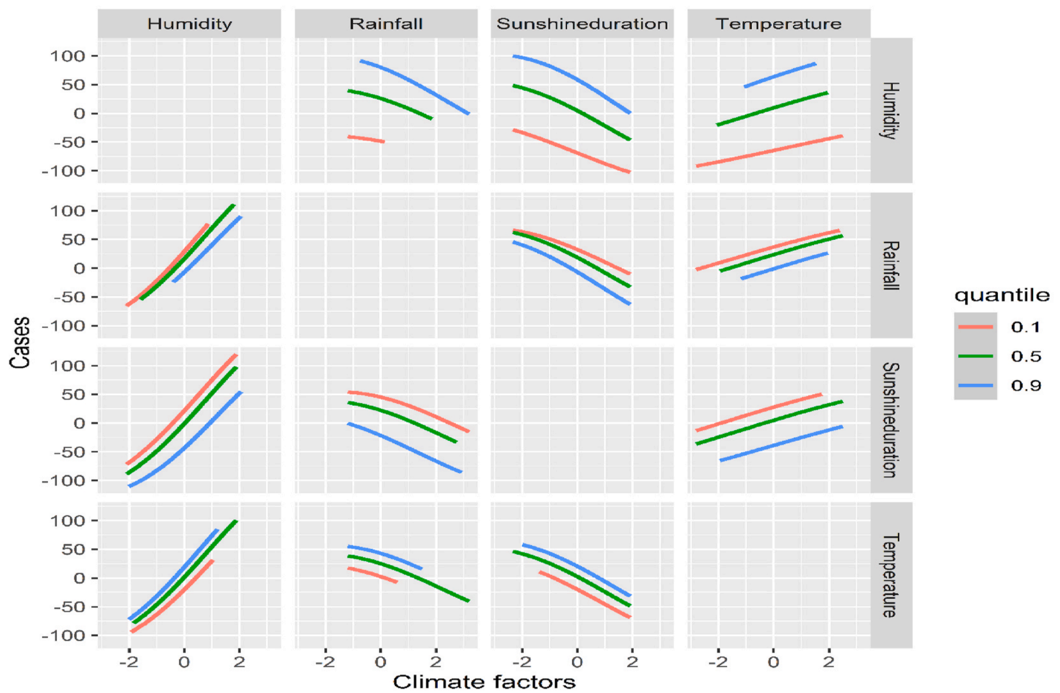
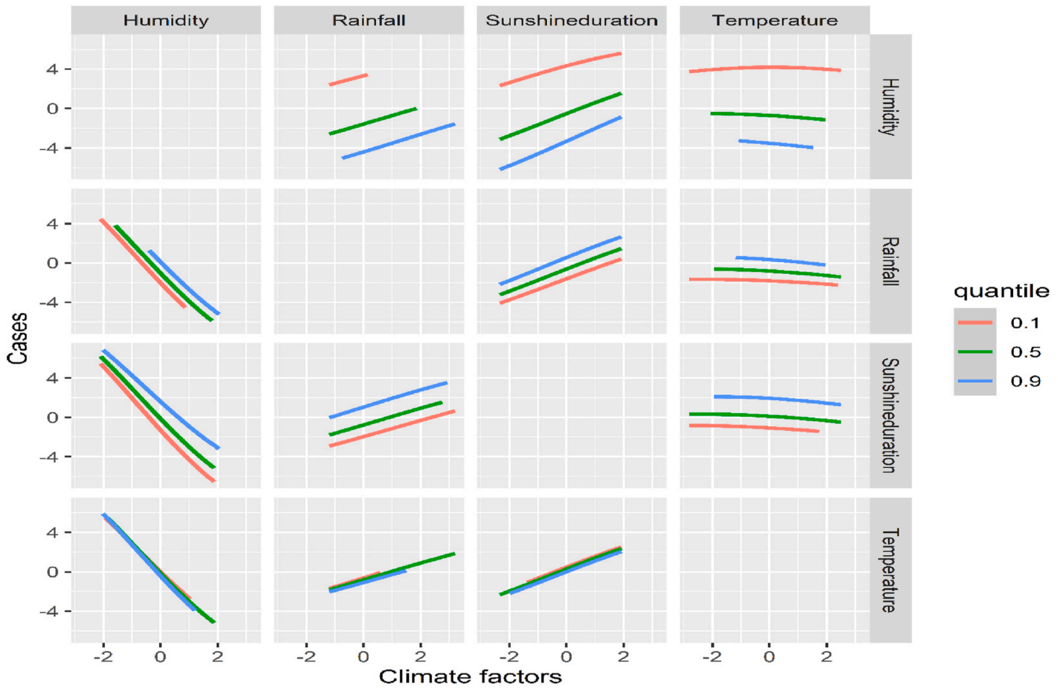


Fig. 5. Interactions Between Climate Factors and Infectious Diseases in Can Tho City (2014–2022). Predicted interactions between climate factors and the incidence of infectious diseases based on Bayesian Kernel Machine Regression (BKMR) models. Panels show results for dengue fever (A), HFMD (B), chickenpox (C), tetanus (D), measles (E), and malaria (F). For each pair of climate factors, the plots depict one factor's relationship with disease incidence while holding the second factor constant at its 10th, 50th, and 90th percentiles, with all other factors set to their median values. Models are adjusted for the year of observation.

C



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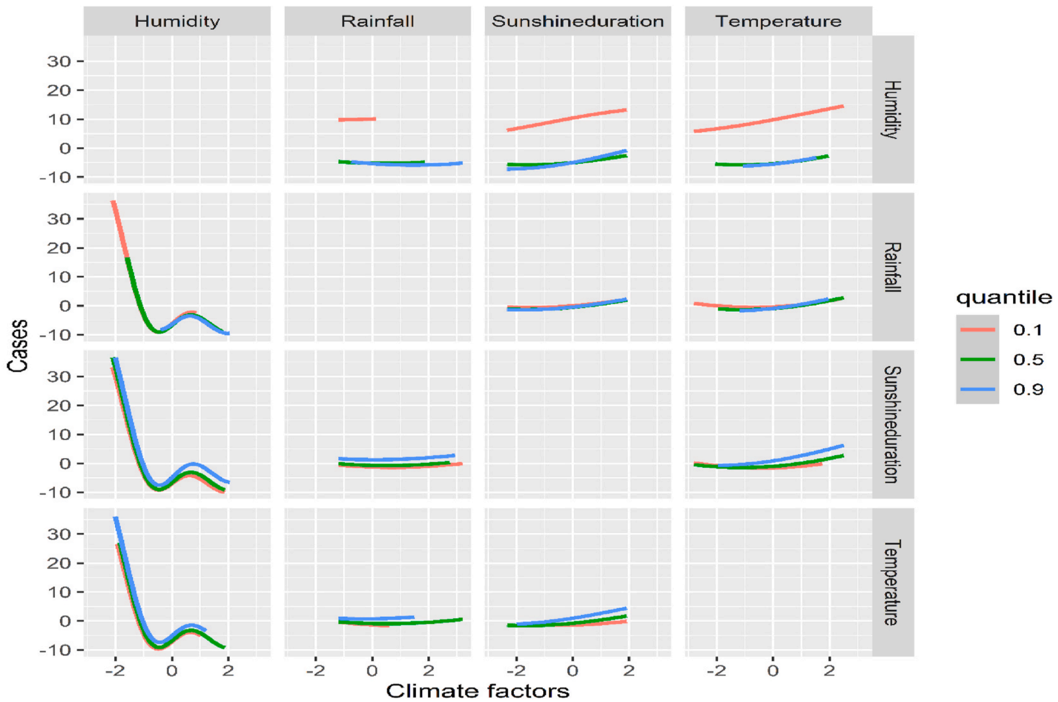
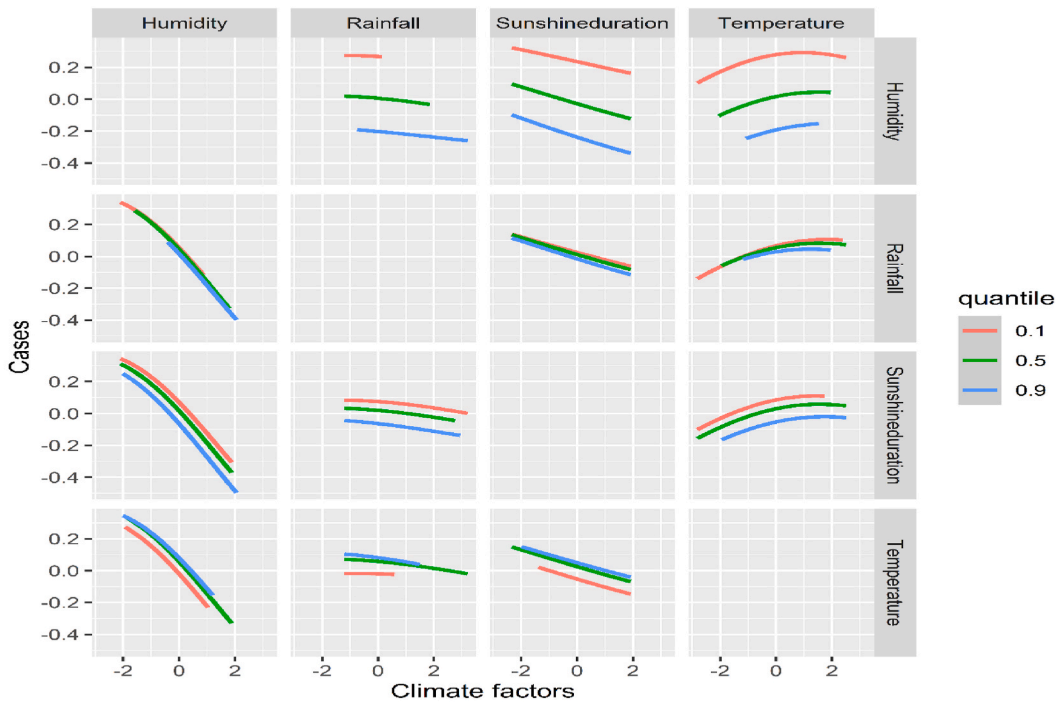


Fig. 5. (*continued*).

3.4. The interactions and mixed effects of climate factors on key infectious diseases in Can Tho City from 2014 to 2022

Using BKMR models, we found substantial evidence indicating significant pairwise interactions among climate factors for various infectious diseases, including dengue fever, HFMD, chickenpox, tetanus, measles, and malaria. Given the pivotal roles of humidity and

E



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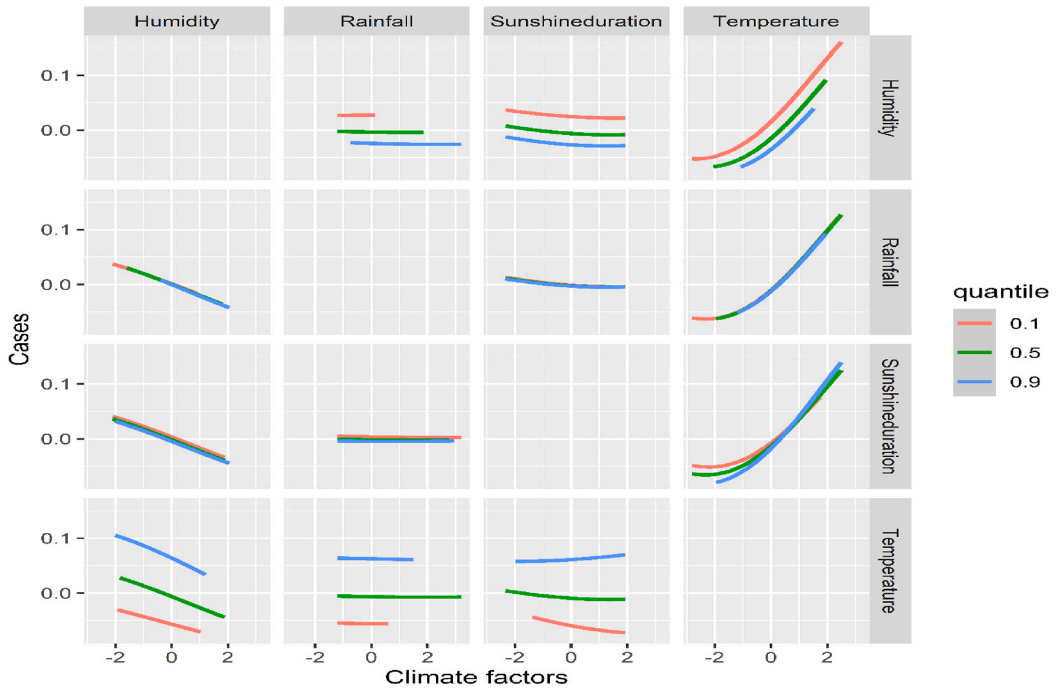


Fig. 5. (*continued*).

temperature in influencing infectious diseases found in previous models, we evaluated the combined effects of humidity and temperature on key infectious diseases. Our analysis revealed a positive correlation between the combined effects of humidity and temperature and the incidence of dengue fever and HFMD, while an inverse association was observed between the combined effects and chickenpox (Fig. 5A–F). Although no significant associations were observed between the overall combination of humidity and temperature and other outcomes (tetanus, measles, and malaria), upward trends were apparent (Fig. 6A–L). In the broader context of infectious diseases, humidity emerged as the predominant contributor in the mixture model for dengue fever (PIP = 0.93), HFMD (PIP = 1.00), chickenpox (PIP = 0.89), tetanus (PIP = 0.53), and measles (PIP = 0.928), while temperature (PIP = 0.87) exerted the most significant influence in the model for malaria (Table S2). To ensure the robustness of our findings, we compared the results from BKMR

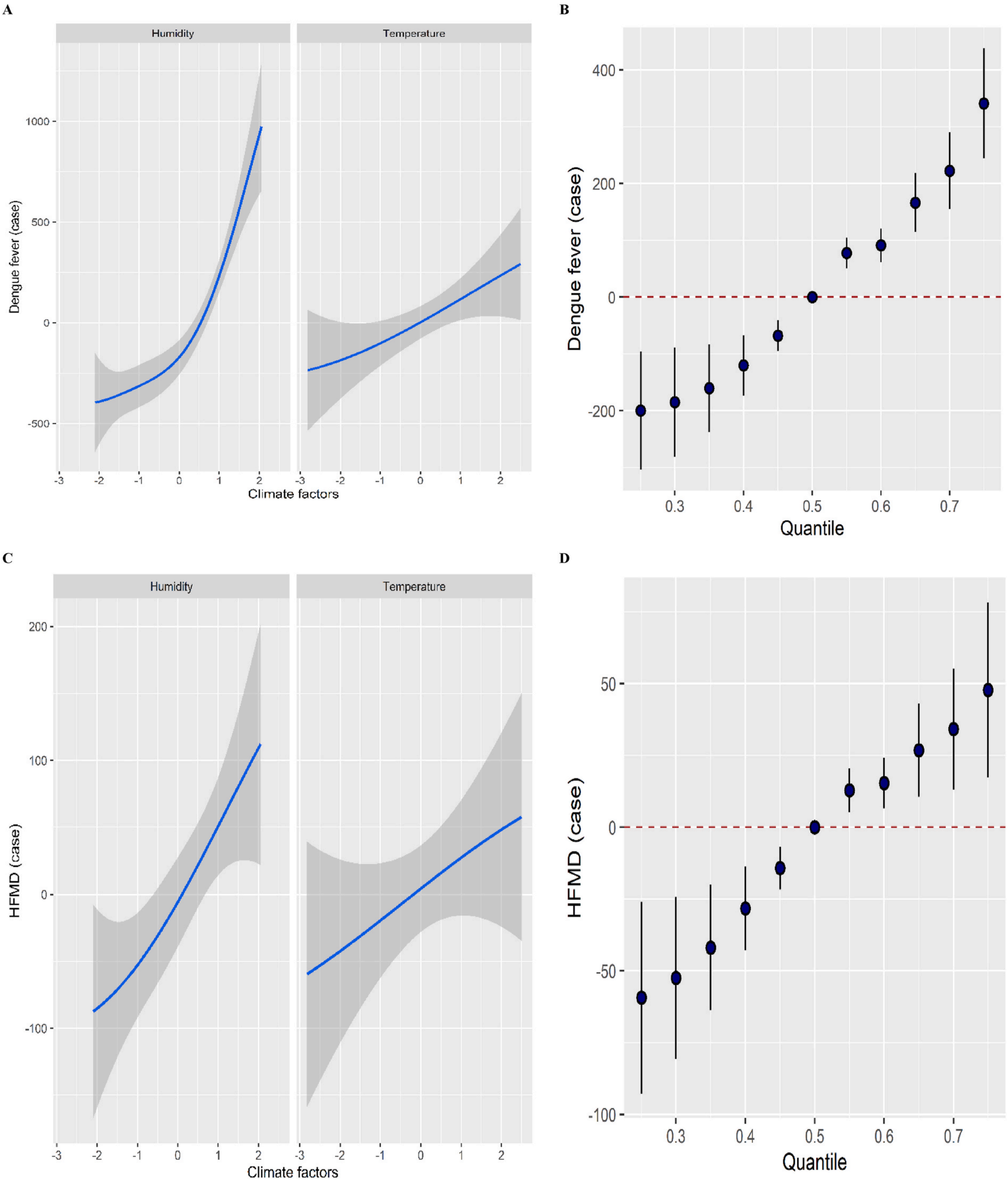


Fig. 6. Univariate exposure–response function and cumulative effect (95 % CI) of key infectious diseases affected by climate factors in Can Tho City, Vietnam, from 2014 to 2022. Figures illustrate the predicted curves from Bayesian kernel machine regression (BKMR) model for dengue fever (A–B), hand, foot, and mouth disease (C–D), chickenpox (E–F), tetanus (G–H), measles (I–J), and malaria (K–L). Models were adjusted for year, rainfall, sunshine duration. A

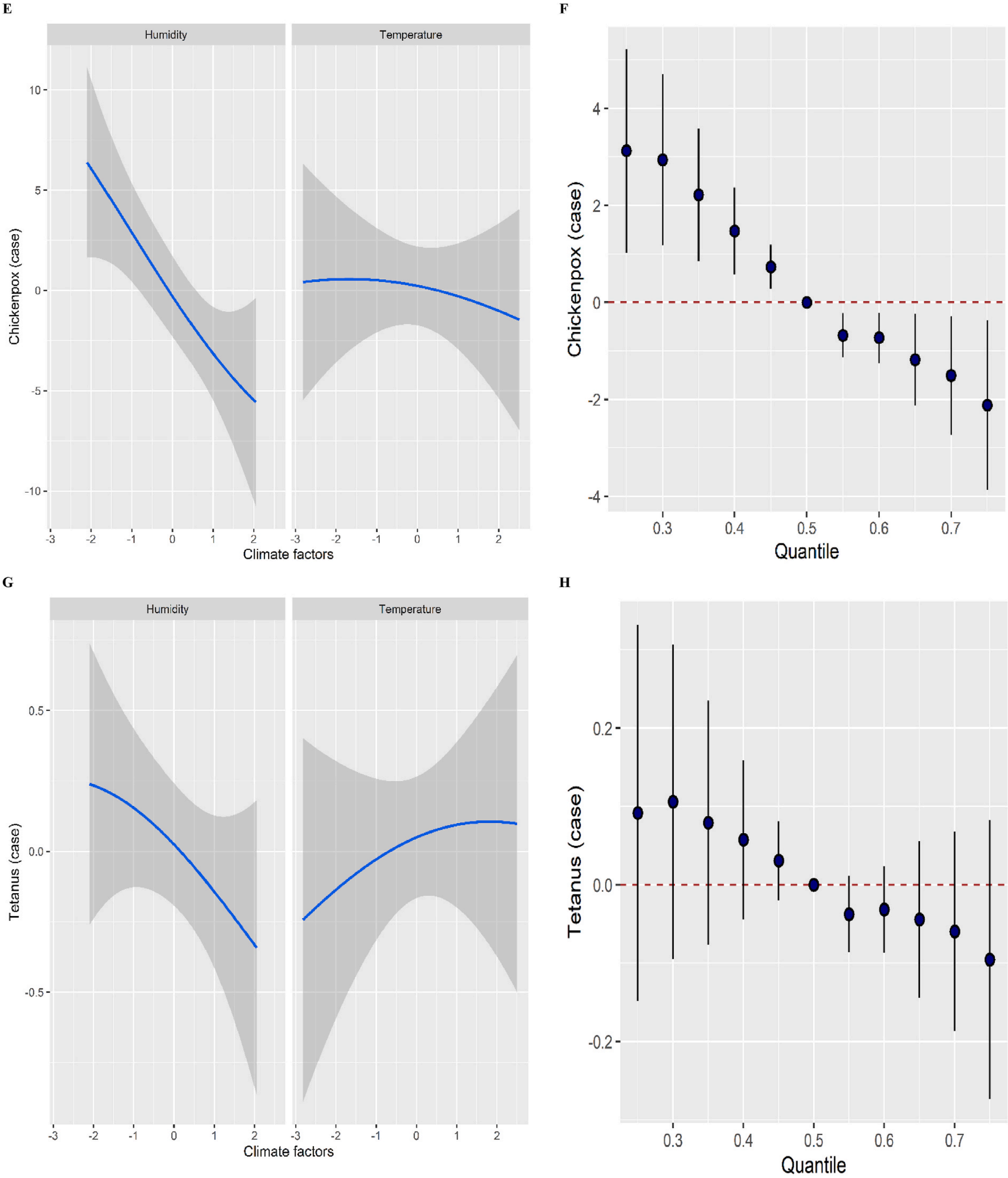


Fig. 6. (*continued*).

with those obtained from multivariate linear regression. The linear model identified significant associations between individual climate variables, such as rainfall and temperature, and disease incidences. However, BKMR revealed additional insights, such as non-linear threshold effects for temperature and humidity, as well as interactions between temperature and rainfall that were not detectable in the linear model. These findings underscore the value of employing BKMR for capturing the nuanced and multidimensional nature of climate-disease relationships.

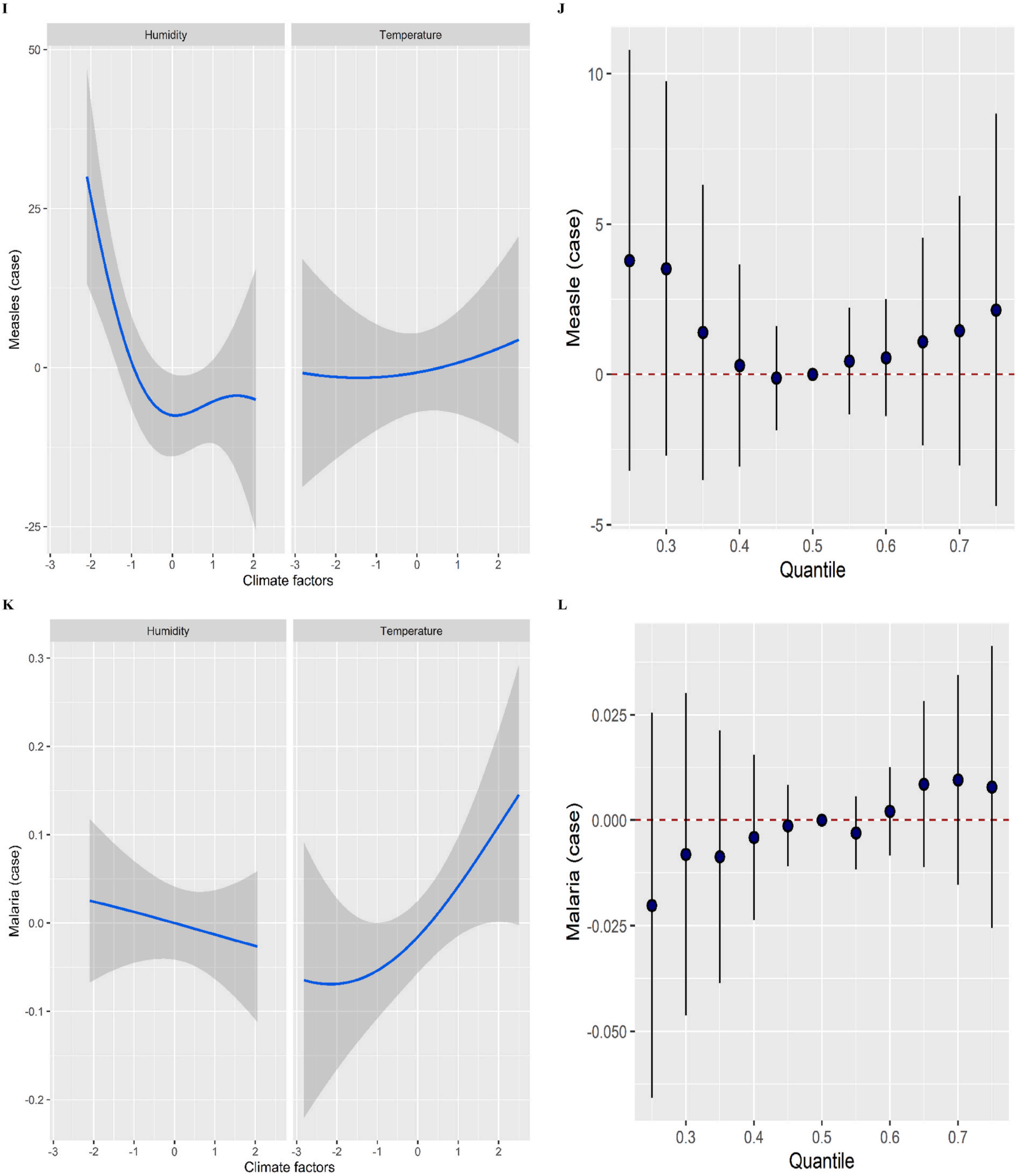
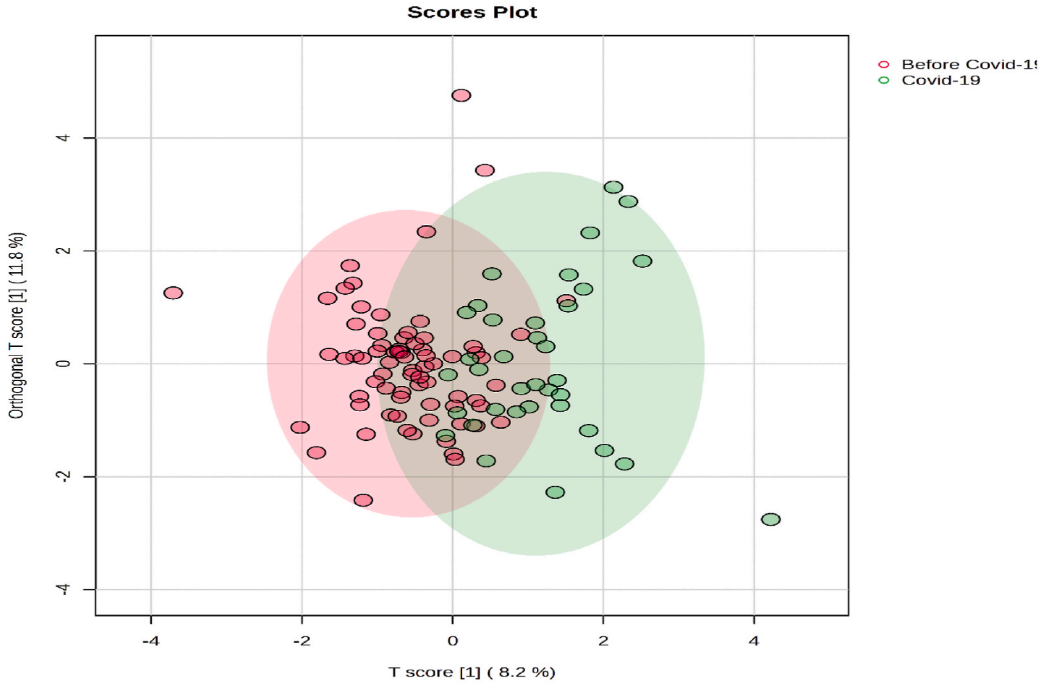


Fig. 6. (*continued*).

3.5. Identification of the presence of infectious diseases affected by climate factors before and during the COVID-19 period

The OPLS-DA approach yielded two components based on T scores. Fig. 7A illustrates the absence of complete separation among these components, implying that these diseases occurred continuously during the study period. Diarrhea and dengue fever emerged as the most prevalent diseases both before and during the COVID-19 period, as depicted in Fig. 7B. The results of ROC analysis and corresponding AUC (95 % CIs) for the presence of infectious diseases before and during the COVID-19 period are presented in Fig. 7C and D and Table S3. The ROC analysis indicated that diarrhea and dengue fever were prevalent diseases before COVID-19 (AUC = 0.79;

A



B

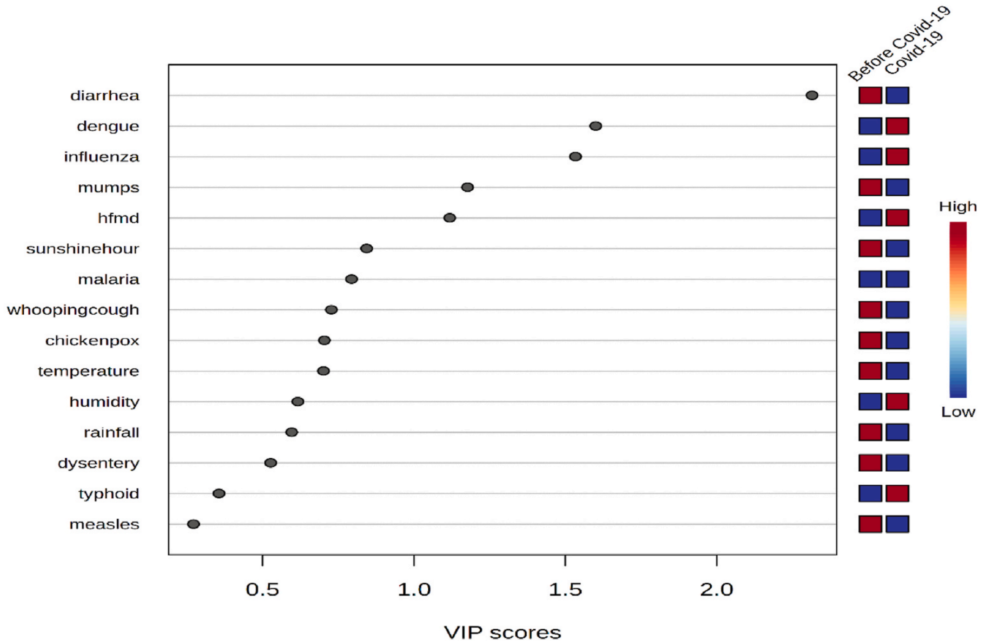
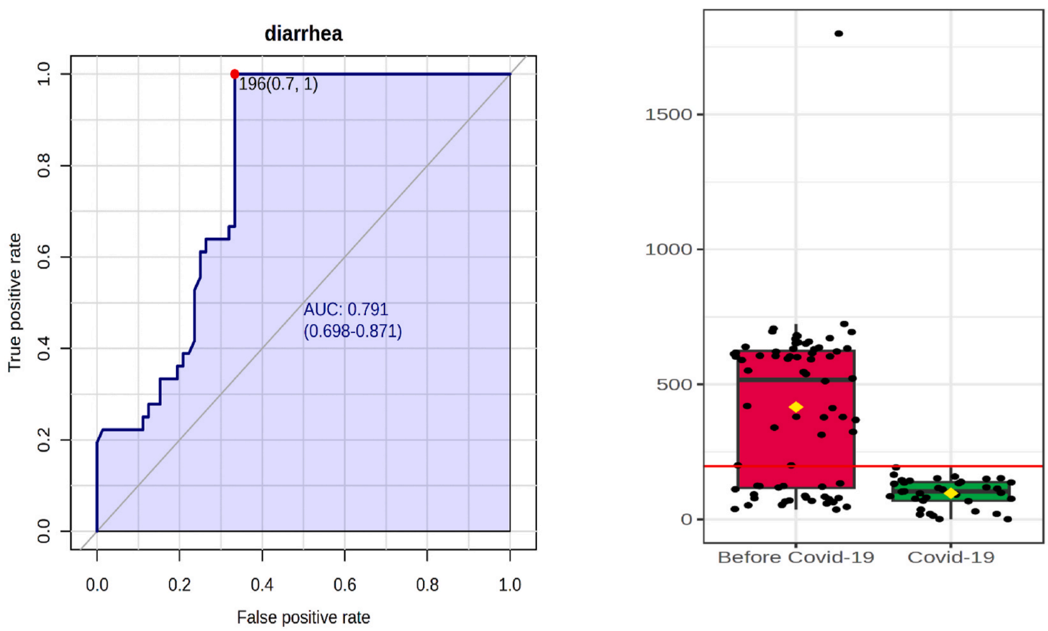


Fig. 7. Identification of presence of infectious diseases affected by climate factors before and during Covid-19 period. AUC, areas under the ROC curves; VIP, variable importance in projection.

C



D

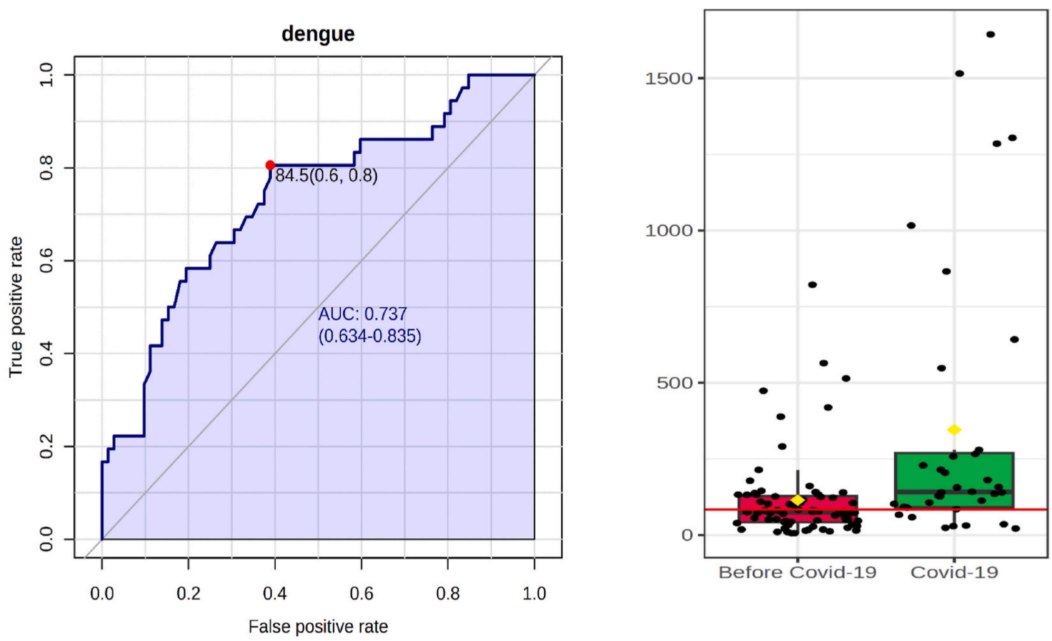


Fig. 7. (*continued*).

95 % CL = 0.70–0.87) and during COVID-19 (AUC = 0.74; 95 % CL = 0.62–0.83), respectively.

4. Discussion

4.1. Climate change in Can Tho City from 2014 to 2022

Effects of climate change in the Can Tho City area include increases in meteorological and environmental measures like temperature, precipitation, flooding, drought, saltwater intrusion, and other natural calamities [20]. Positioned within the Mekong Delta climatic region, Can Tho exhibits elevated and relatively stable temperatures with minimal diurnal temperature fluctuations. The climate is delineated by two discernible seasons: the wet season, from May to October, and the dry season, November to April. The annual mean temperature registers at 27 °C, with precipitation averaging between 1500 and 1800 mm annually. The duration of sunshine amounts to 2300–2500 h per year with an average relative humidity level of 83 %. Prevailing winds originate predominantly from the northeast during the dry season and from the southwest during the wet season, maintaining an average speed of 1.8 m/s. Although tropical cyclones are infrequent, thunderstorms and tornadoes are common during the summer rainy season.

An analysis of both empirical statistical data and predictive models reveals a consistent upward trajectory in average air temperatures observed across Can Tho City and in Vietnam overall, demonstrating an approximate increase of 0.7–0.8 °C. These heightened temperatures, particularly elevated nightly minimum temperatures, contribute to disturbances in sleep patterns, hinder recovery from health conditions, and elevate stress levels. The impact of heat on human health, especially among vulnerable populations like children and older adults, exacerbates the prevalence of tropical and infectious diseases by fostering the proliferation of bacteria, insects, and disease vectors, compounded by insufficient nutrition and poor environmental sanitation [21]. Our research indicates a relatively stable temperature range in Can Tho City, ranging from 27.5 °C to 28.3 °C throughout 2014–2022, but an increasing trend from 2019 onwards, culminating in its peak in 2022. The temperature variance between the highest and lowest years amounts to 0.8 °C.

Rainfall patterns in Can Tho City exhibited fluctuations with a discernible trend towards higher levels during 2014–2022, with notable peaks in 2017 (2088.4 mm) and 2022 (2424.7 mm). The substantial volume of rainfall, averaging between 1500 and 1800 mm annually, serves multifarious purposes, including domestic use and irrigation, contributing to the conservation of underground and surface water resources amidst changing climate conditions and upstream water resource deficiencies. Concomitant with the rise in rainfall is the emergence of drought and heightened saltwater intrusion. The influence of the El Niño Southern Oscillation (ENSO) in 2015 delayed the onset and curtailed the duration of the rainy season, resulting in basin-wide rainfall totals 20–50 % lower than the multi-year average [22]. Humidity levels in Can Tho city reached their zenith in 2022 (83.95 %) and nadir in 2015 (79.25 %), consistently maintaining levels above 79 % throughout 2014–2022. In Can Tho, average sunshine duration amounts to approximately 8 h per day or 240 h per month, but our study revealed a decreasing trend in sunshine duration from 2014 to 2022, declining from 224 h to 202 h per month. Given the evident correlation between climate change and the prevalence of tropical and infectious diseases, proactive strategies are imperative to mitigate these effects [21].

4.2. Common infectious diseases in Can Tho City 2014–2022

In this study, we found that the prevalent infectious diseases in Can Tho City during 2014–2022 (the highest incidence rates per 100,000 people) were diarrhea, dengue fever, HFMD, viral hepatitis, and influenza.

Rapid pathogen dissemination facilitates diarrheal outbreaks in densely populated regions where people use communal water sources for drinking and daily activities [23]. The disease typically surges during hot and humid summer conditions, which encourage pathogen proliferation. Diarrhea cases in Can Tho City exhibited an overall downward trajectory owing to enhanced environmental hygiene practices and heightened public awareness. Between 2015 and 2017, we recorded peaks with over 7000 annual cases, but the incidence declined to 76 cases in 2021 before rising to 1111 cases in 2022. It is plausible because it is associated with COVID-19 preventive measures and quarantines, curfews, and activity bans.

Incidence rates of dengue fever fluctuated cyclically, surging from 181 cases in 2014 to 1211 cases in 2017, dipping to 1035 cases in 2018, and peaking at 9348 cases in 2019 before gradually declining. Dengue fever, a mosquito-borne disease, poses a significant public health challenge globally. Climatic, environmental, and urbanization factors can all contribute to heightened mosquito breeding, particularly in urban and semi-urban locales [24]. Despite initial low prevalence rates for influenza, cases have exhibited an upward trend since 2018.

HFMD cases rose from 510 cases in 2014, stabilizing to an average of appropriately120 cases per year from 2015 to 2017, followed by notable increases to 1270 cases in 2018 and 2738 cases in 2019. Case numbers have fluctuated since 2020, with a decline during 2020–2021 followed by an increase to 2713 cases in 2022. HFMD predominantly affects children under 5 years old, and rates are highest between August and December, coinciding with the beginning of the school year [25]. Preventive measures include stringent hygiene practices, such as regular handwashing and disinfecting children's belongings. The incidence of viral hepatitis surged dramatically from 2014 to 2019, escalating from 4 cases in 2014 to 705 cases in 2019. Subsequent trends indicate fluctuation, with a resurgence noted in 2022. Viral hepatitis poses a grave public health threat due to its diverse transmission routes, ranging from bloodborne to foodborne [26]. Advancements in diagnostic technologies have augmented case detection rates, contributing to the observed rise in reported cases.

4.3. The relationship between climate change and infectious diseases in Can Tho City from 2014 to 2023

In the context of Southeast Asia, several studies have highlighted the significant impact of climate factors on the incidence of vector-borne diseases like dengue fever. For instance, Xu et al. (2024) explored the long-term effects of temperature and rainfall on dengue transmission over a 40-year period in similar climates [27], and their findings echo the patterns we observed in Can Tho, Vietnam. Similarly, Colón-González et al. (2023) projected the future incidence and burden of dengue in Southeast Asia, emphasizing the role of climate change in disease transmission dynamics [28]. Our study aligns with these findings, particularly in terms of temperature and rainfall being key climate factors influencing the incidence of diseases like dengue and HFMD. These studies, alongside our results, underscore the growing relevance of climate factors in shaping public health outcomes in the region. However, while the findings are consistent with previous research, the local factors specific to Can Tho—such as urbanization trends and local interventions—also need to be considered in future comparative studies.

We observed positive associations between humidity and the incidence of dengue fever and HFMD, but humidity was negatively associated with both chickenpox and tetanus. Temperature was positively correlated with malaria incidence (Table 2). These findings align with prior research conducted by Chowdhury et al., who highlighted the relationship between climate change and infectious diseases, noting associations between temperature, rainfall, and humidity with malaria, enteric fever, and diarrhea, respectively [29]. Studies in Asia have established the influence of temperature, wind speed, and rainfall on dengue fever outbreaks [30–33]. In our study, we observed a significant relationship between climate change dynamics and the incidence rates of HFMD, dengue fever, and chickenpox. Excessive rainfall during the rainy season accumulates in containers and shallow puddles as stagnant water, an ideal breeding ground for mosquito larvae, leading to increased mosquito populations and a corresponding increase in the many diseases spread by this vector [34,35]. Conversely, the dry season, characterized by hot weather and low humidity, curtails the spread of these diseases.

Anthropogenic climate change causes alterations in humidity, average annual temperature, and precipitation patterns on a global scale. These climatic shifts directly impact the reproduction and development of disease-transmitting mosquitoes like *Aedes aegypti*, which is responsible for transmitting dengue fever and other diseases [36], and studies suggest that conditions will continue to be more conducive to the proliferation of these vectors. Following periods of drought, dengue fever outbreaks often intensify due to diminished population immunity, rendering individuals more susceptible to infection. Subsequently, increased rainfall and humidity promote rapid mosquito growth, exacerbating epidemic development [37]. Strong ENSO events can lead to increased rainfall, which significantly increases the incidence of dengue fever, amplifying epidemic conditions twofold compared to the dry season [38].

Climate change exacerbates the risk of dengue fever, malaria, diarrhea, and HFMD, leading to increased hospitalization rates [39]. Dengue hemorrhagic fever is correlated with rainfall patterns [40]. Shifting seasons, increased humidity levels, and fluctuating temperatures create favorable conditions for chickenpox outbreaks [41]. During winter and spring, when daily temperatures are variable and humidity is high, the risk of disease outbreaks rises, particularly for respiratory-transmitted diseases such as measles and chickenpox [42]. In this study, we examined the influence of climate factors on the prevalence of infectious diseases before and during the COVID-19 pandemic. We found that diarrhea and dengue fever were the most prevalent diseases during the COVID-19 pandemic. Despite a reduction in the number of COVID-19 cases and its transition to endemic status, it is crucial to recognize that the simultaneous emergence of other diseases can have significant implications for human health. These findings highlight the complex interplay between climatic factors and infectious diseases, underscoring the importance of implementing climate change mitigation strategies in public health interventions.

4.4. Public health and policy implications

The findings from this study underscore the growing threat posed by climate change on public health, specifically in relation to infectious diseases. As observed in Can Tho City, climate factors such as temperature, humidity, and rainfall have direct and significant impacts on the incidence rates of diseases like diarrhea, dengue fever, and HFMD. Given the increasing frequency of extreme weather events and shifting seasonal patterns, there is a pressing need for robust public health strategies that are responsive to these evolving challenges. This section outlines key public health and policy recommendations that are informed by our study's findings, which can guide both local and global responses to climate-sensitive health risks.

One critical recommendation is the development of integrated climate-health surveillance systems that can monitor real-time changes in both environmental conditions and disease prevalence [43]. By combining climate data with health statistics, authorities can detect early warning signs of disease outbreaks and take timely action to mitigate their spread. For instance, the observed correlation between increased rainfall and higher dengue fever incidence highlights the need for forecasting models that predict the likelihood of vector-borne disease outbreaks based on weather patterns. Such systems would enable public health agencies to allocate resources more efficiently, deploy vector control measures more strategically, and better prepare for disease surges during the rainy season [44].

In addition, region-specific public health interventions are necessary to account for the unique climate characteristics and health risks of different areas [45]. For example, in Can Tho City, where humidity and rainfall contribute to the proliferation of mosquito larvae, targeted vector control measures, such as insecticide spraying and the promotion of community-based mosquito breeding site management, could help reduce the incidence of dengue fever. Moreover, public awareness campaigns that emphasize environmental sanitation, water purification, and personal protection against mosquito bites would be critical in high-risk areas. Public health education programs should also stress the importance of vaccination and hygiene practices, particularly during seasonal shifts when the risk of diseases like HFMD and influenza increases [46].

Another key area for policy intervention is strengthening healthcare infrastructure, especially in regions vulnerable to climate-related disasters. The increased burden of climate-sensitive diseases calls for expanded healthcare capacity to ensure rapid and effective responses to outbreaks. Investments should focus on improving healthcare access in rural and underserved areas, where the impact of climate change is often most severe. Furthermore, healthcare facilities should be equipped with adequate resources to handle climate-induced spikes in disease prevalence, including stockpiles of vaccines, medications, and medical supplies [47].

Lastly, it is imperative that climate-resilient policies be integrated into broader public health planning at both the local and national levels [48]. The evidence presented in this study suggests that climate change is altering the patterns of infectious diseases, which calls for a shift in public health policy. Governments should consider incorporating climate projections into long-term health plans, ensuring that public health interventions remain effective under changing climate conditions. This could involve updating disease control strategies to account for new climate patterns, such as extended rainy seasons or prolonged dry spells, which directly influence disease dynamics. By implementing these recommendations, Can Tho and other regions facing similar challenges can better protect their populations from the health risks associated with climate change. Furthermore, the global health community must recognize the importance of these findings and collaborate to develop universal frameworks for addressing climate-sensitive infectious diseases. The intersection of climate change and public health presents an opportunity to not only protect vulnerable populations but also to advance our understanding of how environmental factors shape the burden of infectious diseases.

4.5. Novel contributions of the study

While the relationship between climate factors and infectious diseases like dengue fever has been widely explored [49], our study offers several novel contributions. First, it focuses on Can Tho City, a region in the Mekong Delta of Vietnam, providing localized insights into how climate change impacts disease incidence. This regional focus is crucial for developing targeted public health strategies. Second, our longitudinal design covering nine years (2014–2022) allows us to capture both seasonal and long-term trends, offering a more comprehensive understanding of climate-disease dynamics over time. The study's use of BKMR and OPLS-DA adds depth by examining non-linear interactions between climate factors and diseases, providing insights that traditional models might miss. A key finding of our study is the interaction between climate factors, particularly temperature and humidity, in influencing the incidence of diseases like dengue fever and HFMD. These interactions suggest that climate factors often work together to affect disease patterns, which can inform more precise public health interventions [50]. Finally, our study offers practical recommendations for Can Tho, including enhanced disease surveillance and targeted vector control programs, based on the specific climate-disease relationships identified. These tailored strategies are essential for addressing the growing health challenges posed by climate change. In summary, while similar studies exist, our work contributes novel, localized insights into the climate-disease relationship, making it valuable for both academic research and public health practice in Can Tho.

4.6. Limitations of the study

One of the key limitations of this study is the unavailability of data on socio-economic factors, healthcare access, and population density, which are important confounders that could influence the relationship between climate variables and disease incidence. These factors are well-documented determinants of health outcomes and may interact with climate variables to shape the patterns of infectious disease transmission [51]. Unfortunately, consistent and granular data for these variables over the study period (2014–2022) in Can Tho City were not accessible. Although our analysis focused on high-quality climate and disease incidence data, the lack of socio-economic and healthcare-related variables limits the ability to account for their potential confounding effects. For instance, population density could amplify or attenuate the impact of climate factors on disease spread, while differences in healthcare access may lead to variability in disease reporting. Without these data, the causal inferences drawn from this study should be interpreted with caution. To address these limitations, future studies should integrate data on socio-economic status, healthcare accessibility, and population distribution to build a more comprehensive model of climate-sensitive disease dynamics. Such efforts could provide a more robust understanding of how these contextual factors mediate the effects of climate change on public health. For example, examining variations in disease incidence across regions with differing levels of healthcare access could uncover additional layers of vulnerability and resilience. Similarly, incorporating population density as a covariate could help disentangle its role in modifying the associations between climate factors and disease patterns.

While the retrospective nature of this study spanning 2014 to 2022 allowed us to explore long-term climate-disease relationships, we acknowledge its inherent limitations. Seasonal variations in climate and disease incidence pose a risk of temporal biases. To mitigate these, we incorporated a temporal covariate (year) into our models and employed advanced statistical approaches like BKMR to capture non-linear and interactive effects of climate variables over time. However, as with all retrospective studies, the potential for unmeasured confounders and incomplete data remains. Future prospective studies could complement this work by collecting detailed real-time data to validate and expand upon these findings.

While our study identifies significant correlations between climate factors and disease incidence, we acknowledge that correlation does not imply causation. The observed associations should be interpreted with caution, as other indirect factors, such as migration patterns, water supply issues, and healthcare access, may also contribute to disease transmission [50]. These factors were not accounted for in this analysis, but future studies could incorporate such variables to gain a more comprehensive understanding of the causal relationships between climate and infectious diseases. Our work highlights the potential links between climate factors and disease trends, laying the foundation for further exploration into these complex interactions.

Although this study is limited to Can Tho, Vietnam, it provides valuable insights into the relationship between climate factors and infectious disease incidence in a region particularly vulnerable to climate change. The findings from this study align with trends observed in other tropical and subtropical regions, where similar climate variables, such as temperature and rainfall, play a significant role in influencing disease dynamics [52]. Given the increasing global relevance of climate-sensitive infectious diseases, this research adds to the growing body of literature exploring the impact of climate change on public health, particularly in Southeast Asia [53]. While our findings are region-specific, they offer important lessons that can be applied to other regions experiencing similar climatic shifts. Future research should aim to compare these results with data from other countries or regions with comparable climates, disease burdens, and socio-economic conditions. This would enhance the generalizability of the findings and contribute to the broader understanding of how climate change affects infectious disease patterns worldwide. Despite these limitations, the observed associations between climate variables and diseases such as diarrhea and dengue fever align with findings from previous studies in similar settings. This consistency lends confidence to the validity of our results. However, the absence of certain confounder data highlights the importance of interpreting our findings as part of a broader narrative on climate-sensitive health outcomes, rather than as definitive causal relationships. A more comprehensive approach, integrating climate data with socio-economic and healthcare-related factors, is essential to better inform targeted public health interventions and policies.

5. Conclusion

This longitudinal study, covering 108 consecutive months from 2014 to 2022, analyzed the incidence rates of prevalent infectious diseases in Can Tho, Vietnam, excluding tuberculosis, HIV, and COVID-19. Among the most prevalent diseases during this period were diarrhea, dengue fever, HFMD, viral hepatitis, and influenza. Our analysis revealed that climate factors—specifically temperature, humidity, and rainfall—exert significant influence on the incidence of HFMD, dengue fever, malaria, and chickenpox.

In our BKMR analysis, we observed that the combined effects of temperature and humidity were particularly pronounced in the case of dengue fever and HFMD, with a notable increase in disease incidence when these climate factors were at or above their 60th percentile, as compared to the 50th percentile. Furthermore, we identified significant interactions between climate variables—namely humidity, temperature, rainfall, and sunshine duration—with temperature emerging as the most influential factor.

These findings underscore the critical role of climate in shaping the epidemiology of infectious diseases in Can Tho. Given these insights, we recommend that public health strategies in the region account for climatic influences when formulating disease prevention and control measures. Specifically, authorities should focus on enhancing surveillance, prevention, and control efforts to mitigate the spread of climate-sensitive diseases. Potential initiatives include vaccination campaigns, vector control programs, public health education on hygiene practices, and strengthening healthcare infrastructure to effectively manage outbreaks. Tailoring these initiatives to local climate patterns and socio-economic conditions will be key to improving their effectiveness and ensuring the long-term protection of public health.

CRediT authorship contribution statement

Cuong Quoc Hoang: Writing – review & editing, Investigation, Data curation. **Quang Phuong Huynh Nguyen:** Investigation, Data curation. **Thao Phuong Huynh Nguyen:** Investigation, Data curation. **Hieu Trung Nguyen:** Investigation, Data curation. **Linh Thuy Hoang:** Visualization, Validation. **Giang Huong Vu:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Woong-Ki Kim:** Writing – review & editing, Visualization, Validation, Supervision. **Hai Duc Nguyen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization.

Ethics approval and consent to participate

Because this study relied on secondary data sources concerning climate and infectious diseases, there were no interventions, impacts on human subjects, or medical ethics considerations. The study was approved by the Scientific Research Council of the City Center for Disease Control in Can Tho.

Data availability statement

All data relevant to the study are included in the article or uploaded as Supplementary information.

Funding statement

None.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2025.e41902.

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