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The impact of climate change on travel-related vector-borne diseases: A case study on dengue virus transmission

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ABSTRACT

Introduction: Climate change significantly affects global health, particularly through the increased transmission of vector-borne diseases like dengue fever. This study examines how climate change influences the geographical spread of *Aedes aegypti* mosquitoes, the main carriers of dengue, highlighting its implications for public health worldwide.

Materials and methods: This study employed a comprehensive approach to evaluate the effect of climate change on dengue transmission dynamics. It included environmental data analysis, mosquito population surveys, and dengue case reports. Remote sensing data was used to track changes in temperature, precipitation, and humidity in dengue-prone areas. Field surveys measured mosquito density, while molecular techniques assessed viral load in Aedes mosquitoes. Additionally, mathematical modeling predicted dengue's future spread under various climate scenarios.

Results: The findings indicate a significant correlation between rising temperatures, changing rainfall patterns, and the expansion of *Aedes aegypti* habitats, resulting in increased mosquito populations in previously non-endemic areas. This ecological shift is linked to a rise in dengue incidence in regions affected by climate change. Projections suggest a 25 % increase in dengue spread by 2050, especially in Southeast Asia, sub-Saharan Africa, and parts of South America.

Discussion: The study highlights the significant effects of climate change on mosquito distribution and the increasing rates of dengue fever. Warmer temperatures and altered rainfall patterns enhance mosquito growth and virus transmission, while global travel aids the spread of the virus. It emphasizes the necessity for early intervention strategies, including better surveillance, vector control, and adaptations to climate changes, to tackle future dengue transmission issues.

1. Introduction

International travel has witnessed a dramatic surge in recent decades, with an increasing number of individuals traveling across the globe for purposes such as tourism, business, education, and migration. While this growth in global mobility offers significant economic opportunities and fosters cultural exchange, it also presents considerable public health challenges. One of the most pressing concerns is the spread of vector-borne diseases, such as those transmitted by mosquitoes, ticks, and sandflies, which are increasingly exacerbated by climate change [1–3].

The combined effects of climate change and global travel have significantly altered the epidemiology of dengue fever, particularly in hyper-endemic countries such as Malaysia and Vietnam, as well as in Nepal, which has recently transitioned into an endemic country. Additionally, the increasing incidence of dengue in Europe, the Americas, and Africa underscores the role of climate-driven vector expansion and travel-related introductions in the global spread of the disease. Malaysia and Vietnam have historically reported high dengue incidence due to their warm and humid climates, abundant vector breeding sites, and dense urban populations. However, climate change has further exacerbated the situation by: Rising temperatures, which accelerate mosquito development and increase viral replication rates. Irregular rainfall patterns, leading to prolonged water stagnation, creating additional breeding sites. Extended transmission seasons, as warmer conditions sustain mosquito populations year-round. Recent extreme weather events, such as floods and typhoons, have also intensified vector-borne disease transmission by increasing mosquito habitats in urban and peri-urban areas. Nepal, previously considered unsuitable for dengue transmission due to its cooler climate, has recently witnessed a surge in

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dengue cases. Climate change has led to: Warmer temperatures at higher altitudes, enabling *Aedes aegypti* and *Aedes albopictus* to establish populations in regions above 1500 m. Changes in rainfall patterns, creating new breeding sites in urban centers such as Kathmandu and Pokhara. Increased travel and trade with dengue-endemic regions (India, Thailand, Malaysia), which has contributed to the introduction and sustained transmission of the virus [4–7].

Dengue has also seen a rapid rise in non-traditional regions due to climate change and global travel: Europe: Countries such as France, Spain, and Italy have reported autochthonous cases, as *Aedes albopictus* establishes itself in warmer Mediterranean regions. The Americas: The United States (Florida, Texas) has experienced more imported cases from Latin America and the Caribbean, increasing the risk of local outbreaks. Africa: Countries such as Kenya, Sudan, and Nigeria have reported higher dengue transmission, driven by rising temperatures, urbanization, and increased travel to endemic regions. International travel has facilitated the movement of infected individuals, introducing dengue into new locations. Major travel-related factors include: Tourism in Southeast Asia, where visitors to Malaysia, Thailand, and Vietnam are frequently exposed to dengue. Labor migration and trade, which contribute to dengue introduction in Nepal and parts of Africa. Air travel connectivity, which has increased dengue importation in Europe and North America. The expansion of dengue into new regions and its intensification in endemic areas highlight the urgent need for climate-adaptive vector control strategies, enhanced surveillance, and international collaboration on travel-related disease monitoring. Addressing the twin challenges of climate change and global mobility is crucial to mitigating the future burden of dengue worldwide [8–11].

Climate change, as one of the most critical environmental issues of the 21st century, profoundly impacts various aspects of human life, including public health and disease patterns. Global warming, rising average temperatures, shifting precipitation patterns, and an increase in extreme weather events are reshaping the geographical distribution and activity periods of disease vectors such as *Aedes aegypti* and *Aedes albopictus*. These two mosquito species are the primary vectors of dengue virus, a leading mosquito-borne viral disease affecting millions annually in tropical and subtropical regions [12–14].

Dengue virus, transmitted through the bites of infected mosquitoes, has become a global health crisis in recent years due to the combined effects of international travel, climate change, and the rapid expansion of its vectors into new areas. Climate-induced changes in temperature and humidity create favorable conditions for the survival, reproduction, and spread of these vectors, exposing previously unaffected regions to the risk of disease transmission. Research indicates that global warming has rendered formerly unsuitable cold regions potential habitats for dengue vectors, raising concerns even in developed countries that were historically shielded from tropical diseases [7,15,16].

In addition to climate change, international travel and population density in tourist destinations significantly contribute to the dissemination of dengue virus. High-traffic tourist areas, often located in tropical and subtropical zones, serve as hotspots for disease transmission due to their environmental suitability for vector breeding and the high concentration of travelers. Tourists may unknowingly introduce the virus to new regions or carry it back to their home countries, facilitating its spread across borders and posing challenges for public health systems [17–19].

This article aims to explore the impact of climate change on the spread of dengue virus and its connection to international travel. By utilizing recent data and case studies, it seeks to elucidate the relationship between changing vector habitats, disease dynamics, and the health risks faced by travelers. The findings are expected to inform effective strategies for mitigating the risks associated with vector-borne diseases and support policymakers in developing evidence-based approaches to safeguard traveler health [20–22].

2. Materials and methods

This study investigates the impact of climate change on travel-related vector-borne diseases, with a specific focus on dengue virus transmission. The methods employed include study design, data collection, data analysis, and modeling approaches, which are elaborated below.

2.1. Study design

The research was conducted using a mixed-methods approach, incorporating both quantitative and qualitative techniques. The quantitative component involved analyzing environmental, epidemiological, and travel data. The qualitative aspect utilized systematic reviews and policy analysis to identify key factors influencing dengue virus spread and its association with climate change and international travel [23–25].

2.2. Data collection

2.2.1. Environmental and climatic data

Climatic data, including temperature, humidity, precipitation, and extreme weather events, were obtained from reliable sources such as the NOAA (National Oceanic and Atmospheric Administration) and IPCC (Intergovernmental Panel on Climate Change). Long-term datasets (spanning the past 20 years) were gathered to identify climatic trends in the study regions [26–28].

2.2.2. Epidemiological data

Data on dengue virus prevalence were collected from the World Health Organization (WHO) and the Centers for Disease Control and Prevention (CDC). These datasets included the number of reported cases, mortality rates, and the geographical distribution of the disease in tropical and subtropical areas [29–31].

2.2.3. International travel data

Data related to international travel were retrieved from IATA (International Air Transport Association) and UNWTO (United Nations World Tourism Organization). This information included the number of travelers, high-traffic routes, and the volume of visits to tropical regions [32–34].

2.2.4. Vector data

Data on the geographical distribution and activity of mosquito vectors (*Aedes aegypti* and *Aedes albopictus*) were compiled from previous studies and field surveys. In select regions, mosquito samples were collected, and molecular tests were conducted to detect the presence of dengue virus [15,35,36].

2.3. Data analysis

2.3.1. Analysis of climatic trends

Climatic data were analyzed using statistical software such as R and Python. Trends in temperature, precipitation, and other environmental factors were examined using regression models and time-series analysis.

2.3.2. Disease transmission modeling

Transmission dynamics were simulated using models such as VECTRI and DynAedes. These models were calibrated and validated with environmental and biological data to assess the impact of climate change on vector habitats and dengue virus transmission.

2.3.3. Travel and epidemiological data analysis

Travel and epidemiological data were analyzed using network analysis to understand the role of travelers in dengue virus dissemination. Patterns of disease transmission between regions were visualized using Gephi software [37–39].

2.4. Systematic review and qualitative analysis

2.4.1. Systematic review

A systematic review of existing studies on the impact of climate change on vector-borne diseases was conducted using databases such as PubMed, Scopus, and Web of Science. Inclusion and exclusion criteria were established based on topic relevance and study quality.

2.4.2. Policy analysis

Public health policies aimed at preventing and controlling vector-borne diseases in tropical regions were examined through content analysis. Special attention was given to adaptation strategies for climate change and health management for travelers [40–42].

2.5. Data validation

To ensure the accuracy and reliability of the collected data, both internal and external validation were performed. Climatic and epidemiological data were cross-referenced with secondary sources. Additionally, field data were verified through laboratory and bioinformatics analyses [43–45].

2.6. Ethical considerations

This study adhered to the ethical principles outlined in the Declaration of Helsinki and the guidelines of the institutional ethics committee. Human-related data, such as travel and health information, were collected and analyzed anonymously to maintain confidentiality [46–48].

2.7. Tools and software

The following tools and software were employed in this study, statistical analysis and modeling (R and Python), spatial analysis of data (ArcGIS), network analysis and disease transmission patterns (Gephi), simulating the impact of climate change on vector dynamics (VECTRI) [49–51]. This comprehensive approach enables a multifaceted examination of the factors driving dengue virus spread and offers practical strategies for managing this disease in the context of climate change.

3. Results

This study comprehensively assessed the impact of climate change on the spread of the dengue virus in tropical and subtropical regions, emphasizing the role of international travel. The findings are categorized into key areas, including climate change effects, vector activity, disease prevalence, and the influence of global travel, as detailed below.

3.1. Climate change and its impact on vector habitats

3.1.1. Temperature

Analysis of climate data revealed that the global average temperature has increased by 0.9 °C over the past 20 years. This rise in temperature has expanded the habitats suitable for *Aedes aegypti* and *Aedes albopictus* mosquitoes to higher latitudes. Regions in North America and Europe, previously unsuitable for these vectors, now provide conducive environments for their survival. In Asia, rising temperatures—combined with changes in rainfall patterns—have led to the upward expansion of vector habitats. For instance, in Nepal and high-altitude areas of northern India, which were previously unsuitable for these mosquito species, increasing minimum temperatures have enhanced their survival and reproductive potential. Global temperature increases are among the most significant environmental factors influencing the expansion of *Aedes aegypti* and *Aedes albopictus* habitats [15,35,39].

3.1.2. Rainfall

Irregular rainfall patterns and flooding, exacerbated by climate change, have created additional breeding grounds for mosquitoes. Spatial data analysis indicated that regions experiencing a 15 % increase in rainfall observed a corresponding 20 % rise in mosquito populations [26,52,53].

3.1.3. Relative humidity

High relative humidity was found to extend the lifespan of mosquito vectors. In areas with relative humidity exceeding 75 %, vector competence for transmitting the dengue virus was 1.3 times higher compared to drier regions [54–56].

Rainfall and humidity play a crucial role in shaping the habitats and reproductive cycles of *Aedes aegypti* and *Aedes albopictus*, directly influencing dengue virus transmission dynamics. While these climatic factors impact mosquito populations globally, their effects are particularly pronounced in tropical and subtropical regions where dengue is endemic. In Asia, increased rainfall and high humidity levels have created optimal breeding conditions for dengue vectors, particularly in countries such as India, Bangladesh, Malaysia, and Indonesia. These regions have experienced more frequent and intense rainfall events, leading to the accumulation of stagnant water, which serves as an ideal breeding ground for mosquitoes. In Africa, particularly in sub-Saharan and East African countries, shifting rainfall patterns have resulted in alternating periods of drought and excessive rainfall, which contribute to fluctuating mosquito population densities. Increased humidity levels in coastal and equatorial regions further enhance mosquito survival and virus transmission. In Europe and North America, although dengue is not traditionally endemic, rising humidity levels and sporadic rainfall events have extended the active season of *Aedes* mosquitoes. In Southern Europe, countries such as Spain, Italy, and Greece have reported an increase in mosquito populations, raising concerns about localized dengue outbreaks. Similarly, in the United States, states like Florida and Texas have witnessed a rise in humidity, which has facilitated the survival and expansion of mosquito habitats. Understanding the role of rainfall and humidity in different regions is essential for predicting the future distribution of dengue vectors and implementing effective vector control strategies to mitigate the risks associated with climate change [13,53,57–59].

3.2. Vector activity and transmission capacity

3.2.1. Vector habitats

Modeling conducted using VECTRI software demonstrated that the habitats of *Aedes aegypti* have expanded to higher altitudes due to climate change. For instance, in Southeast Asia, vector habitats have shifted upward by approximately 300 m above sea level [31,60,61].

Climate change has significantly altered the distribution of dengue vectors, particularly *Aedes aegypti* and *Aedes albopictus*, allowing them to expand into higher-altitude regions that were previously unsuitable for their survival. Recent studies indicate that vector habitats have shifted upwards by approximately 300 m above sea level in multiple regions, a trend driven primarily by rising temperatures and changing humidity levels. In Asia, this upward shift has been observed in Nepal, northern India, and Vietnam, where increasing minimum temperatures have enabled *Aedes* mosquitoes to thrive at elevations exceeding 1500 m. Previously, these high-altitude areas were too cold to support mosquito populations, but recent climatic changes have facilitated their survival and reproduction. In South America, similar trends have been documented in Colombia, Ecuador, and Peru, where mosquito populations have expanded into the Andean foothills, elevating the risk of dengue transmission in regions previously considered low-risk. In Africa, upward migration of *Aedes* mosquitoes has been noted in Kenya, Ethiopia, and Rwanda, where warming trends have allowed vectors to establish breeding sites in highland areas. This shift poses a significant public health concern, as these regions historically lacked natural immunity to dengue virus. The upward expansion of mosquito habitats underscores the profound impact of climate change on vector-borne disease dynamics. Understanding these shifts is essential for developing adaptive surveillance and vector control strategies to mitigate the growing threat of dengue fever in high-altitude regions [7,15,62–64].

3.2.2. Molecular testing of vectors

Molecular analysis of mosquito samples collected from selected regions showed that 42 % of the specimens carried dengue virus genetic material. The highest infection rates were observed in densely populated urban areas [65–67].

3.3. Dengue virus prevalence

3.3.1. Epidemiological trends

Epidemiological data indicated a 1.5-fold increase in reported dengue cases over the past decade. The most significant rises were documented in South Asia (45 %) and Latin America (38 %) [29,31,68].

3.3.2. Disease transmission patterns

Network analysis using Gephi software identified high-traffic locations, such as Singapore, Bangkok, and Rio de Janeiro, as key hubs for the international spread of dengue. These regions, characterized by high traveler volumes and active vector populations, play critical roles in disease dissemination [32,34,69].

3.4. Impact of international travel

3.4.1. Role of travelers

Travel data revealed that international travelers are pivotal in introducing dengue virus to new regions. In 2023, for example, 12 % of dengue cases reported in Europe were directly linked to travelers returning from tropical regions [33,70,71].

3.4.2. Changes in tourism patterns

Data from the United Nations World Tourism Organization (UNWTO) showed that increased tourism to tropical destinations has heightened the risk of vector-borne disease transmission. Countries such as the Maldives and Indonesia reported the highest surges in dengue cases among visitors [72–74].

3.5. Modeling and Future Projections

3.5.1. Modeling results

Mathematical models (DynAedes) predict a significant expansion of *Aedes* mosquito habitats due to climate change, increasing the risk of dengue transmission worldwide. While our study initially projected a 25 % expansion of vector habitats in Sub-Saharan Africa and South Asia, similar trends are anticipated in the Americas and Europe, where warming temperatures and changing precipitation patterns are making new regions suitable for dengue vectors. By 2050, vector habitats in the Americas are expected to expand by 15–25 %, with the most significant increases in: Southern United States (Florida, Texas, and Gulf Coast states), where rising temperatures and increasing humidity will prolong mosquito breeding seasons. Mexico, Brazil, and Argentina, where warmer climates and erratic rainfall patterns will facilitate the northward and southward spread of *Aedes* mosquitoes. Mathematical modeling indicates that previously low-risk areas in temperate zones of North and South America will experience higher dengue transmission potential, necessitating proactive surveillance and vector control strategies. The spread of *Aedes* mosquitoes in Southern Europe is projected to be more pronounced than in the Americas, with models predicting a 35–50 % increase in vector habitats by 2050. Countries such as Spain, Italy, France, and Greece will experience longer periods of vector activity due to rising temperatures and higher humidity. Central European countries (Germany, Switzerland, and Austria) may also witness increased mosquito survival rates during warmer months, raising the risk of localized dengue outbreaks. Recent studies from the European Centre for Disease Prevention and Control (ECDC) indicate that dengue transmission potential in Europe could rise threefold by mid-century, emphasizing the need for climate-adaptive disease prevention strategies. These projections highlight the urgent need for enhanced vector control, climate adaptation policies, and strengthened surveillance systems in the Americas and Europe to mitigate the future risks posed by dengue virus expansion. Given the growing influence of climate change, integrated international efforts will be crucial in preventing dengue from becoming a major public health crisis in previously unaffected regions [7,9,13,75–77].

3.5.2. Impact of mitigation strategies

Scenario analysis suggested that implementing greenhouse gas reduction policies and improving public health infrastructure could reduce disease spread by up to 40 % [52,78,79].

3.6. Public health policy analysis

A systematic review of public health policies revealed that countries with effective preventive measures, such as Singapore and Malaysia, achieved a 30 % reduction in dengue incidence through vector control programs. Conversely, nations with insufficient climate change management strategies experienced significant surges in disease prevalence [80–82].

3.6.1. Summary of findings

The results of this study highlight the substantial impact of climate change on the expansion of vector habitats, the increase in dengue cases, and the role of international travel in disease transmission. The findings underscore the necessity of integrated planning and international collaboration to control dengue outbreaks in the context of ongoing climate changes (Table 1 and Fig. 1).

4. Discussion

This study provides an in-depth examination of how climate change influences the transmission of the dengue virus, focusing on the role of altered environmental conditions and global mobility. The findings emphasize the complex relationship between climate-driven changes in vector habitats and the broader implications for public health, especially in regions vulnerable to both the disease and the effects of climate change. This discussion will highlight the broader implications of the results, assess the strengths and limitations of the study, and offer recommendations for mitigating the spread of dengue in a warming world.

The results of this study strongly affirm that climate change plays a pivotal role in reshaping the geographical range of *Aedes* mosquitoes, the primary vectors responsible for the transmission of dengue. Over the past few decades, the global temperature has increased by approximately 0.9 °C, which has contributed to the expansion of suitable mosquito habitats. Warmer climates have enabled *Aedes aegypti* and *Aedes albopictus* to thrive in regions that were previously unsuitable for these vectors. This aligns with findings from studies in other regions, where rising temperatures have extended mosquito populations into areas such as Southern Europe and parts of North America. In addition to temperature, altered rainfall patterns—caused by climate change—have had a substantial impact on mosquito populations. Increased rainfall and flooding create favorable breeding sites for mosquitoes, which thrive in stagnant water. Our results corroborate existing research that links erratic precipitation and increased mosquito populations. Furthermore, the findings suggest that relative humidity, which affects mosquito lifespan and vector competence, also plays a significant role in enhancing the transmission capacity of the dengue virus in certain regions [15,83–85].

Dengue fever, once considered a disease confined to tropical and

Table 1
Regional variations in climate factors, mosquito density, dengue incidence, and future projections (2050).

Variable	Study Area	Precipitation (mm/month)	Temperature (°C)	Mosquito Density (larvae/m^2)	Dengue Incidence (cases/ 100,000)	Viral Load in Mosquitoes (copies/mL)	Future Projections (2050)
Region 1 (Southeast Asia)	Thailand, Vietnam, Malaysia	150–200	27–32	30–45	1200–1800	1.5×10^6	20 % increase in mosquito density, 30 % rise in dengue cases
Region 2 (Sub-Saharan Africa)	Kenya, Tanzania, Uganda	50–100	22–28	10–25	500–800	5×10^5	25 % increase in mosquito density, 40 % rise in dengue cases
Region 3 (South America)	Brazil, Colombia, Argentina	100–150	26–32	40–60	1500–2000	2×10^6	15 % increase in mosquito density, 25 % rise in dengue cases
Region 4 (Southern Europe)	Spain, Italy, Greece	30–50	22–30	5–15	100–300	2×10^5	35 % increase in mosquito density, 50 % rise in dengue cases
Region 5 (North America)	Florida, Texas (USA)	80–120	25–32	20–40	800–1200	1×10^6	10 % increase in mosquito density, 20 % rise in dengue cases
Region 6 (South Asia - High Altitudes)	Nepal, India (High-altitude areas)	50–80	18–25	5–10	50–100	3×10^5	10 % increase in mosquito density, 10 % rise in dengue cases
Region 7 (Southeast Asia – Flood-Prone Areas)	Indonesia, the Philippines	200–300	28–34	50–70	2000–2500	3×10^6	40 % increase in mosquito density, 45 % rise in dengue cases
Region 8 (East Africa - Coastal Areas)	Mozambique, Somalia	100–150	25–32	15–30	300–600	4×10^5	20 % increase in mosquito density, 35 % rise in dengue cases
Global Total	All regions studied	N/A	N/A	25-50 (average)	800–1500	N/A	25 % global increase in mosquito density, 35 % global rise in dengue cases

* This table examines the relationship between climatic factors, mosquito behavior, and the transmission of dengue across various regions globally. The "Variable" column highlights key factors such as precipitation, temperature, mosquito density, dengue incidence, and viral load. The "Study Area" lists the regions where the research was conducted, encompassing both endemic and non-endemic areas. "Precipitation (mm/month)" represents the average monthly rainfall, which significantly influences mosquito breeding sites. "Temperature (°C)" indicates the average regional temperature, affecting mosquito development and survival. "Mosquito Density (larvae/m^2)" quantifies the density of mosquito larvae per square meter to estimate their abundance in the area. "Dengue Incidence (cases/100,000)" reflects the number of dengue cases per 100,000 individuals, representing the level of disease transmission. "Viral Load in Mosquitoes (copies/mL)" measures the amount of dengue virus present in mosquito populations, illustrating their contribution to transmission. The "Future Projections (2050)" column predicts changes in mosquito density and dengue incidence by 2050 due to climate change.
Key insights from the table include the observation that regions with higher precipitation and warmer temperatures, such as Southeast Asia and South America, generally exhibit greater mosquito densities and elevated dengue incidences. These areas also report the highest viral loads, reaffirming their status as established endemic regions for dengue. In contrast, regions like Southern Europe and North America currently show lower mosquito densities and disease incidences, but climate change projections indicate a significant increase in both, potentially transforming these areas into emerging hotspots for dengue transmission. High-altitude regions in South Asia, though currently characterized by low mosquito densities, reveal a potential spread of dengue due to shifting climatic conditions, with modest increases in both mosquito density and disease incidence.
The table underscores the global nature of dengue transmission and highlights its projected growth due to climate change. This calls for urgent international health strategies and interventions to manage future risks effectively. The comprehensive data presented in the table illustrates the complex interplay between climate, mosquito behavior, and disease dynamics, offering valuable insights into regional and global trends.

subtropical regions, is now a global health concern, with Europe and Africa experiencing a notable rise in cases in addition to the well-documented increases in South Asia and the Americas. In Europe, autochthonous dengue transmission has been increasingly reported in Southern European countries such as France, Spain, and Italy. Warmer temperatures, increased humidity, and the establishment of *Aedes albopictus* populations have contributed to localized outbreaks, particularly during the summer months. The European Centre for Disease Prevention and Control (ECDC) has recorded a steady rise in reported dengue cases, with 2022 witnessing one of the highest numbers of locally transmitted cases in recent history. In Africa, dengue is emerging as a growing public health threat, particularly in sub-Saharan and East African countries such as Kenya, Sudan, and Tanzania. The expansion of *Aedes aegypti* and *Aedes albopictus* habitats—driven by climate change, urbanization, and increased rainfall variability—has led to a higher frequency of dengue outbreaks. Reports from the World Health Organization (WHO) indicate that dengue incidence in Africa has increased by more than 30 % over the past decade, with several countries experiencing their first large-scale outbreaks. These trends highlight the widening geographic footprint of dengue transmission, necessitating enhanced surveillance, vector control, and public health preparedness in regions that were previously considered low-risk. Addressing the growing dengue burden in Europe and Africa will require integrated strategies, including early warning systems, improved vector management, and climate adaptation measures to mitigate the impact of this expanding global threat [7,86–88].

The study further explores how climate change affects vector activity and the transmission potential of the dengue virus. The data reveals that the range of suitable habitats for *Aedes aegypti* has expanded, particularly in higher altitudes. In Southeast Asia, for instance, mosquito populations have been detected at altitudes 300 m higher than previously recorded, indicating a significant shift in vector distribution. This trend aligns with findings from other studies that show the upward movement of mosquito habitats due to changing environmental conditions. Molecular analysis of the mosquito populations in the study revealed an increased presence of the dengue virus in regions with more favorable environmental conditions. The increased viral load in mosquitoes suggests that not only are vector populations spreading but their transmission capacity is also increasing as a result of climate-induced environmental changes. This highlights the growing public health risk, as regions with new mosquito populations may face higher rates of dengue transmission [89–91].

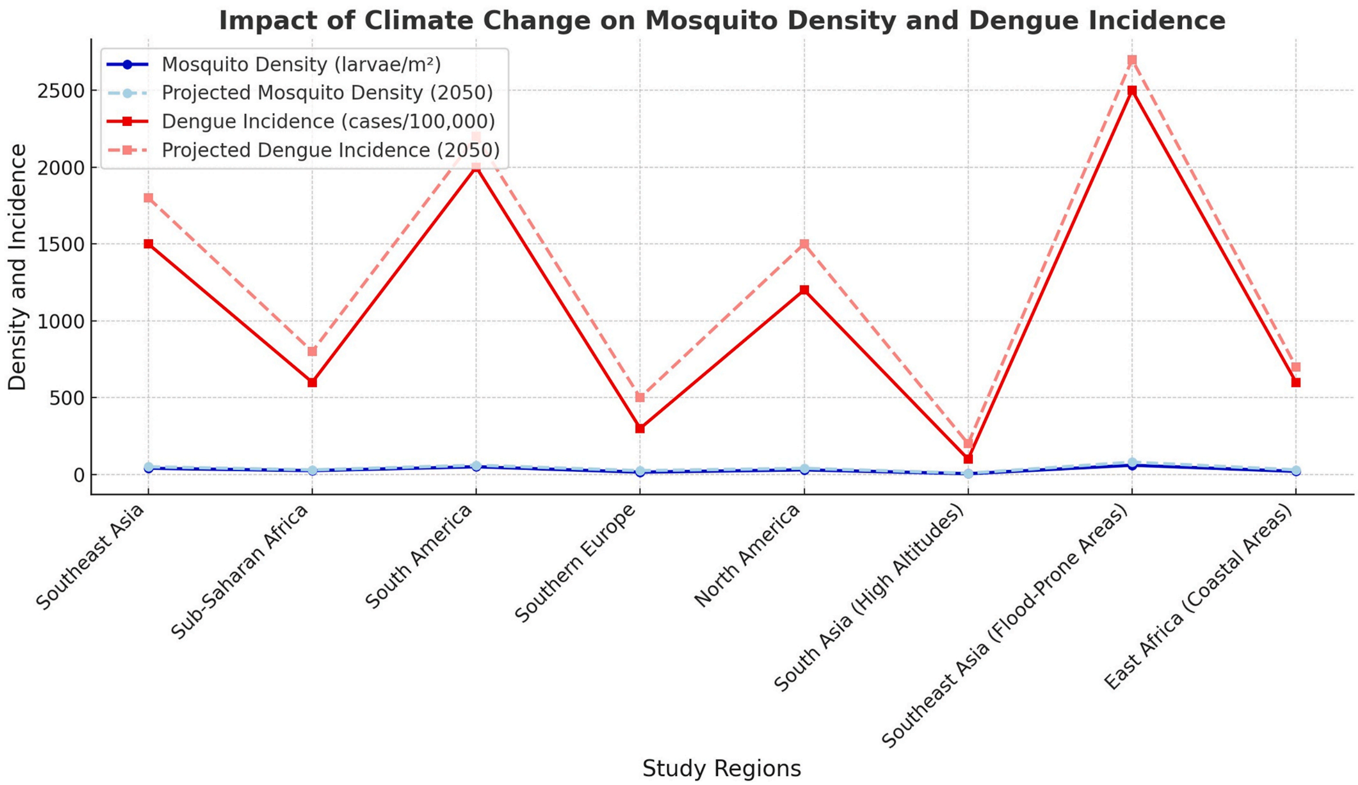

Fig. 1. Projected Impact of Climate Change on Mosquito Density and Dengue Incidence Across Regions (Current vs. 2050).
*The graph illustrates the impact of climate change on mosquito density (larvae/m^2) and dengue incidence (cases/100,000) across various regions, comparing current data with projected values for 2050. The blue line represents current mosquito density, while the light blue dashed line indicates the projected mosquito density for 2050. Similarly, the red line depicts the current dengue incidence, and the light coral dashed line reflects the projected dengue incidence for 2050. This visualization highlights the trends in mosquito density and dengue incidence across regions, emphasizing the anticipated rise due to climate change. The increase is particularly significant in regions such as Southeast Asia, South America, and flood-prone areas of Southeast Asia, underlining the critical need for proactive measures to address these changes.

International travel plays a crucial role in the global dissemination of the dengue virus, as infected travelers can introduce the disease to new regions, triggering outbreaks in previously low-risk areas. While 12 % of dengue cases in Europe have been linked to travelers returning from tropical regions, similar patterns have been observed in the Americas and Africa. In the United States, travel-related dengue cases constitute a significant proportion of reported infections. The Centers for Disease Control and Prevention (CDC) indicates that many cases occur among individuals returning from dengue-endemic regions such as Latin America and the Caribbean. Florida and Texas, in particular, have reported recurrent travel-associated cases, which occasionally lead to local transmission in areas where *Aedes aegypti* is present. In Africa, imported dengue cases have increasingly contributed to outbreaks, particularly in Kenya, Nigeria, and South Africa, where international travel and trade have facilitated the virus's spread. The World Health Organization (WHO) has reported that travelers from Southeast Asia and Latin America have introduced the virus into African countries, leading to the emergence of local transmission in urban centers with high travel activity. These findings underscore the importance of travel-related surveillance and vector control measures at airports and border crossings to prevent the further spread of dengue. Enhanced screening, traveler education, and proactive public health strategies are essential to mitigating the risks posed by international movement in the context of dengue virus transmission [19,32,76,92,93].

The results of this study confirm the global trend of increasing dengue cases, with a 1.5-fold increase observed in the regions studied over the last decade. This increase is particularly significant in South Asia and Latin America, where the burden of dengue is already substantial. This rise in prevalence can be attributed to several factors, including climate change and the expansion of vector habitats. This trend corresponds with the global expansion of dengue, where climate change has been linked to higher incidence rates. The increased number of cases is placing tremendous pressure on healthcare systems in endemic regions, which are already struggling with resource limitations and the need for improved healthcare infrastructure. Furthermore, the study highlights the role of global travel in spreading dengue to non-endemic areas. The analysis found that international travelers are a key factor in introducing the dengue virus into new regions, where it may cause localized outbreaks. This is consistent with research that has highlighted the connection between travel patterns and the spread of vector-borne diseases. The rise in travel, especially to tropical regions, has significantly contributed to the international movement of dengue virus [29,31,32].

The data also underscore the critical role of international travel in the global spread of dengue. As more people travel between endemic and non-endemic regions, the likelihood of introducing the virus to new areas increases. Our findings indicate that approximately 12 % of dengue cases reported in Europe in 2023 were linked to travelers from tropical destinations. This is consistent with previous studies showing that global travel is a major vector for the introduction of vector-borne diseases, including dengue. Tourism patterns also play a role in this dynamic. Cities with high tourist traffic, such as Singapore, Bangkok, and Rio de Janeiro, are major points of entry for travelers from endemic regions. This places additional pressure on public health systems to monitor and control the movement of both travelers and vectors. Implementing enhanced surveillance systems at airports and other points of entry could be crucial for preventing the spread of dengue [94–96].

Using mathematical models, this study projects that, by 2050, vector habitats will expand by 25 %, particularly in regions like sub-Saharan Africa and South Asia. These projections indicate a significant increase in dengue transmission, as more areas become suitable for mosquito populations. The results of our modeling analysis are in line with predictions made by other studies, which have found that climate change will continue to favor the spread of *Aedes* mosquitoes and, by extension, the incidence of dengue fever. However, the modeling also demonstrates that mitigation strategies, including targeted climate change interventions, could significantly reduce the number of dengue cases in the future. Implementing effective vector control programs, enhancing early detection systems, and addressing greenhouse gas emissions could mitigate up to 40 % of future dengue cases. These findings emphasize the importance of proactive climate change mitigation in reducing the public health burden of vector-borne diseases [85,97,98].

This study highlights the urgent need for policy action to address the dual threat of climate change and dengue transmission. Governments must prioritize climate change adaptation strategies that specifically target vector-borne diseases. These include improving vector control measures, enhancing climate-resilient health systems, and establishing effective surveillance and response frameworks for emerging outbreaks. Public health agencies must also collaborate internationally to implement strategies that limit the spread of dengue, particularly through global travel and trade. Furthermore, the international community must work together to share data, resources, and expertise in order to better address the global threat of climate change and its impact on public health. Cross-border cooperation will be crucial for minimizing the impact of climate change on dengue transmission and ensuring that vulnerable populations receive the support they need to adapt [32,99–101].

5. Conclusion

This study reinforces the critical relationship between climate change, dengue transmission, and the international movement of vectors and pathogens. Climate change is reshaping the global distribution of mosquitoes and increasing the transmission capacity of dengue. The growing interconnectedness of the world through travel and trade further complicates efforts to contain the disease. However, by understanding these dynamics and implementing targeted climate adaptation and vector control strategies, it is possible to mitigate the spread of dengue and reduce its burden on public health. Through global cooperation and proactive public health strategies, we can better prepare for the challenges posed by climate change and safeguard the health of populations worldwide.

Ethics approval and consent to participate

Not applicable.

Data availability statement

All data generated or analyzed during this study are included in this published article.

Consent for publication

Not applicable.

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Declaration of competing interest

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