Review Article

Climate Change and Vector-Borne Diseases: A Scoping Review on the Ecological and Public Health Impacts.

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ABSTRACT

Climate change is increasingly recognized as a significant driver of ecological and public health changes, particularly concerning vector-borne diseases. This scoping review aims to systematically map the current research on the impact of climate change on vector ecology and the subsequent effects on disease transmission dynamics. We conducted a comprehensive literature review across multiple databases to identify critical vectors, such as mosquitoes, ticks, and fleas. We examined how climate variables like temperature, precipitation, and humidity affect their populations, behaviors, and life cycles. Additionally, we explored the shifting geographic distributions of these vectors, investigating how climate change influences their spread and the emergence of diseases such as malaria, dengue, and Lyme disease in new regions.

The review highlights the complex and multifaceted interactions between climate change and vector-borne diseases, emphasizing the necessity of understanding these relationships to inform effective public health strategies. Our findings indicate considerable variability in the impacts of climate change across different regions and vector species, underscoring the need for localized studies and tailored interventions. Moreover, significant research gaps were identified, particularly in predictive modeling, long-term surveillance, and the socio-economic impacts of vector-borne diseases exacerbated by climate change. We suggest directions for future research, including the development of integrated climate-health models and enhanced disease surveillance systems, to better anticipate and mitigate the effects of climate change on vector-borne disease transmission. This review underscores the urgency of addressing climate change as a critical component of global health initiatives and the importance of interdisciplinary approaches in tackling this complex issue.

Keywords

Zoonotic diseases, vector adaptation, epidemiology, vector control, environmental health, disease emergence, climate variability, public health strategies, predictive modeling, disease surveillance.,

INTRODUCTION

Climate change is one of the most significant global environmental challenges of the 21st century, with profound implications for public health, mainly through its impact on vector-borne diseases. The Intergovernmental Panel on Climate Change (IPCC) has reported that rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events already affect the distribution and abundance of disease vectors [1, 2]. These changes are expected to exacerbate the burden of vector-borne diseases,

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particularly in low- and middle-income countries where health systems are often less resilient [3, 4].

Vectors such as mosquitoes, ticks, and fleas are susceptible to climatic conditions, influencing their life cycles, breeding habitats, and geographic distribution. For instance, the Aedes aegypti mosquito, a primary vector for dengue, chikungunya, and Zika viruses, thrives in warm and humid conditions. Studies have shown increased temperatures can accelerate the development time from larva to adult, potentially increasing transmission rates [5, 6]. Similarly, the geographic range of the Ixodes scapularis tick, responsible for transmitting Lyme disease, is expanding northward in North America due to milder winters and extended growing seasons [7, 8].

The relationship between climate change and vector-borne diseases is complex and influenced by multiple factors, including human behavior, land use changes, and socio-economic conditions. Urbanization and deforestation can create new breeding sites for vectors and bring humans closer to these vectors, thereby increasing the risk of disease transmission [9,10]. Furthermore, socio-economic factors such as poverty and lack of access to healthcare can exacerbate the vulnerability of populations to vector-borne diseases [11,12].

Despite the growing body of evidence, significant research gaps remain, particularly in understanding the regional variations in the impact of climate change on vector-borne diseases. There is a need for more localized studies that consider specific ecological and socio-economic contexts [13,14]. Predictive modeling and long-term surveillance are crucial for anticipating future trends and informing public health interventions [15, 16]. Addressing these gaps is essential for developing effective strategies to mitigate the impact of climate change on vector-borne diseases and protect public health.

To comprehensively understand the multifaceted interactions between climate change and vector-borne diseases, this review systematically maps the current research landscape, identifying key vectors and the

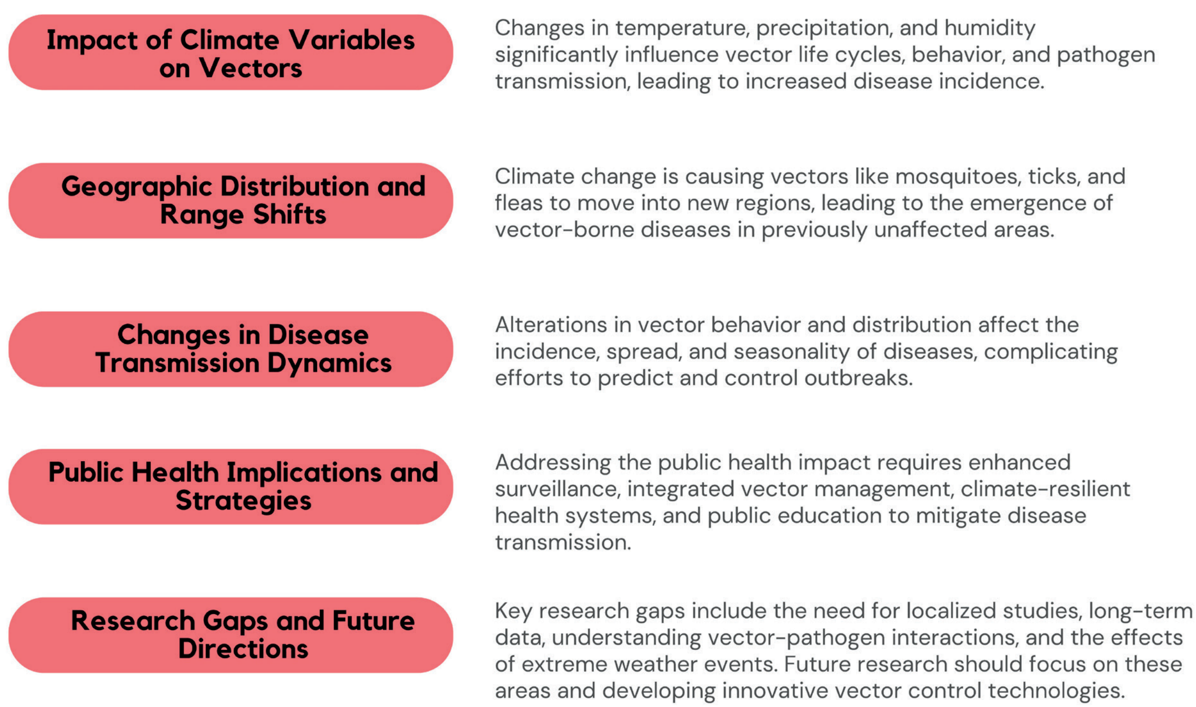

Figure 1: Objectives of the scoping review.

Image Credit: Nor Faiza Mohd. Tohit[1] diseases they transmit, examining the influence of climate variables on vector ecology, and exploring the shifting geographic distributions of these vectors. By highlighting the complexity of these interactions and identifying critical research gaps, this review aims to inform future research directions and public health strategies, ultimately contributing to a more robust response to the challenges posed by climate change in the context of vector-borne diseases.

This scoping review aims to assess the impact of climate variables on vector ecology, evaluate geographic shifts, understand disease transmission dynamics, identify public health implications, and highlight research gaps for future study (Figure 1).

MATERIALS AND METHODS

Search strategy

A systematic search followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [17] (Figure 2). The search aimed to identify studies examining the impact of climate change on vector ecology and vector-borne diseases. Databases searched included PubMed, with the search restricted to articles published in the last 10 years (2013-2023). The search terms used included combinations of keywords such as "climate change," AND "vector-borne diseases," AND "mosquitoes," AND "ticks," AND "fleas," AND "temperature," AND "precipitation," AND "public health."

Inclusion and exclusion criteria

Studies were included if they met the following criteria: (1) published in peer-reviewed journals, (2) focused on the impact of climate change on vectors (mosquitoes, ticks, fleas) and vector-borne diseases, (3) provided empirical data or modeling studies, and (4) published in English. Exclusion criteria included (1) studies focusing solely on non-climatic factors influencing vectors, (2) reviews or meta-analyses without new empirical data, and (3) articles not accessible in full text.

Study selection

The initial search yielded a total of 1,500 articles. After the initial screening (removing duplicates, unrelated articles, insufficient methodological details, and inaccessible full texts), 200 articles remained. Titles and abstracts of these articles were screened independently by two reviewers. Articles not meeting the inclusion criteria were excluded, resulting in 300 articles for full-text review. Discrepancies between reviewers were resolved through discussion, and a third reviewer was consulted when necessary. After a full-text review, 90 articles were deemed eligible for inclusion in the scoping review.

Data extraction and synthesis

Data were extracted from the included studies using a standardized extraction form. The extracted data included: (1) study characteristics (author, year, country), (2) vector species studied, (3) climate variables examined (temperature, precipitation, humidity), (4) critical findings on the impact of climate change on vector populations and disease transmission, (5) public health implications, and (6) identified research gaps. The extracted data were synthesized qualitatively to provide a comprehensive overview of the current state of research on the impact of climate change on vector-borne diseases.

Quality assessment and bias control

Although not mandatory for scoping reviews, a quality assessment of the included studies was conducted to provide context for interpreting the findings [18]. The assessment criteria included study design, sample size, methodology, and the robustness of the conclusions. Studies were categorized as high, medium, or low quality based on these criteria. Several strategies were implemented to control for potential bias. First, the comprehensive search strategy included multiple databases to ensure a wide range of studies were considered. Second, the inclusion and exclusion criteria were clearly defined and consistently applied. Third, two reviewers performed data extraction independently to minimize selection and extraction bias, with discrepancies resolved through discussion or consultation with a third reviewer. Fourth, the quality assessment helped identify biases in individual studies, allowing for a more nuanced interpretation of the findings. By implementing these measures, we aimed to minimize bias and ensure the reliability and validity of the scoping review's findings.

Literature Review

Introduction to Climate Change and Vector Ecology

Climate change, characterized by rising global temperatures, altered precipitation patterns, and increased frequency of extreme weather events, profoundly impacts ecosystems worldwide [19]. These changes influence biodiversity, habitat distribution,

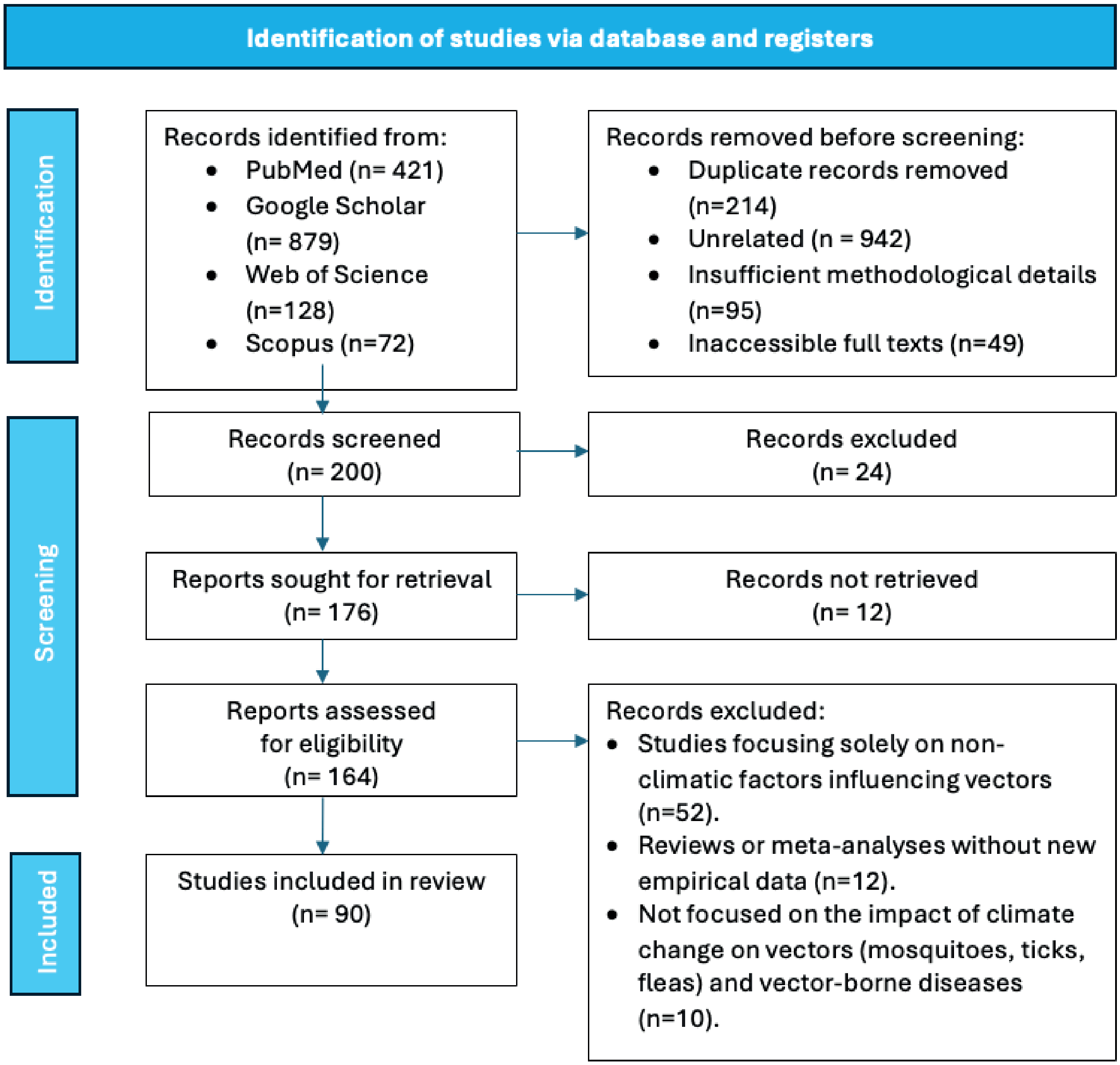

Figure 2: Prisma-Scr (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) flow chart regarding methods of this sopping review.

Image Credit: Nor Faiza Mohd. Tohit

and the functioning of ecosystems, often leading to disruptions in the delicate balance of natural processes [20,21]. Vector ecology studies the interactions between vectors, their environment, and the pathogens they transmit. It encompasses understanding habitat preferences, life cycles, reproductive behaviors, and host-feeding patterns (Figure 3). Seasonal activity and pathogen transmission dynamics are also vital aspects. Insights from vector ecology are crucial for developing effective strategies to predict, prevent, and control vector-borne diseases, safeguarding public health. One of the critical areas of concern is the effect of climate change on vector ecology, which has significant implications for the transmission of vector-

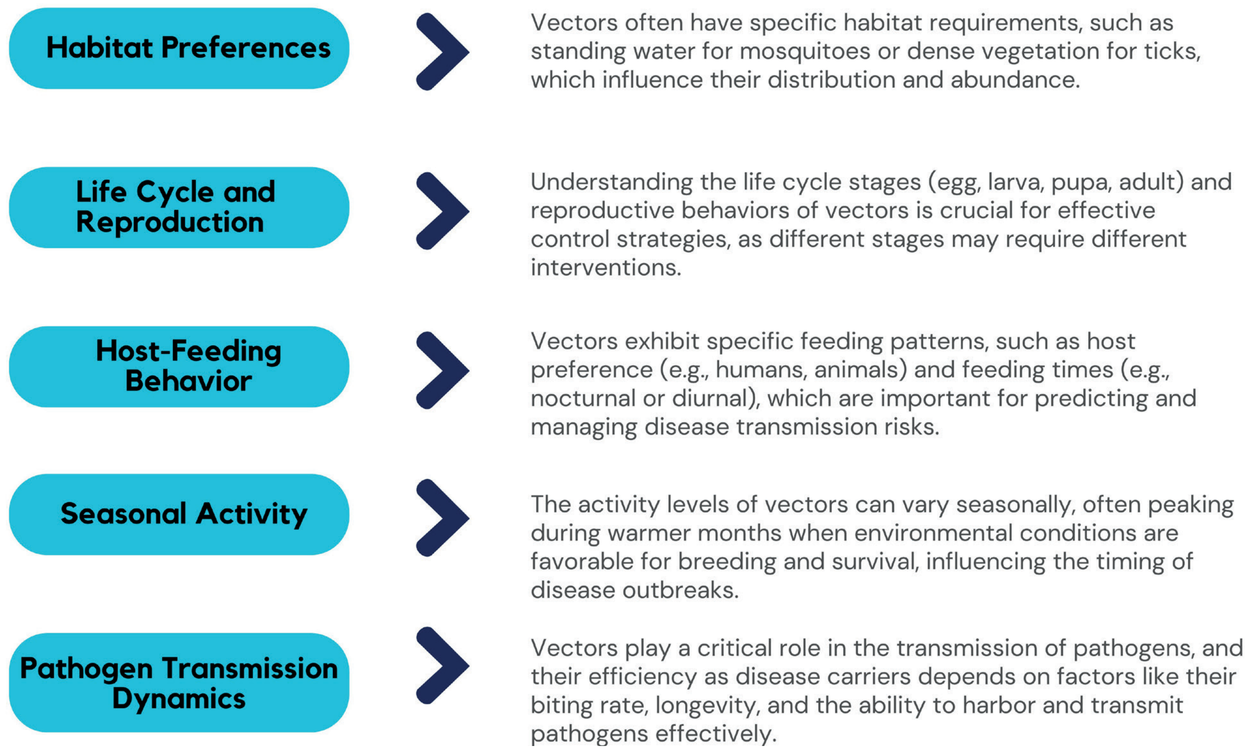

Figure 3: Core Elements of Vector Ecology.
Image Credit: Nor Faiza Mohd. Tohit.

borne diseases. Vectors like mosquitoes, ticks, and fleas are susceptible to climatic conditions. Temperature, humidity, and precipitation are critical determinants of their life cycles, population dynamics, and geographic distribution [22,23]. For instance, warmer temperatures can accelerate the development of mosquito larvae into adults, increase biting rates, and shorten the incubation period of pathogens within vectors, thereby enhancing the potential for disease transmission [24,25]. Similarly, changes in precipitation patterns can create new breeding sites for mosquitoes, as standing water is essential for their reproduction [26,27].

The impact of climate change on vector ecology is not uniform across different regions and vector species. In tropical and subtropical areas, increased temperatures and altered precipitation patterns can exacerbate the prevalence of diseases such as malaria, dengue, and chikungunya by creating optimal conditions for vector proliferation [28, 29]. Conversely, milder winters and longer growing seasons in temperate regions can enable vectors such as ticks to expand their geographic range, leading to diseases like Lyme disease in previously unaffected areas [30,31]. Human activities, including urbanization and land use changes, interact with climatic factors to further influence vector ecology. Urban environments can provide breeding sites for vectors and facilitate human-vector contact, while deforestation can alter habitats and force vectors closer to human populations [32,33]. These interactions underscore the complexity of predicting and managing the impacts of climate change on vector-borne diseases. Understanding the intricate relationship between climate change and vector ecology is essential for developing effective public health strategies to mitigate the risks associated with vector-borne diseases. This requires an interdisciplinary approach, integrating climate science, ecology, epidemiology, and public health to anticipate future trends and implement adaptive measures [34,35].

Key vectors and diseases

Climate change significantly impacts the ecology of primary vectors, such as mosquitoes, ticks, and fleas, which are responsible for transmitting various infectious diseases to humans. Understanding these vectors and the diseases they transmit is crucial for developing effective public health strategies.

i) Mosquitoes

Mosquitoes are among the most well-known vectors because they transmit numerous diseases. The Anopheles mosquito is the primary vector for malaria, a disease caused by Plasmodium parasites, which remains a significant public health challenge in many parts of the world [36]. Another critical mosquito species is Aedes aegypti, which transmits dengue, chikungunya, Zika, and yellow fever viruses [37]. Dengue has seen a dramatic increase in incidence, with climate change contributing to its spread by creating favorable conditions for Aedes mosquitoes [38].

ii) Ticks

Ticks are another significant group of vectors known for transmitting diseases such as Lyme, caused by the bacterium Borrelia burgdorferi. The black-legged tick Ixodes scapularis) is the primary vector in North America, and its range is expanding due to milder winter temperatures and longer growing seasons, thanks to climate change [39]. Ticks also transmit other pathogens, including the causative agents of anaplasmosis, babesiosis, and tick-borne encephalitis [40,41].

iii) Fleas

Fleas, mainly the rat flea (Xenopsylla cheopis), are well-known vectors of plague, a disease caused by the bacterium Yersinia pestis. While plague is less common today, it remains endemic in some regions, and climate variations can influence flea populations and the prevalence of plague outbreaks [42,43]. Fleas also transmit murine typhus, caused by Rickettsia typhi, which can be influenced by climatic factors affecting rodent populations and flea activity [44].

iv) Other Vectors

In addition to mosquitoes, ticks, and fleas, other arthropods, such as sandflies and blackflies, also play significant roles in disease transmission. Sandflies are vectors for leishmaniasis, a disease caused by protozoan parasites of the genus Leishmania. The distribution and activity of sandflies are highly influenced by temperature and humidity, which are affected by climate change [45]. Blackflies transmit onchocerciasis, also known as river blindness, caused by the parasitic worm Onchocerca volvulus. The breeding sites of blackflies are often fast-flowing rivers and streams, which can be altered by changes in precipitation and water flow patterns resulting from climate change [46,47].

Impact of climate variables

Climate variables such as temperature, precipitation, and humidity play crucial roles in influencing vector populations and their behaviors. These climatic factors can directly affect vectors' life cycles, reproduction rates, and geographical distribution, subsequently impacting the transmission dynamics of vector-borne diseases.

i) Temperature

Temperature is a primary factor affecting vector biology. Higher temperatures can accelerate the development rates of vectors from larval to adult stages. For instance, increased temperatures have been shown to shorten the development time of Anopheles mosquitoes, the primary malaria vectors, potentially increasing their population density and malaria transmission rates [48,49]. Similarly, for Aedes mosquitoes, which transmit dengue and Zika viruses, warmer temperatures can enhance virus replication within the mosquito, reducing the extrinsic incubation period and increasing the likelihood of transmission to humans [50-52].

ii) Precipitation

Precipitation influences the availability of breeding sites for many vector species [10] Mosquitoes, for example, require standing water for egg-laying and larval development. Increased rainfall can create numerous breeding sites, leading to higher mosquito populations and a greater risk of disease outbreaks [53]. Conversely, drought conditions can also impact vector populations by concentrating them in remaining water sources, potentially increasing human-vector contact [10,54,55]. The abundance of ticks, such as those that transmit Lyme disease, can also be influenced by precipitation, as humidity levels in the environment affect tick survival and questing behavior [56].

iii) Humidity

Humidity affects vector longevity and activity levels. High humidity is generally favorable for mosquito survival, reducing desiccation rates. Anopheles and

Aedes mosquitoes, for instance, thrive in humid environments, which support their survival and biting activity [57,58]. On the other hand, low humidity can reduce the survival and activity of these vectors, potentially lowering disease transmission rates [10,57]. Ticks also depend on humid microclimates to prevent desiccation while questing for hosts. Changes in humidity levels can thus influence their behavior and the likelihood of human-tick encounters [31,59,60]. The interactions between these climate variables and vector ecology are complex and often non-linear [61]. For example, while higher temperatures may increase vector populations in some regions, they can also reach thresholds beyond which vector survival and reproductive rates decline [1,62]. Similarly, changes in precipitation patterns, such as the increased frequency of intense rainfall events, can create and destroy breeding habitats, leading to unpredictable effects on vector populations [63]. Understanding how these specific climate variables influence vector populations and behaviors is critical for predicting and mitigating the impacts of climate change on vector-borne diseases [1]. Integrating climate data with vector surveillance and disease incidence reports can help develop predictive models and targeted interventions to protect public health [1,64].

Geographic Distribution and Range Shifts

Climate change is significantly altering many vector species' geographic distribution and range. These shifts are primarily driven by changes in temperature, precipitation patterns, and humidity, which affect the habitats and survival rates of vectors such as mosquitoes, ticks, and fleas. Understanding geographic distribution (Figure 4) and range shifts (Figure 5) is essential for comprehending their impacts on vector populations and dynamics. This knowledge helps inform strategies for managing vector-borne diseases and adapting to ecological changes, ultimately contributing to better public health outcomes and biodiversity conservation.

i) Mosquitoes

Mosquitoes, particularly those in the genera Anopheles and Aedes, are experiencing shifts in their geographic ranges due to climate change [65]. For instance, the distribution of Anopheles mosquitoes, which transmit malaria, is expanding into higher altitudes and latitudes as temperatures rise, making new regions susceptible to malaria transmission [66]. Similarly, the Aedes aegypti mosquito, responsible for transmitting dengue, Zika, and chikungunya, is expanding its range into temperate regions previously too cool for survival [25]. Studies have shown that areas in North America and Europe that were once free of these mosquitoes now face increased risks of vector-borne diseases [67,68].

ii) Ticks

Ticks, such as the Ixodes scapularis, which transmits Lyme disease, are also experiencing significant range shifts. Warmer temperatures and milder winters allow these ticks to survive and thrive in previously inhospitable regions [59,69]. As a result, the geographic range of Ixodes scapularis is expanding northward in North America and into higher altitudes, leading to an increased incidence of Lyme disease in previously unaffected areas [70,71]. This northward expansion is expected to continue as climate change progresses, increasing the risk of tick-borne diseases [72].

iii) Fleas

Fleas, vectors for diseases such as plague and murine typhus, are also impacted by climate change [73]. Changes in temperature and humidity can influence rat flea populations and their interactions with rodent hosts, leading to shifts in their geographic distribution [74,75]. Warmer temperatures can enhance flea survival and reproduction, potentially increasing the risk of plague outbreaks in regions previously under control [74,76,77].

iv) Other Vectors

Other vectors, including sandflies and blackflies, are similarly affected by climate change [78]. Sandflies, which transmit leishmaniasis, expand their range into new areas as temperatures rise and habitats become suitable for survival [79]. Blackflies, which transmit onchocerciasis (river blindness), are also experiencing changes in their distribution due to altered precipitation patterns and water flow in rivers and streams, which are their breeding sites [80,81]. These vectors' geographic distribution and range shifts have significant public health implications. As vectors move into new areas, populations previously unexposed to certain vector-borne diseases may face increased risks. This necessitates enhanced surveillance, public health preparedness, and targeted interventions to mitigate the impact of climate change on vector-borne diseases [82,83].

Disease Transmission Dynamics

Changes in vector behavior and distribution due to climate change profoundly affect the transmission dynamics of vector-borne diseases. These changes

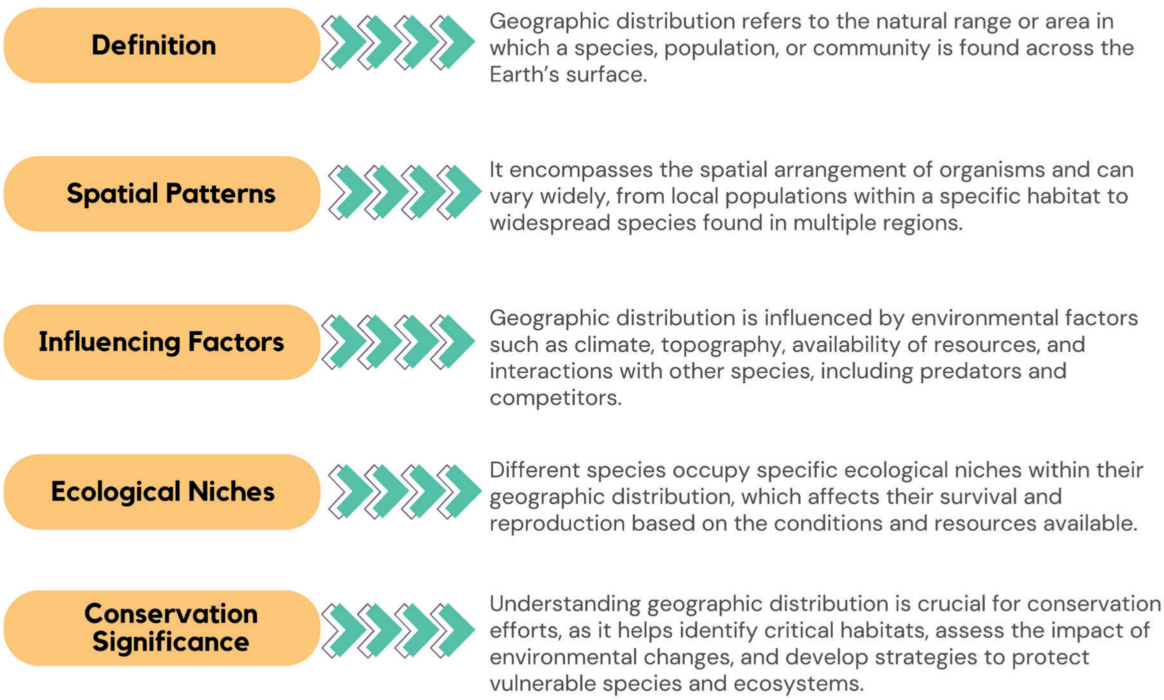

Figure 4: Geographic Distribution of Vector Populations.

Image Credit: Nor Faiza Mohd. Tohit.

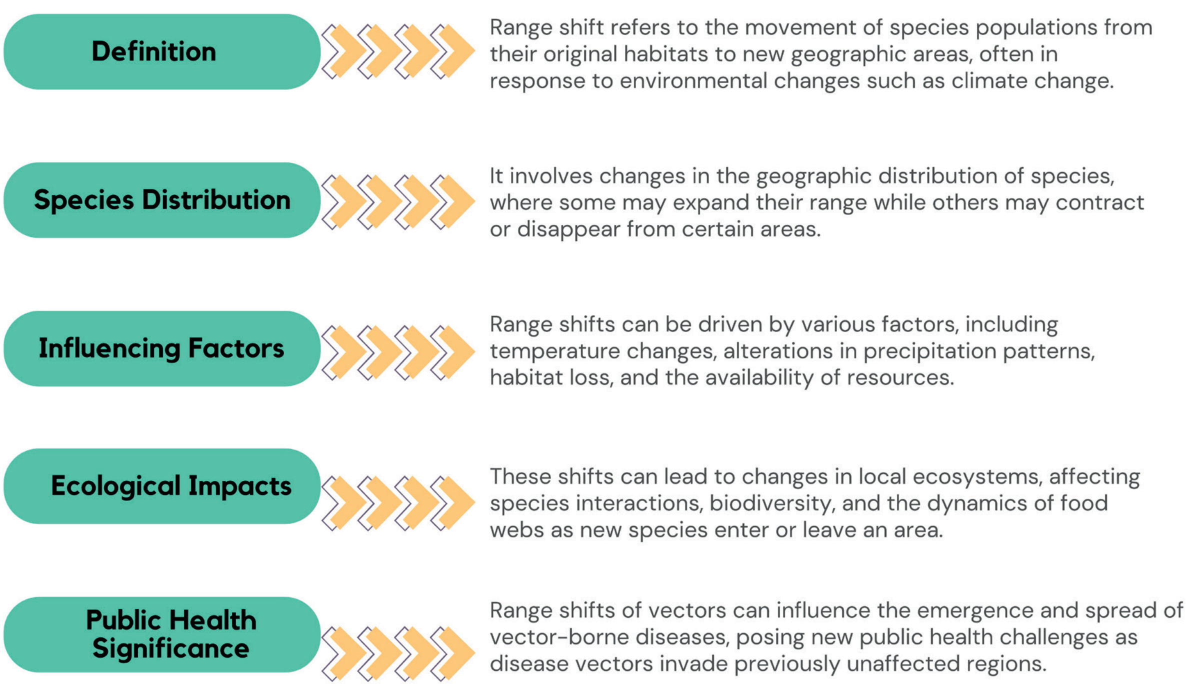

Figure 5: Range Shift of Vector Populations.

Image Credit: Nor Faiza Mohd. Tohit.

can alter disease incidence, geographic spread, and seasonality, posing significant challenges for public health management.

i) Incidence and Transmission Rates

Climate change can increase vector-borne disease incidence and transmission rates by creating favorable conditions for vectors. For instance, higher temperatures can enhance the replication rates of pathogens within vectors, reducing the extrinsic incubation period and increasing the likelihood of transmission [1]. For example, the transmission of dengue by Aedes mosquitoes is susceptible to temperature, with warmer conditions accelerating virus replication and increasing vector competence [25]. Similarly, malaria transmission by Anopheles mosquitoes can intensify as rising temperatures and increased humidity boost mosquito survival and biting rates [49].

ii Geographic Spread

The geographic spread of vector-borne diseases expands as vectors move into new areas with suitable climatic conditions. The northward expansion of Ixodes scapularis ticks in North America increases Lyme disease in previously unaffected regions [65,70,84,85]. This expansion is driven by milder winters and longer growing seasons, which enhance tick survival and reproduction [39]. Similarly, spreading Aedes mosquitoes into temperate regions increases the risk of dengue, chikungunya, and Zika virus outbreaks in previously considered low-risk areas [65].

iii Seasonality

Climate change can also affect the seasonality of vector-borne diseases, altering the timing and duration of transmission seasons. Warmer temperatures can extend the transmission season of diseases such as malaria and dengue by allowing vectors to remain active for extended periods [1,66,86]. In temperate regions, the earlier onset of spring and the delayed onset of winter can prolong the activity period of vectors like ticks, increasing the risk window for diseases like Lyme disease [87,88]. Changes in precipitation patterns can also influence the seasonality of vector-borne diseases by creating or eliminating breeding sites for mosquitoes, thereby affecting the timing of disease outbreaks [1,63,89].

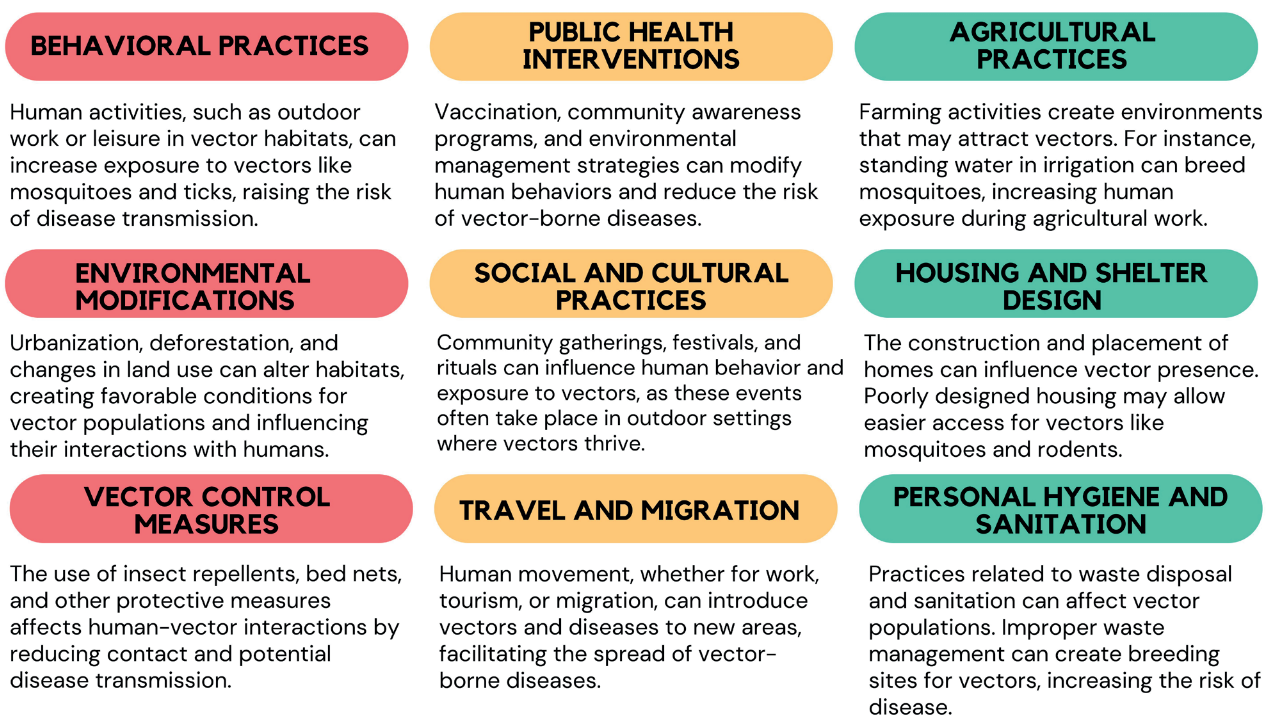

Figure 6: Human-vector interactions in everyday environments significantly influence disease transmission dynamics.

Image Credit: Nor Faiza Mohd. Tohit.

iv) Human-Vector Interactions

Human-vector interactions in everyday environments significantly influence disease transmission dynamics [90] (Figure 5). Behavioral practices, environmental modifications, and agricultural activities create conditions that affect vector populations [4,33,91]. Public health interventions and personal hygiene also play crucial roles in managing these interactions, ultimately shaping the risk of vector-borne diseases in communities [92]. Changes in vector behavior and distribution due to climate change can alter human-vector interactions, impacting disease transmission dynamics [93]. Urbanization, deforestation, and climate change can bring humans closer to vectors, increasing the risk of disease transmission [94]. For instance, increased rainfall and flooding can increase mosquito populations in urban areas, raising the risk of diseases like dengue and chikungunya [95,96]. Additionally, agricultural practices and land use changes can influence vector habitats and human exposure to vectors, further complicating disease transmission dynamics [97]. Understanding these changes in disease transmission dynamics is crucial for developing effective public health strategies to mitigate the impact of climate change on vector-borne diseases [98]. This includes enhancing vector surveillance, implementing targeted control measures, and developing predictive models to anticipate future trends and inform public health interventions [15,64,99].

Public health implications and strategies

Climate change's impact on vector-borne diseases poses significant global challenges for public health systems. The shifting distribution and behavior of vectors, coupled with the increased incidence and spread of diseases, necessitate comprehensive strategies for mitigation and adaptation.

i) Public Health Implications

a. **Increased Disease Burden**: The expansion of vector ranges and increased transmission rates can lead to higher incidences of diseases such as malaria, dengue, Lyme disease, and chikungunya, placing additional strain on healthcare systems [73,100]. Regions previously unaffected by these diseases may experience outbreaks, leading to increased morbidity and mortality.

b. **Emergence of New Disease Hotspots**: As vectors move into new areas, regions with limited experience and infrastructure to deal with vector-borne diseases may become hotspots. This can lead to delayed diagnosis, inadequate treatment, and ineffective control measures, exacerbating the public health impact [1,82,100,101].

c. **Economic Impact**: The economic burden of vector-borne diseases includes direct healthcare costs and indirect costs such as loss of productivity. Increased disease prevalence can lead to significant financial losses, particularly in low- and middle-income countries where resources are constrained [102].

d. **Social and Environmental Disruption**: Vector-borne diseases can disrupt social structures and livelihoods, particularly in communities reliant on agriculture and tourism, which can be severely affected by disease outbreaks [100,103]. Climate-induced vector behavior and distribution changes can also alter ecosystems, affecting biodiversity and ecosystem services [104,105].

ii) Mitigation and Adaptation Strategies

a. **Enhanced Surveillance and Monitoring**: Implementing robust surveillance systems to monitor vector populations and disease incidence is crucial. Early detection of changes in vector distribution and disease patterns can facilitate timely public health responses [64,106,107]. Utilizing geographic information systems (GIS) and remote sensing technology can improve the accuracy and efficiency of vector surveillance efforts [108,109].

b. **Integrated Vector Management (IVM)**: Adopting an integrated approach to vector management that combines chemical, biological, environmental, and personal protective measures can effectively reduce vector populations and disease transmission [110]. Community participation and education are essential to IVM, ensuring public cooperation and sustainable outcomes [111,112].

c. **Climate-Resilient Health Systems**: Strengthening health systems to be resilient to climate change involves improving infrastructure, training healthcare workers, and ensuring adequate resources and supplies. Health systems must be prepared to handle increased disease burdens and potential outbreaks [113,114].

d. **Public Health Education and Communication**: Educating communities about the risks of vector-borne diseases and preventive measures is vital [82,115]. Public health campaigns should focus on behavioral changes, such as using bed nets, eliminating standing water, and seeking timely medical attention for vector control management [116,117].

e. **Research and Innovation**: Investing in research to understand the complex interactions between climate change and vector-borne diseases is essential. Developing new tools and technologies, such as vaccines, diagnostics, and vector control methods, can enhance public health responses [118]. Additionally, predictive modeling can help anticipate future trends and inform policy and planning for vector control strategy [15].

f. **International Collaboration**: Vector-borne diseases do not respect borders; hence, international collaboration is necessary for effective control and prevention. Sharing data, resources, and best practices can strengthen global efforts to combat the impact of climate change on vector-borne diseases [100].

By implementing these strategies, public health systems can better mitigate and adapt to the challenges posed by climate change, ultimately protecting populations from the increasing threat of vector-borne diseases.

Research gaps and future directions

Despite significant advancements in understanding the impact of climate change on vector-borne diseases, several research gaps remain. Addressing these gaps is crucial for developing comprehensive strategies to mitigate the effects of climate change on public health.

i) Research Gaps

a. **Regional Variability**: Much of the current research focuses on global trends in vector-originated disease management, but there is a need for more localized studies that consider regional climatic, ecological, and socio-economic contexts. These studies can help identify specific vulnerabilities and tailor intervention strategies [119,120].

b. **Long-term Data**: There is a lack of long-term, high-resolution data on vector populations, disease incidence, and climate variables. Such data is essential for understanding temporal trends and developing predictive models [121].

c. **Vector-Pathogen Interactions**: More research is needed on how climate change affects the interactions between vectors and pathogens [122,123]. This includes understanding how temperature, humidity, and precipitation influence pathogen replication and transmission dynamics within vectors [124].

d. **Impact of Extreme Weather Events**: While gradual changes in climate variables are well-studied, the effect of extreme weather events such as hurricanes, floods, and droughts on vector-borne diseases is less understood [125]. These events can immediately and profoundly impact vector populations and disease transmission [1,126].

e. **Human Behavior and Adaptation**: There is limited research on how human behavior and adaptation strategies influence the spread of vector-borne diseases. Understanding how communities perceive and respond to climate change and vector-borne disease risks can inform more effective public health interventions [82,119].

f. **Multisectoral Approaches**: Research often focuses on health impacts in isolation. There is a need for studies that integrate health, environmental, and socio-economic data to provide a holistic understanding of the impacts of climate change on vector-borne diseases [82,127].

ii) Future Directions

a. **Localized Climate and Health Models**: Developing localized models that integrate climate data, vector surveillance, and socio-economic factors can improve predictions of disease outbreaks and guide targeted interventions [1,64,128].

b. **Innovative Vector Control Technologies**: Investing in research to develop new vector control technologies, such as genetically modified mosquitoes, novel insecticides, and biological control agents, can provide more effective and sustainable solutions [129,130].

c. **Community-Based Interventions**: Research should focus on designing and evaluating community-based interventions that leverage local knowledge and practices to control vector populations and reduce disease transmission [131,132].

d. **Interdisciplinary Research**: Encouraging multidisciplinary research that brings together climatologists, ecologists, epidemiologists, and social scientists can provide a more comprehensive understanding of the complex interactions between climate change and vector-borne diseases [35,126].

e. **Global Surveillance Networks**: Establishing and strengthening global surveillance networks can facilitate data sharing and best practices, enhancing the ability to detect and respond to emerging vector-borne disease threats [133-136].

f. **Policy and Governance Research**: Investigating the effectiveness of different policy approaches and governance structures in managing the impacts of climate change on vector-borne diseases can inform more effective and equitable public health strategies [1,91,122].

By addressing these research gaps and pursuing these future directions, the scientific community can better understand and mitigate the impacts of climate change on vector-borne diseases, ultimately protecting public health.

Strengths and Limitations of the Review

This review provides a comprehensive examination of the current state of knowledge regarding the impact of climate change on vector-borne diseases. Synthesizing findings from various disciplines offers valuable insights into the complex interactions between climate variables and vector ecology, emphasizing the practical implications for public health. However, like any systematic review, it has inherent strengths and limitations. The following sections outline the key strengths of the review, highlighting its comprehensive and interdisciplinary approach and its focus on public health strategies. Additionally, the limitations are discussed, including potential biases and gaps that may affect the generalizability and applicability of the findings. Understanding these strengths and limitations is crucial for interpreting the results and identifying areas for future research and policy development.

Strengths

a. **Comprehensive Literature Review**: This review utilized a systematic approach to comprehensively search and include relevant studies from the past decade, ensuring that the most recent and pertinent research findings were considered.

b. **Multi-Disciplinary Perspective**: The review integrates findings from various disciplines, including climatology, vector ecology, epidemiology, and public health. This interdisciplinary approach provides a holistic understanding of the complex interactions between climate change and vector-borne diseases.

c. **Identification of Research Gaps**: By highlighting current gaps and suggesting future directions, the review provides valuable insights for researchers and policymakers to prioritize areas requiring further investigation and resources.

d. **Focus on Public Health Implications**: The review emphasizes the practical implications of climate change on public health and suggests actionable strategies for mitigation and adaptation. This focus ensures that the findings are relevant and valuable for public health practitioners and policymakers.

e. **Inclusion of Diverse Vectors and Diseases**: The review covers a wide range of vectors (mosquitoes, ticks, fleas) and the diseases they transmit (malaria, dengue, Lyme disease), providing a comprehensive overview of the impact of climate change on various vector-borne diseases.

Limitations

a. **Language and Database Restrictions**: The review only included studies published in English and sourced from PubMed. This may have excluded relevant studies published in other languages or indexed in other databases, potentially limiting the breadth of the review.

b. **Variability in Study Quality**: The included studies varied in design, methodology, and quality. Although a quality assessment was conducted, the variability in study quality may affect the consistency and reliability of the synthesized findings.

c. **Focus on Recent Studies**: By restricting the search to studies published in the past decade, the review may have overlooked earlier foundational research that could provide meaningful context and historical perspectives.

d. **Limited Regional Specificity**: While the review discusses general trends and implications, it may lack detailed regional analyses considering local climatic, ecological, and socio-economic factors. This limitation could affect the applicability of the findings to specific regions or communities.

e. **Potential Publication Bias**: The review may be subject to publication bias, where studies with

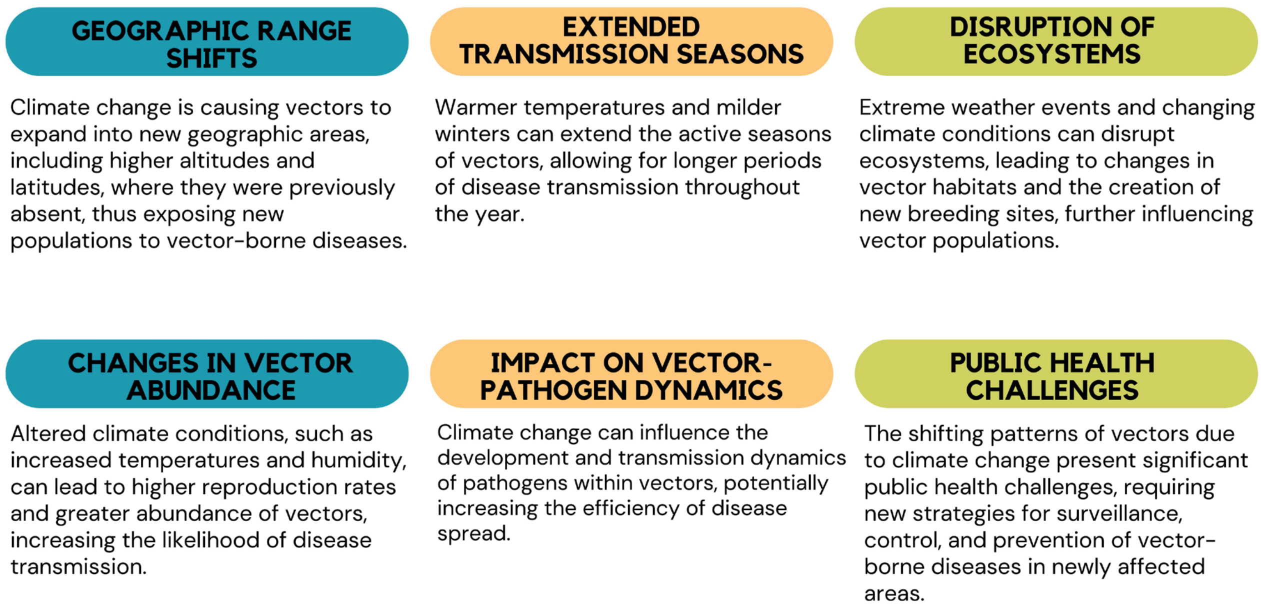

Figure 7: Key findings from the scoping review impacts of climate change on vector-borne diseases.
Image Credit: Nor Faiza Mohd. Tohit.

significant or positive findings are more likely to be published and included in the review. In contrast, studies with negative or non-significant results are underrepresented.

f. **Dynamic Nature of Climate Change**: Climate change rapidly evolves, and new data and insights are continually emerging. The findings of this review represent a snapshot in time and may need to be updated regularly to reflect the latest research and trends.

Despite these limitations, the review provides a valuable synthesis of current knowledge on the impact of climate change on vector-borne diseases and offers practical recommendations for public health strategies.

CONCLUSION

This scoping review has highlighted the significant impact of climate change on vector-borne diseases, emphasizing the complex interplay between climatic variables, vector ecology, and disease transmission dynamics. The key findings are summarized in Figure 7. The review underscores the urgent need for comprehensive and localized research to understand these relationships better and inform effective public health interventions. The review provides a holistic perspective that can guide future research and policy development by integrating climatology, vector ecology, epidemiology, and public health findings. The identified research gaps, particularly in regional variability, long-term data, vector-pathogen interactions, and the impact of extreme weather events, indicate critical areas where further investigation is necessary. Additionally, understanding human behavior and adaptation strategies and the development of innovative vector control technologies are essential for building climate-resilient health systems.

The review also highlights the importance of interdisciplinary collaboration and international cooperation in addressing the global challenge of vector-borne diseases in the context of climate change. By enhancing surveillance, adopting integrated vector management, and investing in research and innovation, public health systems can better mitigate and adapt to the evolving threat of vector-borne diseases. In conclusion, while significant progress has been made in understanding the impact of climate change on vector-borne diseases, ongoing research and adaptive strategies are crucial to protect public health in an increasingly changing climate. This review provides a foundation for such efforts, aiming to inform and inspire future research and policy actions that can effectively address this pressing global health issue.

CONSENT FOR PUBLICATION

The author reviewed and approved the final version and has agreed to be accountable for all aspects of the work, including any accuracy or integrity issues.

DISCLOSURE

The author declares that they do not have any financial involvement or affiliations with any organization, association, or entity directly or indirectly related to the subject matter or materials presented in this editorial. This includes honoraria, expert testimony, employment, ownership of stocks or options, patents, or grants received or pending royalties.

Data Availability

Information is taken from freely available sources for this editorial.

AUTHORSHIP CONTRIBUTION

All authors contributed significantly to the work, whether in the conception, design, utilization, collection, analysis, and interpretation of data or all these areas. They also participated in the paper's drafting, revision, or critical review, gave their final approval for the version that would be published, decided on the journal to which the article would be submitted, and made the responsible decision to be held accountable for all aspects of the work.

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