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Assessing climate change effects on vector-borne disease patterns to strengthen surveillance, prevention and adaptive global public health policies

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Abstract

Climate change has emerged as a defining public health challenge of the 21st century, profoundly influencing the distribution, transmission dynamics, and seasonality of vector-borne diseases (VBDs) worldwide. Rising temperatures, altered precipitation patterns, and extreme weather events are reshaping ecosystems, expanding the geographic range of disease vectors such as mosquitoes, ticks, and sandflies into previously non-endemic regions. This environmental shift has contributed to the resurgence and spread of major diseases, including malaria, dengue, chikungunya, Zika virus, and Lyme disease, particularly in vulnerable low- and middle-income countries with limited health infrastructure. At a broader scale, these changes underscore the need for integrated climate–health modeling frameworks to anticipate vector proliferation and disease outbreaks under varying emission and climate scenarios. However, current surveillance and control strategies remain fragmented and often reactive, lacking the capacity to address the complex interactions between climate, vector ecology, and human behavior. Strengthening global health resilience requires adaptive and predictive systems that merge satellite-based climate data, remote sensing, and machine learning to monitor environmental determinants in real time. A transition toward proactive, evidence-based policymaking anchored in One Health principles and supported by international collaboration is essential to mitigate disease burden. This approach not only enhances surveillance and early warning systems but also informs targeted interventions, resource allocation, and community-based adaptation strategies. Ultimately, integrating climate intelligence into vector-borne disease management can enable nations to anticipate emerging health threats, protect at-risk populations, and build sustainable public health systems resilient to ongoing and future climate change impacts.

Keywords: Climate change; Vector-borne diseases; Surveillance systems; Public health policy; Adaptive strategies; One Health

1. Introduction

1.1. Background and Global Significance

Climate change has emerged as one of the most profound determinants of public health in the 21st century, reshaping disease patterns, environmental stability, and population well-being worldwide [1]. Rising global temperatures, fluctuating humidity, and extreme precipitation events are creating ecological conditions favorable to the proliferation of disease vectors such as mosquitoes, ticks, and sandflies [2]. These climatic variations not only alter the geographical range of vectors but also influence their breeding cycles, biting rates, and pathogen development within hosts. The World Health Organization (WHO) identifies vector-borne diseases (VBDs) as among the most climate-sensitive infections, accounting for over 17% of all infectious diseases globally [3].

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As regions previously unsuitable for vector survival become habitable, populations in temperate zones are increasingly exposed to tropical pathogens [4]. The interconnection between environmental change and infectious disease transmission reflects complex interactions involving vector ecology, human migration, and socioeconomic conditions. Furthermore, climate-induced disruptions such as flooding, deforestation, and agricultural expansion intensify human–vector contact, creating new epidemiological niches for transmission [5]. These dynamics highlight an urgent need to understand and predict disease shifts through interdisciplinary frameworks integrating climatology, epidemiology, and data science. Such understanding supports global preparedness and informs evidence-based adaptation measures essential for safeguarding health security amid accelerating climate transformations [2].

1.2. Rationale for Studying Vector-Borne Diseases

Vector-borne diseases pose a growing challenge to global health systems, with climate change amplifying their spread, frequency, and unpredictability [3]. Diseases such as malaria, dengue fever, chikungunya, Zika virus, and Lyme disease have demonstrated strong correlations with changes in temperature, rainfall, and humidity, which directly affect vector breeding habitats and parasite replication rates [6]. For instance, even a slight increase in ambient temperature can accelerate the mosquito life cycle, enhancing transmission potential and expanding endemic zones to higher altitudes and latitudes.

The global burden of these diseases is disproportionately concentrated in low- and middle-income countries, where health infrastructure, sanitation, and surveillance capacities remain limited [7]. However, recent outbreaks in southern Europe and North America suggest that no region is immune to the climate-driven spread of infectious vectors [3]. Studying VBDs through the lens of climate variability enables the identification of hotspots, prediction of transmission windows, and design of adaptive intervention frameworks. Understanding these linkages is vital for strengthening resilience in public health systems and informing international policies that address climate impacts not merely as environmental phenomena but as pressing determinants of global health equity and security [8].

1.3. Scope and Objectives

This article aims to assess how climate change influences vector-borne disease patterns across ecological and geopolitical boundaries and to propose adaptive strategies that enhance surveillance, prevention, and policy resilience [6]. It integrates multidisciplinary perspectives combining climatology, epidemiology, and public health governance to examine both the macro-level drivers of vector expansion and micro-level health impacts. The discussion progresses from foundational ecological principles to applied public health interventions, emphasizing technological and policy innovation as levers of adaptive capacity [2].

Section 2 explores the ecological mechanisms underpinning vector proliferation, while Section 3 analyzes regional disease patterns supported by empirical evidence. Sections 4 and 5 focus on surveillance and prevention frameworks, followed by governance and data-driven policy strategies in Sections 6 and 7. The concluding sections synthesize actionable insights for strengthening global resilience.

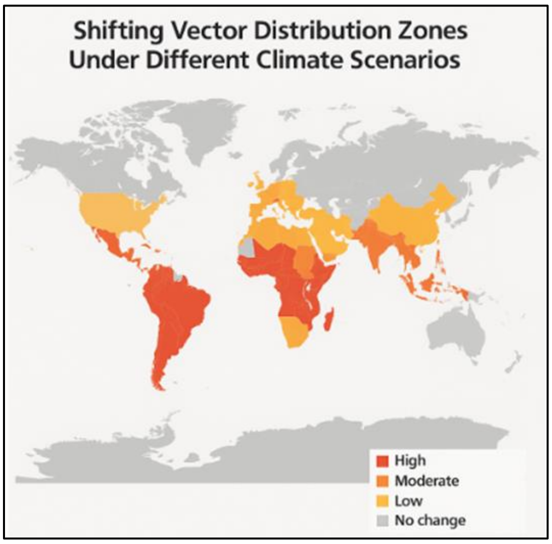


Figure 1 Shifting global distribution of major disease vectors under varied climate change scenarios [10]

Figure 1 illustrates the shifting global distribution of major disease vectors under varied climate change scenarios, providing visual context for emerging epidemiological transitions [9].

2. Climate change and disease ecology

2.1. Ecological Drivers of Vector Proliferation

Ecological changes driven by climate variability profoundly affect the survival, reproduction, and distribution of disease vectors [13]. Temperature, humidity, and precipitation act as key determinants shaping mosquito, tick, and sandfly populations across diverse ecosystems [9]. Warmer temperatures accelerate the developmental stages of vectors and pathogens, shortening extrinsic incubation periods and increasing transmission rates [15]. For instance, the *Anopheles* mosquito, responsible for malaria transmission, exhibits enhanced feeding frequency and faster parasite maturation under elevated temperature conditions. Similarly, the *Aedes aegypti* mosquito carrier of dengue and Zika viruses breeds more efficiently in urban environments where standing water and waste accumulation coincide with rising humidity levels [12].

Precipitation influences vector breeding through the creation of transient aquatic habitats, while prolonged droughts can paradoxically promote container-based breeding in urban settlements [10]. These climatic shifts interact with anthropogenic forces such as deforestation, agricultural expansion, and urbanization, resulting in altered vector habitats and increased human exposure [16]. The removal of forest canopies not only changes microclimatic conditions but also brings humans and wildlife into closer proximity, facilitating zoonotic spillover [11]. Urban sprawl further amplifies risk through poor drainage, overcrowding, and heat island effects. Thus, the combination of climatic and land-use changes forms a synergistic driver of vector proliferation, amplifying the potential for disease outbreaks across both tropical and temperate regions [14].

2.2. Changing Transmission Dynamics

Climate change is transforming the temporal and spatial patterns of vector-borne diseases, redefining the boundaries of endemic regions [8]. Seasonal shifts are extending transmission periods, allowing vectors to remain active for longer durations each year. In Sub-Saharan Africa, increased rainfall variability has resulted in irregular malaria transmission cycles, while rising minimum night temperatures enable vectors to survive in high-altitude zones once considered inhospitable [12]. The highlands of Ethiopia and Kenya, for example, have witnessed a resurgence of malaria, attributed to warming trends that sustain *Anopheles* populations at higher elevations [13].

In South Asia, intensifying monsoon patterns and erratic humidity levels have accelerated dengue and chikungunya transmission, particularly in rapidly urbanizing cities such as Dhaka and Mumbai [15]. These climatic anomalies influence not only vector survival but also virus replication within mosquitoes, producing prolonged outbreak seasons [9]. Similarly, in Latin America, El Niño–Southern Oscillation events correlate strongly with increased mosquito-borne disease prevalence, as warmer waters and altered rainfall patterns expand breeding habitats [16]. The re-emergence of Zika virus in tropical America exemplifies how climate-driven shifts intersect with global mobility and land-use changes [10].

These evolving transmission dynamics underscore the importance of integrating climatic, ecological, and sociobehavioral data into public health surveillance systems [14]. The capacity to forecast emerging hotspots requires cross-sectoral monitoring frameworks capable of adapting to rapid environmental transitions, ensuring that prevention and response measures remain both timely and geographically relevant [11].

2.3. Modeling Climate–Disease Relationships

Modeling the relationship between climate variables and disease transmission provides critical insights into predicting future outbreaks under different climate scenarios [8]. Degree-day models are among the most widely used tools for estimating vector development thresholds by quantifying the cumulative temperature required for life cycle completion [9]. For instance, these models predict increased malaria transmission potential in regions where average temperatures surpass the developmental threshold for *Plasmodium falciparum*, extending endemicity into previously unaffected areas [15]. Dynamic simulation models, incorporating rainfall, humidity, and vegetation indices, further refine predictions by representing nonlinear ecological interactions [13].

However, these models face considerable uncertainties. Climate projections are influenced by variations in greenhouse gas emission trajectories, regional topography, and land-use dynamics [12]. Moreover, the absence of high-resolution meteorological and entomological data limits the accuracy of vector distribution forecasts [16]. While satellite-based remote sensing has improved spatial coverage, temporal inconsistencies in data calibration and local reporting biases continue to challenge validation efforts [10]. Additionally, existing models often underestimate socioecological variables such as migration, behavioral adaptation, and urban heat islands that critically shape transmission risk [14].

To enhance reliability, future modeling approaches must adopt hybrid frameworks that integrate empirical surveillance data, climate reanalysis, and machine learning-based predictions [11]. These integrative systems can provide early warnings for vector proliferation and inform evidence-based policy decisions aimed at mitigating disease burden in the face of environmental change [9].

Table 1 Climate Variables Influencing Major Vector-Borne Diseases

Climate Variable	**Mechanism of Influence**	**Quantified Impact / Thresholds**	**Examples of Affected Diseases and Vectors**	**Implications for Transmission Dynamics**
Temperature	Regulates vector metabolism, feeding frequency, and pathogen development within the vector.	- Optimal temperature for *Anopheles* spp. mosquito development: 25–27°C. - *Plasmodium falciparum* sporogony accelerates 8–10% per 1°C increase within 20–30°C range. - *Aedes aegypti* survival declines sharply above 35°C.	- Malaria (*Anopheles* mosquitoes). - Dengue, Zika, Chikungunya (*Aedes aegypti*, *Aedes albopictus*).	Rising temperatures expand vector habitats into higher altitudes and latitudes; extended transmission seasons.
Humidity	Affects vector survival and host-seeking activity; low humidity increases desiccation risk.	- Optimal relative humidity for mosquito survival: 60–80%. - Tick activity peaks above 70% relative humidity.	- Malaria, Dengue, Tick-borne Encephalitis (TBE).	Sustained high humidity extends vector lifespan and enhances biting rates, increasing infection potential.
Rainfall	Creates breeding sites; influences larval habitat stability and vector density.	- Rainfall between 80–200 mm/month associated with increased malaria and dengue incidence. - Excessive rain (>250 mm/month) may flush larvae, reducing short-term populations.	- Malaria (*Anopheles spp.*). - Dengue/Zika (*Aedes spp.*).	Moderate rainfall supports vector proliferation, while extremes (flood/drought) produce cyclical transmission surges.
Vegetation Index (NDVI)	Proxy for surface moisture and habitat suitability derived from satellite data.	- NDVI > 0.4 correlated with high *Anopheles* abundance. - NDVI anomalies predict Rift Valley Fever outbreaks with >80% accuracy.	- Rift Valley Fever, Malaria, Leishmaniasis.	Dense vegetation supports vector breeding and reservoir host populations; NDVI-based models enhance spatial risk prediction.
Wind Speed and Direction	Influences vector dispersal and pathogen	- Wind speeds of 1–3 m/s can aid *Aedes* dispersal up to 10 km.	- West Nile Virus, Dengue.	Determines local versus regional spread potential;

	dissemination patterns.	- Strong winds (>5 m/s) reduce flight activity.		impacts control targeting and border surveillance.

3. Regional patterns and epidemiological evidence

3.1. Africa and the Resurgence of Malaria

The African continent remains the epicenter of malaria transmission, accounting for approximately 94% of global cases and deaths annually [18]. Climate change is exacerbating this burden by reshaping the ecological dynamics of *Anopheles* mosquitoes, the primary vectors of *Plasmodium* parasites. Fluctuations in rainfall intensity, seasonal droughts, and rising temperatures have significantly altered mosquito breeding cycles and parasite incubation periods [16]. Warmer climates shorten the extrinsic incubation period of *Plasmodium falciparum*, thereby increasing transmission efficiency and extending the duration of epidemic seasons [21].

Rainfall variability, particularly in the Sahel and East African regions, has a dual influence on vector ecology. Moderate rainfall increases stagnant water pools ideal for mosquito breeding, while prolonged flooding can wash away larvae and disrupt breeding sites [19]. Conversely, drought conditions often trigger human migration toward water bodies, inadvertently increasing exposure to vector habitats [17]. This oscillation between drought and flood cycles complicates malaria control programs, as traditional vector control strategies such as larviciding and indoor residual spraying struggle to adapt to shifting environmental conditions [23].

Furthermore, deforestation and irrigation projects have created microhabitats conducive to vector proliferation, undermining historical gains achieved through insecticide-treated nets and pharmaceutical interventions [15]. The resurgence of malaria in highland regions of Kenya, Ethiopia, and Rwanda underscores how incremental warming enables *Anopheles* species to colonize previously inhospitable altitudes [22]. These trends highlight an urgent need for climate-informed vector management systems that align environmental forecasting with public health interventions [20].

3.2. Asia-Pacific and Arboviral Expansion

The Asia-Pacific region has witnessed a marked expansion of arboviral infections particularly dengue, chikungunya, and Zika virus due to rising temperatures, increased humidity, and rapid urbanization [17]. Urban heat islands amplify the effects of climate warming, accelerating mosquito life cycles and promoting viral replication within vectors [15]. Cities such as Bangkok, Dhaka, and Manila now experience nearly year-round *Aedes aegypti* activity, transforming seasonal diseases into endemic threats [23]. The high adaptability of *Aedes* mosquitoes to artificial breeding containers and household environments further intensifies urban transmission [20].

Unplanned urban growth, combined with inadequate sanitation and poor waste management, creates optimal conditions for vector proliferation [19]. In South Asia, heavy monsoon rains followed by warm dry periods produce alternating wet–dry cycles that sustain mosquito populations and extend transmission windows [21]. Meanwhile, in the Pacific Islands, rising sea levels and increased rainfall associated with climate change have expanded the habitats of *Aedes polynesiensis*, facilitating outbreaks of dengue and Zika across island chains [18].

Socioeconomic factors exacerbate these climatic impacts. Population density, migration, and insufficient health infrastructure hinder effective vector control and outbreak response [16]. Moreover, widespread insecticide resistance among *Aedes* species complicates traditional interventions, necessitating integrated approaches that combine environmental management with genetic and biological control strategies [22].

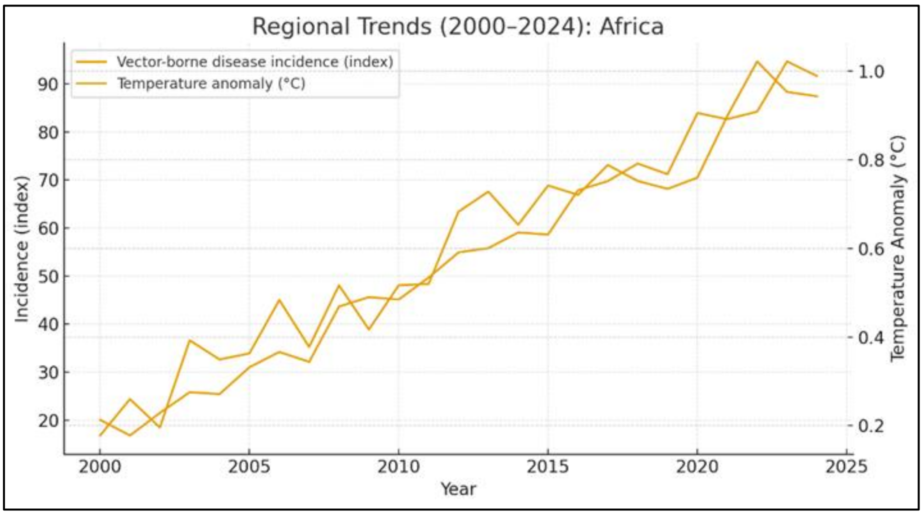
National surveillance systems across Southeast Asia are increasingly integrating meteorological data and predictive modeling to improve outbreak preparedness [17]. Initiatives in Singapore and Vietnam, for example, employ real-time vector surveillance supported by artificial intelligence to predict hotspots and optimize resource allocation [23]. The regional escalation of arboviral diseases thus underscores how climate change, urbanization, and global interconnectedness jointly redefine the epidemiological landscape of infectious disease transmission [20].

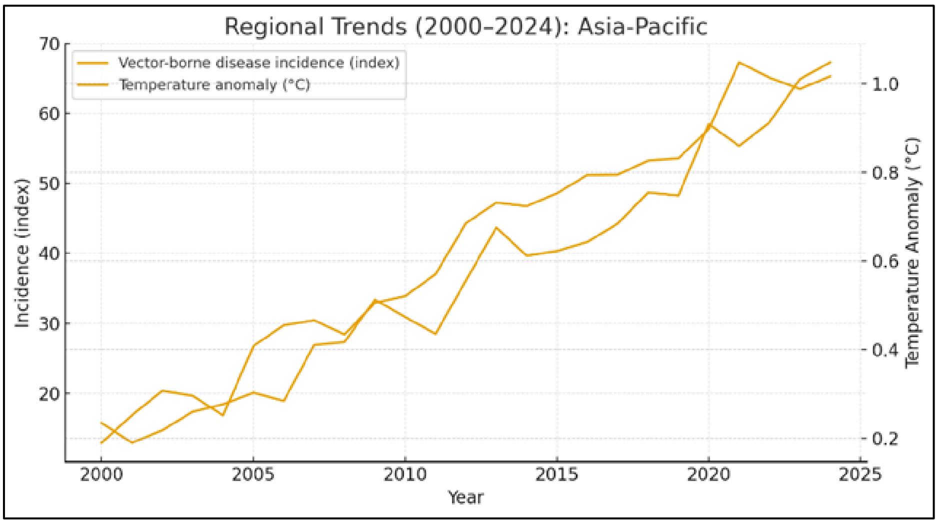
3.3. Europe and the Americas: Emerging Frontiers

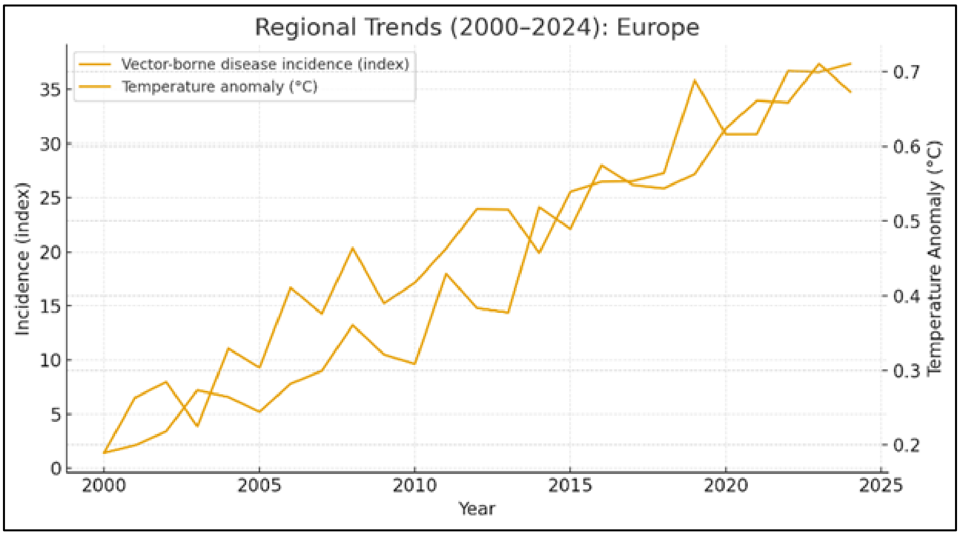
In recent decades, Europe and the Americas have become emerging frontiers for vector-borne diseases once confined to tropical regions [19]. Warmer winters and milder summers have extended the breeding seasons of mosquitoes and ticks, facilitating the spread of pathogens such as West Nile virus, chikungunya, and tick-borne encephalitis (TBE) [15]. In southern and central Europe, *Culex pipiens* populations have increased under rising average temperatures, leading to sporadic but recurrent West Nile virus outbreaks [23]. Simultaneously, *Ixodes ricinus* ticks vectors of TBE have migrated northward into Scandinavia and alpine regions where cooler climates previously inhibited their survival [18].

In the Americas, climate-induced shifts in precipitation and vegetation patterns have expanded vector habitats into subtropical and even temperate zones [21]. The introduction of *Aedes albopictus* in the United States and southern Europe demonstrates the adaptability of invasive species under changing environmental conditions [16]. North America, once largely protected from mosquito-borne diseases, now faces increasing risks of West Nile and dengue virus transmission, particularly in urban areas experiencing heat island effects [20]. Likewise, in Latin America, the interplay between climate anomalies such as El Niño events and deforestation has intensified the spread of malaria and arboviral infections [22].

Cross-border migration further complicates disease control efforts, as mobile populations transport both pathogens and vectors across national boundaries [17]. Ecological adaptation, coupled with global trade and tourism, accelerates the transcontinental spread of vectors and emerging diseases [15]. The integration of transnational surveillance networks and harmonized data-sharing mechanisms has thus become imperative for coordinated response strategies [19].







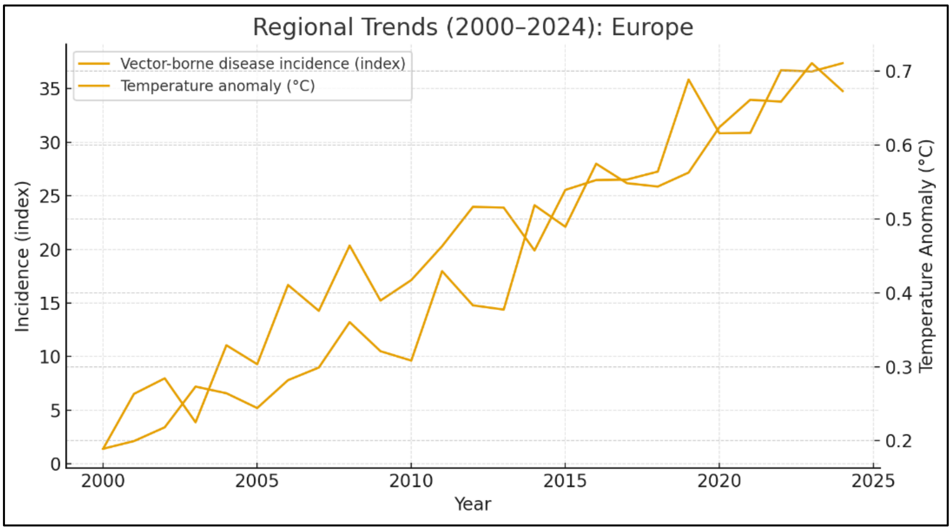


Figure 2 a, b, c and d illustrates regional trends in vector-borne disease incidence from 2000 to 2024, highlighting correlations between temperature anomalies and shifts in disease distribution across Africa, Asia-Pacific, Europe, and the Americas [23]

4. Surveillance systems and early warning mechanisms

4.1. Current Global Surveillance Infrastructure

Global surveillance systems for vector-borne diseases (VBDs) have evolved substantially over the past two decades, with the World Health Organization (WHO) leading efforts through its Global Vector Control Response (GVCR) 2017–2030 framework [25]. The GVCR emphasizes integrated vector management, capacity building, and cross-border collaboration to enhance early detection and response mechanisms [28]. Complementary national initiatives such as the U.S. Centers for Disease Control and Prevention's (CDC) ArboNET and the European Centre for Disease Prevention and Control's (ECDC) VectorNet collect and analyze entomological and epidemiological data to monitor disease spread [22]. These systems enable policymakers to map transmission patterns, identify outbreak hotspots, and allocate resources efficiently.

Despite progress, several challenges hinder the full effectiveness of global VBD surveillance. A major limitation lies in the fragmentation of data collection, with varying methodologies and reporting standards across countries [26]. Many low- and middle-income nations lack interoperable health information systems capable of integrating environmental and entomological data in real time [30]. Inadequate internet connectivity, insufficient technical training, and inconsistent funding further undermine national surveillance capacity [27]. Additionally, information-sharing between regional databases remains limited due to geopolitical barriers and data sovereignty concerns [24].

Efforts to standardize digital reporting frameworks and promote open-access databases, such as WHO's Global Health Observatory, represent important steps toward harmonization [29]. Nevertheless, achieving a cohesive, data-driven global surveillance network requires sustained international cooperation, technical investment, and governance mechanisms that prioritize transparency, interoperability, and equitable data access [23].

4.2. Remote Sensing and Climate Data Integration

Remote sensing technologies have become indispensable tools in modern vector surveillance, enabling real-time tracking of environmental factors that influence disease transmission [28]. Satellite imagery, geospatial mapping, and meteorological datasets allow researchers to model ecological changes that affect vector breeding and survival [24]. Geographic Information Systems (GIS) are widely used to overlay climate data with epidemiological trends, identifying high-risk zones for targeted interventions [22]. By correlating rainfall patterns, vegetation indices, and land surface temperature, these systems help predict where and when outbreaks are most likely to occur [27].

Successful early warning systems (EWS) demonstrate the practical utility of climate-informed surveillance. In Kenya, the Malaria Early Warning System (MEWS) integrates satellite rainfall estimates, temperature forecasts, and epidemic monitoring to provide region-specific alerts that guide vector control activities [26]. Similarly, Brazil's Integrated Dengue Surveillance System (IDSS) combines meteorological data, urban density mapping, and vector population modeling to forecast dengue outbreaks up to eight weeks in advance [30]. These examples highlight the potential of climate data integration in shifting from reactive to proactive disease management.

However, challenges persist regarding data accessibility, sensor calibration, and the scalability of predictive models to local contexts [23]. The high cost of satellite data processing and limited technical capacity in developing nations often restrict consistent application [29]. Collaborative initiatives involving NASA, ESA, and WHO aim to overcome these constraints by expanding open-data programs and building regional analytic capabilities [25]. Ultimately, remote sensing provides a bridge between environmental science and public health policy, enabling a multidimensional understanding of vector ecology that supports sustainable and adaptive health interventions [28].

4.3. Artificial Intelligence and Predictive Analytics

Artificial intelligence (AI) and machine learning (ML) are revolutionizing the capacity of public health systems to forecast vector-borne disease outbreaks and optimize surveillance operations [24]. Predictive analytics models can analyze large, heterogeneous datasets—including climate variables, entomological records, and social media reports—to identify early signals of transmission [22]. Neural networks and ensemble learning algorithms have demonstrated strong performance in predicting malaria and dengue incidence weeks before clinical detection, allowing for preemptive resource allocation [30]. For instance, in Sri Lanka and Thailand, hybrid ML models integrating rainfall, temperature, and population data have achieved over 85% accuracy in forecasting dengue epidemics [26].

AI-driven tools also enhance vector surveillance by automating mosquito species recognition through image analysis and optimizing larval habitat mapping using drone-collected data [27]. These innovations improve temporal resolution and reduce manual workload, especially in resource-limited regions [29]. Moreover, coupling predictive models with mobile health platforms facilitates real-time information sharing between laboratories, field officers, and national health agencies [23].

Despite their transformative potential, AI-enabled systems raise concerns related to data governance, algorithmic bias, and privacy protection [28]. Inconsistent data quality and underrepresentation of certain geographic regions can lead to inequitable model performance [25]. Ethical frameworks emphasizing transparency, data anonymization, and accountability are thus critical to ensure fairness and trust in automated decision-making [24].

The convergence of AI and climate analytics represents a new frontier in disease prediction, offering actionable insights that enhance early warning systems and support evidence-based policymaking.

Table 2 Comparison of Global and Regional Vector Surveillance Tools and Their Predictive Capacities

Surveillance System / Program	Coordinating Organization(s)	Geographical Coverage	Core Data Integration Features	Predictive and Analytical Capabilities	Key Strengths and Limitations
VectorNet	European Centre for Disease Prevention and Control (ECDC) & European Food Safety Authority (EFSA)	Europe, Mediterranean Basin	Integrates entomological, epidemiological, and environmental data; includes species distribution mapping.	Uses GIS-based spatial modeling for vector presence and climate suitability predictions.	Strengths: Robust cross-border harmonization and high-quality geospatial mapping. Limitations: Limited real-time data sharing with non-EU regions.
ArboNET	U.S. Centers for Disease Control and Prevention (CDC)	North and South America	Collects arboviral surveillance data from human, animal, and mosquito populations; integrates with climatic variables.	Employs statistical modeling and early outbreak detection algorithms for West Nile, Zika, and Dengue.	Strengths: Strong laboratory network and multi-source integration. Limitations: Restricted international data access and temporal reporting delays.
MEWS (Malaria Early Warning System)	World Health Organization (WHO) & National Ministries of Health	Sub-Saharan Africa	Links meteorological, epidemiological, and entomological datasets using satellite rainfall and temperature data.	Predicts malaria epidemics 1–3 months in advance using climate anomalies and ENSO indices.	Strengths: Proven operational success in Kenya and Ethiopia; supports proactive vector control. Limitations: Dependent on local data reliability and funding continuity.
IDSS (Integrated Dengue Surveillance System)	Ministry of Health, Brazil (in collaboration with PAHO)	Latin America & Caribbean	Combines real-time meteorological monitoring with epidemiological and remote-sensing data.	AI-supported models forecast dengue incidence up to 8 weeks ahead, guiding local interventions.	Strengths: Advanced AI integration and community-based validation. Limitations: Regional application; requires high computational resources.

DHIS2 Vector Module	University of Oslo & WHO-supported implementers	Global (used in >75 LMICs)	Open-source health information platform integrating climate and surveillance indicators.	Supports customizable dashboards for risk mapping and real-time analytics.	Strengths: Scalable and interoperable with other national health systems. Limitations: Dependent on local IT infrastructure and data management capacity.
VectorMap	U.S. Defense Health Agency (DHA)	Global (with military and civilian data nodes)	Aggregates vector occurrence, pathogen testing, and geoclimatic data.	Provides ecological niche modeling for global vector distribution under multiple climate scenarios.	Strengths: High-resolution predictive modeling. Limitations: Limited open-access availability for civilian health authorities.

5. Prevention and control strategies under climate stress

5.1. Traditional Vector Control Approaches

Traditional vector control strategies remain the cornerstone of global public health efforts against malaria, dengue, and other climate-sensitive diseases [29]. Core interventions—such as insecticide-treated nets (ITNs), indoor residual spraying (IRS), and environmental management have historically contributed to significant reductions in transmission across endemic regions [34]. ITNs, in particular, have been one of the most cost-effective tools, providing both personal protection and community-wide benefits by lowering mosquito density [28]. Similarly, IRS targets mosquitoes resting on interior walls, reducing vector survival and interrupting parasite transmission cycles [30].

Environmental management interventions, including larval source reduction, proper waste disposal, and improved drainage systems, mitigate breeding opportunities in urban and rural environments [33]. However, the sustainability of these interventions is increasingly threatened by the effects of climate change and vector adaptation [37]. Rising temperatures accelerate mosquito development and shorten insecticide efficacy, while erratic rainfall patterns generate new breeding habitats that traditional control programs often fail to anticipate [31]. Moreover, the growing prevalence of insecticide resistance among *Anopheles* and *Aedes* species reduces the long-term effectiveness of chemical interventions [35].

Financial and logistical constraints also limit large-scale implementation in resource-poor settings, where infrastructure deficits and inconsistent funding hinder sustained intervention coverage [32]. Consequently, while conventional methods remain indispensable, they require integration with adaptive and predictive systems capable of responding dynamically to climate variability and ecological complexity [38].

5.2. Climate-Adaptive Public Health Interventions

As climate variability increasingly drives disease transmission, adaptive public health interventions are essential for building resilience and sustaining control efforts [30]. These strategies leverage meteorological forecasting, risk mapping, and community-based participation to anticipate and prevent outbreaks before they occur [28]. Integrating weather and climate models with health surveillance enables authorities to allocate resources based on predicted disease hotspots, reducing both morbidity and economic loss [33]. For example, seasonal climate forecasts have been used successfully in East Africa to time malaria control campaigns around anticipated rainfall peaks [35].

Community engagement remains central to the success of adaptive strategies. Participatory health initiatives empower local populations to identify environmental risks, monitor mosquito habitats, and implement low-cost preventive measures [37]. Climate-adaptive programs in Kenya and Bangladesh have demonstrated that when communities are involved in early warning dissemination and vector control, intervention coverage and behavioral compliance improve significantly [31].

Institutionalizing such interventions requires intersectoral coordination among health, environment, and meteorological agencies [32]. The use of digital platforms to distribute climate-risk alerts and train field workers enhances real-time decision-making capacity at the local level [36]. Furthermore, decentralizing climate–health data systems supports localized responses tailored to environmental diversity and population vulnerability [34].

Ultimately, climate-adaptive public health interventions represent a paradigm shift from reactive crisis management toward proactive, data-informed prevention, emphasizing equity, sustainability, and inclusivity in disease control frameworks [29].

5.3. Vaccine Development and Integrated Control

Vaccines offer a promising complementary tool in reducing the burden of vector-borne diseases aggravated by climate variability [28]. The approval of the RTS,S/AS01 malaria vaccine and the more recent R21/Matrix-M candidate mark important milestones in global malaria control, showing efficacy rates exceeding 70% in trial settings [33]. Similarly, the Dengvaxia and Qdenga vaccines for dengue provide partial protection, though their deployment remains limited due to serotype variability and cost constraints [36].

However, the success of vaccination programs depends on their integration with other preventive measures such as vector control, surveillance, and public education [31]. Synergistic approaches that combine immunization, entomological monitoring, and climate forecasting enable a multilayered defense against outbreaks [30]. Strengthening vaccine supply chains and ensuring equitable distribution are also critical to sustaining global health gains in a warming world [35].

Comprehensive integration of vaccination strategies into climate-informed disease control frameworks will ensure continuity of protection even under rapidly changing environmental conditions.

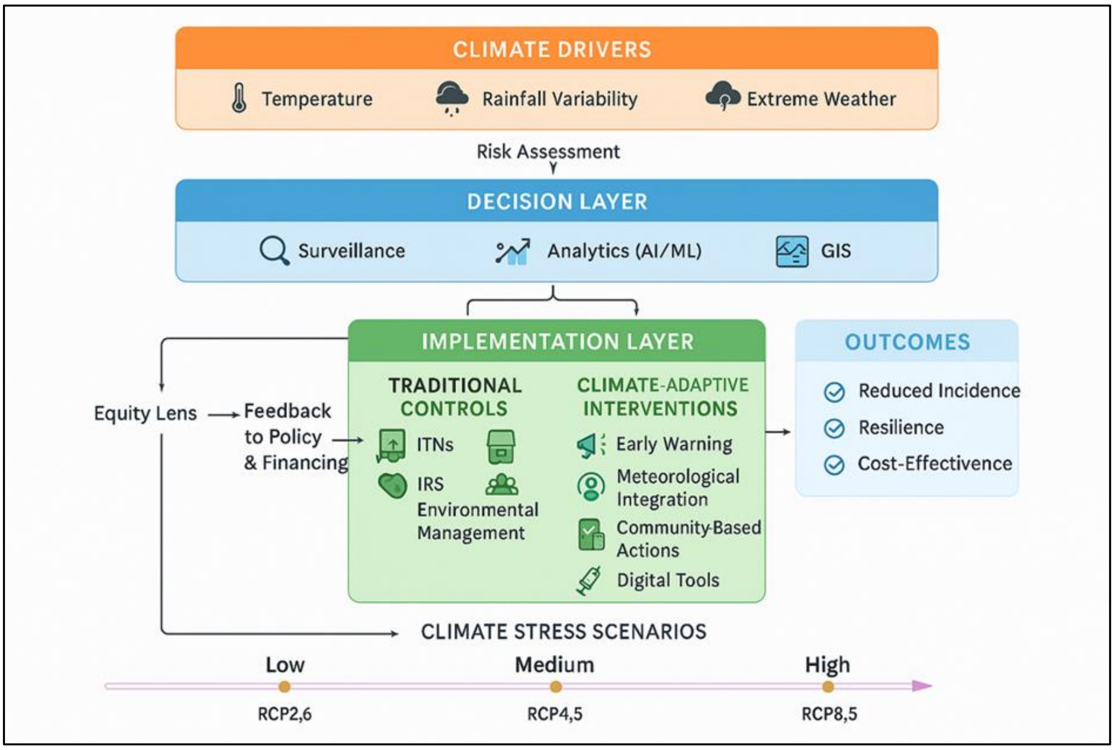


Figure 3 The framework for integrated vector control and adaptive intervention pathways, illustrating how traditional, climate-adaptive, and vaccine-based measures interact under varying climate stress scenarios to achieve sustainable disease prevention [38]

6. Policy frameworks and global governance

6.1. International Climate–Health Policy Synergies

Global policy frameworks have increasingly recognized the intricate relationship between climate change and public health, prompting multi-agency collaborations between the World Health Organization (WHO), the United Nations Framework Convention on Climate Change (UNFCCC), and the Intergovernmental Panel on Climate Change (IPCC) [39]. These institutions jointly emphasize the integration of health considerations into global climate action, framing disease surveillance and adaptive preparedness as essential components of climate resilience [36]. The WHO's *Operational Framework for Building Climate Resilient Health Systems* outlines strategies to strengthen epidemiological monitoring, enhance workforce training, and improve data integration across environmental and health sectors [42].

The UNFCCC supports countries through the National Adaptation Plan (NAP) process, enabling governments to identify health-related priorities within broader climate adaptation agendas [35]. Health is now increasingly represented in Nationally Determined Contributions (NDCs), signaling a paradigm shift toward proactive inclusion of disease prevention within global climate policy [38]. Additionally, the IPCC's Sixth Assessment Report provides strong scientific evidence linking temperature rise and vector-borne disease expansion, urging nations to mainstream climate–health linkages into mitigation and adaptation strategies [41].

Collaborative initiatives such as the *Climate and Clean Air Coalition* and the *Global Framework for Climate Services (GFCS)* exemplify the value of cross-sectoral coordination in addressing air quality, extreme weather, and infectious disease risk simultaneously [40]. These efforts collectively underscore the necessity of embedding health-centered climate intelligence into global governance to anticipate, rather than react to, emerging threats [37].

6.2. National-Level Adaptation and Resilience Policies

At the national level, climate–health adaptation policies reflect diverse approaches shaped by socioeconomic capacity, political will, and environmental vulnerability [38]. Rwanda, for instance, has integrated health into its National Adaptation Plan by prioritizing malaria surveillance, community health worker training, and weather-based epidemic prediction systems [36]. This alignment between meteorological and health data has improved early warning capabilities and reduced response delays during peak transmission seasons [35].

India presents another example of inter-ministerial coordination where the Ministry of Health and Family Welfare collaborates with the Indian Meteorological Department to operationalize the National Action Plan on Climate Change and Human Health (NAPCCHH) [42]. The program links vector monitoring with air pollution and heatwave management, ensuring that adaptive measures span across agriculture, energy, and water sectors [37]. Such multi-sectoral approaches foster systemic resilience, preventing disease outbreaks while sustaining agricultural productivity and water security [41].

In the Philippines, the Climate Change Commission's *National Climate Change Action Plan* (NCCAP) integrates public health within disaster risk management frameworks, emphasizing community participation and local governance [39]. By connecting environmental and health ministries, the Philippines has advanced a "whole-of-government" approach that aligns national adaptation targets with the Sustainable Development Goals (SDGs) [43]. These national experiences illustrate that effective resilience building depends on coherent coordination between environment, health, and agricultural sectors, supported by stable financing and policy continuity [40].

Collectively, these country-level examples demonstrate that integrating climate–health priorities within policy frameworks not only strengthens surveillance and preparedness but also promotes sustainable development through enhanced governance and inclusivity [35].

6.3. Ethical and Socioeconomic Dimensions

The ethical and socioeconomic implications of climate–health governance are profound, as climate change disproportionately impacts vulnerable populations [36]. Communities in low-income countries, indigenous groups, and marginalized urban populations often face the greatest exposure to vector-borne diseases while possessing the fewest adaptive resources [38]. Addressing these disparities requires an approach grounded in climate justice ensuring that adaptation funding, technology transfer, and healthcare investments reach those most at risk [39].

Equitable health adaptation also demands participatory policy processes that amplify community voices and integrate indigenous knowledge into climate–health decision-making [43]. Socioeconomic inequities, including housing conditions, access to clean water, and education levels, directly influence vulnerability to disease and determine the effectiveness of adaptation measures [37]. Therefore, ethical frameworks must guide global and national strategies to ensure that technological innovations, surveillance systems, and policy instruments do not exacerbate inequality but rather promote inclusivity and resilience [41].

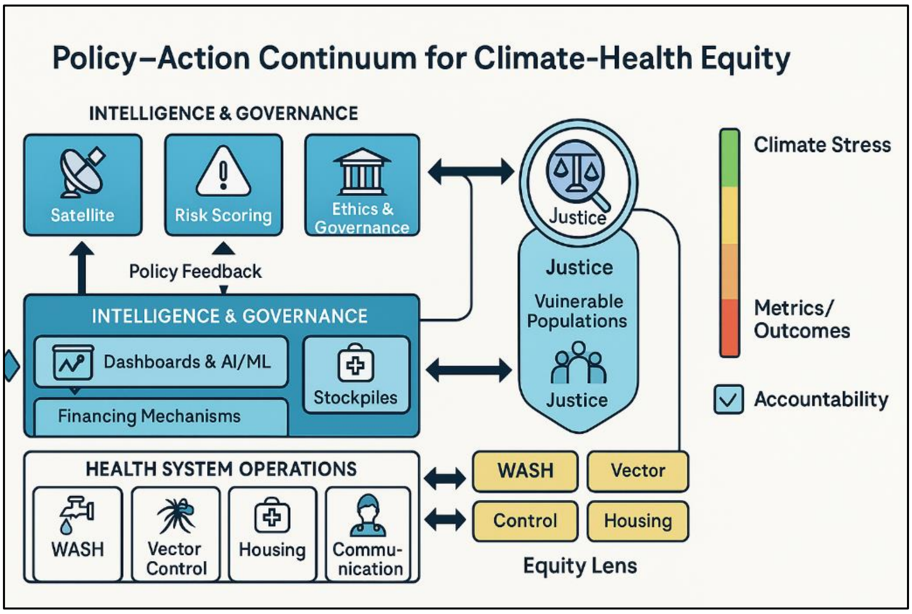


Figure 4 The policy–action continuum linking climate data integration, public health systems, and community-level adaptation, emphasizing how ethical, socioeconomic, and governance dimensions converge to support equitable health resilience under climate stress [35]

7. Data-driven decision support systems

7.1. Integrating Epidemiological and Climate Datasets

The integration of epidemiological and climate datasets has become a critical foundation for enhancing disease prediction and adaptive health policy design [43]. Linking health information systems (HIS) with real-time meteorological and satellite-derived data enables the creation of comprehensive risk mapping frameworks that capture the dynamic interplay between environmental and health variables [48]. These integrated systems facilitate near real-time surveillance, allowing for early detection of climatic triggers such as rainfall anomalies, humidity shifts, or temperature spikes that may precede disease outbreaks [41].

Interoperable data architectures are key to achieving this synergy. Platforms that merge epidemiological indicators with remote sensing data such as NASA's Earth Observing System Data and WHO's HealthMapper enable the visualization of spatial and temporal disease trends across scales [47]. Such frameworks support localized interventions by linking clinical case data with environmental predictors, empowering policymakers to allocate resources more strategically [44]. However, data integration remains challenging in many developing nations, where fragmented information systems and limited computational infrastructure hinder interoperability [49].

Efforts to harmonize data standards and enhance inter-agency collaboration are vital for ensuring consistency, accuracy, and comparability of datasets [46]. When effectively synchronized, these integrated systems form the backbone of adaptive surveillance, transforming climate intelligence into actionable public health strategies that improve preparedness and minimize disease burden [45].

7.2. Evaluating Policy Outcomes Using Analytics

Data analytics and artificial intelligence (AI) are transforming how public health systems evaluate the effectiveness of climate–health policies [50]. Big data analytics integrates diverse datasets ranging from hospital admissions and vector surveillance to meteorological records to monitor policy performance and guide adaptive decision-making [42]. Predictive algorithms can model the impact of interventions under different climate scenarios, helping governments assess whether policy objectives align with real-world health outcomes [44]. These tools not only improve transparency but also enable continuous optimization of resource allocation and program design [48].

Machine learning (ML) models are increasingly being used to evaluate disease control strategies by detecting correlations between intervention timing, environmental fluctuations, and disease incidence [46]. For example, random forest and neural network models can identify lag periods between rainfall and malaria spikes, allowing for the adjustment of preventive actions such as insecticide distribution or vaccination scheduling [43].

Furthermore, integrating analytics dashboards into national health systems facilitates multi-sectoral collaboration among environment, health, and policy agencies [47]. These dashboards transform complex data into visual, decision-ready insights, promoting evidence-based governance [45]. To maximize utility, data governance frameworks must ensure data quality, protect privacy, and prevent algorithmic bias, ensuring that technological innovation strengthens equity and accountability in health adaptation [49].

Through the combined power of AI, big data, and robust evaluation systems, analytics-driven feedback loops are reshaping how governments respond to climate-induced health risks, fostering a cycle of continuous learning, policy refinement, and adaptive resilience [41].

8. Challenges and research gaps

8.1. Limitations in Modeling and Data Resolution

Despite significant advances in climate–health analytics, modeling vector-borne disease dynamics remains constrained by limited data resolution and methodological uncertainties [46]. Spatial–temporal granularity is often inadequate, particularly in regions where disease surveillance networks and meteorological stations are sparse or inconsistent [50]. Many existing models depend on coarse climate datasets that overlook micro-environmental variations such as urban heat islands or local humidity fluctuations that critically influence vector breeding and transmission [48].

Underreporting of disease cases further undermines model accuracy, as national health databases frequently lack standardized reporting protocols and cross-border data exchange mechanisms [52]. Missing or incomplete climate variables, including soil moisture and wind speed, can skew projections, especially in complex ecosystems with overlapping vector species [49]. Additionally, most predictive models fail to incorporate sociobehavioral determinants such as human migration, housing quality, and land-use patterns which modulate exposure risk and disease spread [47].

Improving model reliability requires the integration of high-resolution climate reanalysis datasets, remote sensing technologies, and ground-truth epidemiological validation [53]. Building regional data-sharing hubs and fostering multidisciplinary collaboration among climatologists, data scientists, and epidemiologists will be crucial for reducing uncertainty and enhancing predictive power across diverse ecological and socioeconomic contexts [51].

8.2. Political and Funding Barriers

Beyond technical challenges, political and financial constraints pose significant obstacles to strengthening climate–health systems [52]. Many low- and middle-income countries lack the fiscal stability to sustain long-term investments in surveillance, vector control, and data infrastructure [46]. International aid programs often provide short-term project funding, resulting in fragmented implementation and limited institutional continuity [53]. Policy inertia exacerbates these challenges, as competing national priorities such as economic recovery, energy policy, and security divert attention from climate-driven health risks [47].

In some regions, governance fragmentation between ministries of health, environment, and agriculture impedes coordinated adaptation planning [50]. Moreover, political transitions and administrative turnover disrupt established programs, eroding institutional memory and slowing policy progress [49]. Limited engagement with local governments and communities further constrains accountability and program effectiveness [48].

Addressing these systemic barriers demands sustained political commitment, innovative financing mechanisms, and multi-sectoral governance structures that institutionalize climate–health integration [51]. Expanding public–private partnerships and leveraging global climate finance initiatives such as the Green Climate Fund can provide steady funding streams for adaptive health infrastructure [46]. Ultimately, aligning financial resources with long-term policy frameworks is essential to ensure resilience, continuity, and equitable protection against climate-sensitive diseases worldwide [53].

9. Strategic recommendations and future outlook

9.1. Enhancing Climate–Health Integration

Strengthening the nexus between climate science and public health requires a transdisciplinary approach that bridges research, policy, and practice [52]. Promoting collaborative research among climatologists, epidemiologists, and data scientists enables the co-production of actionable intelligence that links meteorological patterns with disease emergence [54]. Integrating health considerations into all sectors a "Health in All Policies" (HiAP) framework ensures that environmental planning, agriculture, and infrastructure development collectively reinforce resilience against vector-borne diseases [53].

Regional and international platforms should prioritize data sharing, joint modeling initiatives, and harmonized adaptation strategies to enhance global preparedness [55]. The development of interoperable climate–health information systems can support real-time policy decision-making and optimize response coordination across borders [52]. Furthermore, incorporating local and indigenous knowledge strengthens adaptation design by contextualizing interventions within specific ecological and cultural settings [54].

Ultimately, embedding climate–health integration into development planning not only mitigates disease risks but also promotes sustainable, equity-centered governance. This alignment advances the dual goals of climate adaptation and global health security by ensuring that public health systems remain dynamic, anticipatory, and evidence-driven in the face of growing environmental uncertainty [53].

9.2. Building Resilient Health Systems

Developing resilient health systems is fundamental to sustaining adaptive capacity under accelerating climate stress [52]. Investment in human capital through specialized training for epidemiologists, vector control experts, and data analysts enhances national capabilities for disease detection, forecasting, and rapid response [56]. Digital transformation of public health infrastructure, including the use of mobile surveillance tools, cloud-based data systems, and decision-support dashboards, enables timely information exchange and decentralized action [53].

Strengthening laboratory networks and emergency operations centers supports early outbreak containment and continuous situational awareness [54]. Equally important is fostering partnerships with private and academic sectors to accelerate technological innovation in vector monitoring and vaccine development [52]. Establishing cross-sector early response networks that link meteorological, environmental, and health institutions ensures that interventions are both predictive and preventive rather than reactive [55].

Long-term resilience depends on stable financing and governance reforms that institutionalize climate-informed decision-making across all levels of government [53]. Prioritizing inclusivity and local participation ensures that adaptation measures remain contextually relevant, equitable, and sustainable. Through sustained collaboration and technological innovation, resilient health systems can transform climate risk into opportunity building a future where health equity and environmental stability advance together [54].

10. Conclusion

The global evidence linking climate change to the resurgence and redistribution of vector-borne diseases (VBDs) is now unequivocal. As rising temperatures, shifting precipitation patterns, and extreme weather events reshape ecological systems, they simultaneously redefine the transmission landscapes of infectious diseases. From the malaria-endemic plains of Sub-Saharan Africa to the dengue-affected megacities of Asia and the emerging tick-borne disease zones in Europe and North America, the influence of a warming climate on vector proliferation and disease spread is increasingly evident. Climate-sensitive vectors, including mosquitoes, ticks, and sandflies, are thriving in new environments once considered inhospitable, extending disease boundaries and exposing new populations to health risks. This shift underscores the interconnectedness of climate and health, where environmental disruptions manifest as direct and indirect threats to global well-being.

The mounting epidemiological data reveal that climate change not only intensifies disease transmission but also complicates traditional control and prevention mechanisms. Conventional interventions such as insecticide spraying, bed net distribution, and environmental management are no longer sufficient when faced with unpredictable weather fluctuations, evolving vector resistance, and changing population dynamics. Adaptive and forward-looking strategies are now imperative. Strengthened surveillance systems, capable of integrating climate forecasts and epidemiological data, can provide early warnings and guide timely interventions. At the same time, investments in artificial intelligence and geospatial analytics offer opportunities for more precise risk mapping and targeted responses. These tools, when embedded in health systems, empower nations to anticipate outbreaks before they escalate into crises.

A coordinated global response must bridge the gaps between climate science, public health, and governance. International cooperation through frameworks such as the World Health Organization's Global Vector Control Response and the UN's climate adaptation mechanisms has demonstrated the potential for integrated action. However, sustained progress depends on consistent political commitment, cross-sectoral collaboration, and equitable access to resources. National and regional policies should align health security with environmental sustainability, ensuring that adaptation strategies are both data-driven and inclusive. Effective governance requires accountability and transparency in implementing climate–health measures, underpinned by reliable financing and capacity development.

Equity must remain at the heart of all efforts to address the climate–health nexus. Vulnerable populations particularly in low-income regions bear the greatest burden of climate-sensitive diseases despite contributing least to global emissions. Closing this disparity demands a justice-oriented approach that prioritizes funding for health infrastructure, technology transfer, and local empowerment. Community engagement, education, and indigenous knowledge systems must guide adaptation efforts to ensure sustainability and ownership.

Ultimately, climate change represents not only an environmental crisis but a defining public health challenge. The path forward lies in reimagining disease prevention and health governance through an equity-centered, adaptive lens. Building resilient, climate-informed health systems capable of anticipating and mitigating vector-borne disease threats will be the cornerstone of sustainable global health security in the decades ahead.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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