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Exploring The Nexus Of Global Climate Changes And Infectious Disease Dynamics: A Depth Review Study

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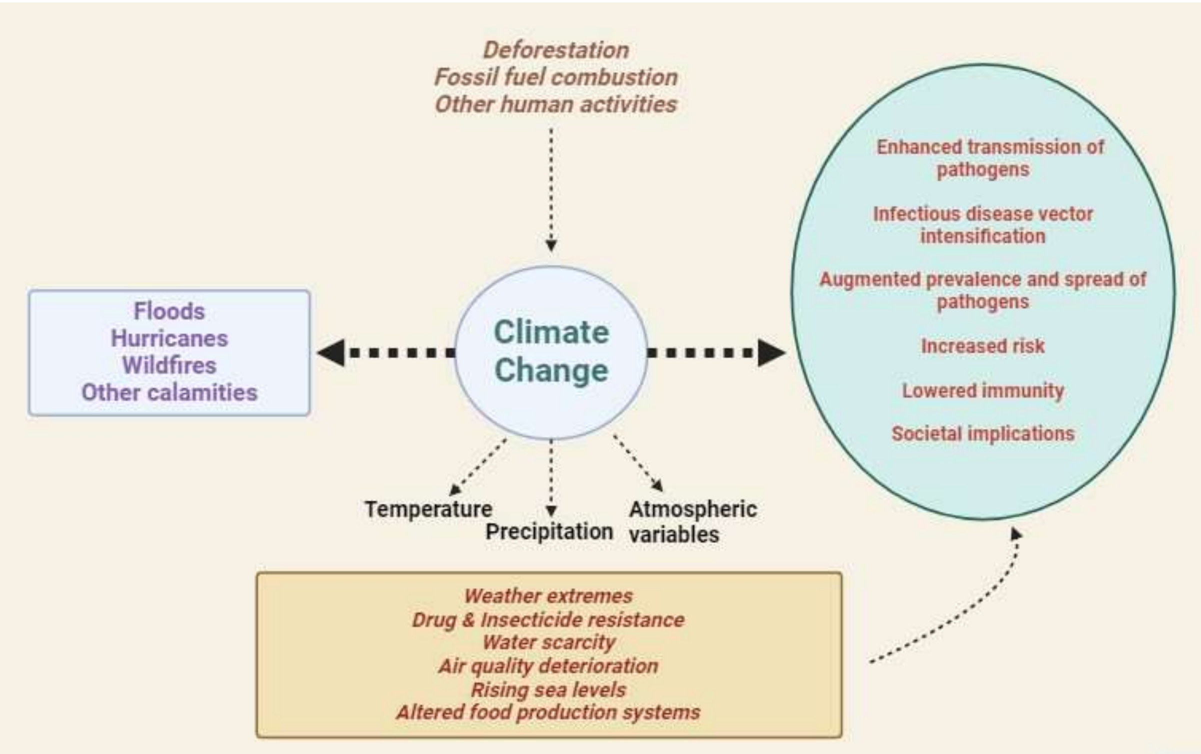
Abstract

Climate change refers to long-term changes in temperature, precipitation patterns and atmospheric variables on the Earth, which mostly result from human activities like deforestation and fossil fuel combustion. There are direct and indirect impacts of these environmental shifts on the well-being of individuals and communities, posing an imminent threat to global human health. Surviving calamities like floods, wildfires, etc. is an area of concern for the healthcare system. Moreover, in the recent years, research has shown a significant change in the transmission dynamics of infectious diseases due to weather extremes, air quality deterioration, rising sea levels, scarcity of water resources and altered food production systems. Activities related with deforestation are also major contributors to the spread of infectious disease vectors. The rise in drug and insecticide resistance has further intensified the risk of infectious diseases in both, humans and animals. A recent meta-analysis has reported that more than 50% of known human pathogens are anticipated to be augmented due to climate change. Further research progress is warranted in this area to bridge the gaps and execute strategies for adapting to the changing climatic conditions. In this article, we provide insights into the impacts of global climate change on the rising infectious disease conditions in humans. The paper shall discuss the current trends, challenges and opportunities persisting in this field of study and provide a comprehensive review to the readers.

KEYWORDS: Climate change; Weather extremes; Infectious diseases; Vectors; Infectious pathogens; Global human health.

Graphical Abstract



1. Introduction

The continuous modifications to the patterns of the global climate, which are generally known as "climate change," represent a complex issue that has significant effects on the ecosystems of Earth **[1]**. The combustion of fossil fuels and deforestation, in particular, are human-induced activities that greatly contribute to the unusual increase in greenhouse gas concentrations **[2]**. The earth warms overall as a result of these gases trapping heat in the atmosphere. Rising sea levels, altering precipitation patterns, and more frequent and severe extreme weather events are just a few of the many effects of climate change **[3]**. Food security, water resources, and biodiversity are all immediately threatened by these changes. Furthermore, the majority of the negative effects fall on vulnerable groups, who are frequently the ones least accountable for the greenhouse gas emissions **[4]**. Reducing emissions, switching to renewable energy sources, and building resilience to the unavoidable changes are all part of the mitigation of climate change **[5]**. Understanding the complexity of climate change and developing practical ways to address its global repercussions require scientific knowledge and creative solutions. The scientific community keeps looking at new ways to lessen the effects of climate change and adjust to its changing challenges as we work towards sustainable practices.

Much of the early research on the relationship between infectious diseases and climate change concentrated on the possibility of increased disease susceptibility in future climate circumstances. Forecasts included the possibility of regional spread or seasonal changes, which were expected to lead to generally higher transmission rates **[6]**. Given the interdependence between the life cycles of many infectious agents and climate conditions, the Intergovernmental Panel on Climate Change (IPCC) has voiced a high degree of confidence in the prediction that dangers to world health will worsen as a result of climate change **[7]**. A number of studies have been conducted in recent years that show how changes in climate affect the spread of infectious diseases **[8]**. The effects of changes in humidity, precipitation, and temperature on the prevalence and transmission of infectious diseases have been thoroughly examined in a number of research. However, it is still unclear to what exact degree, in which direction, and to what degree climate change is influencing the spread of infectious diseases. The biodiversity and ecosystems of Earth are negatively impacted by human activity, which also contributes to anthropogenic pollution, climate change, and global warming **[9]**. Significantly, the abundance of many stressors has increased, and when they are imposed together, the health of plants and ecosystems is markedly worsened. Although a great deal of information is known about how individual stressors affect plants and ecosystems, more recent research efforts have directed their attention towards learning how these biological systems react to a mixture of stress conditions. Coastal zones, which are defined as the densest locations on Earth, are increasingly threatened by the stresses associated with climate change, which include rising sea levels, rising temperatures, stronger storms and droughts, and acidification of the ocean **[10]**. Although local human activities have historically had an impact on coastal zones, the complex interactions between these human impacts and the stresses brought on by climate change that jeopardise coastal ecosystems are still not fully understood **[11, 12]**. **Figure 1** depicts a simple representation of the relationships and association between the global climate change, human societal implications and infectious diseases.

With major effects on public health, climate change has become an important issue. In order to educate adaptive tactics and reduce possible health catastrophes, a thorough analysis of the complex interactions between infectious illnesses and extreme weather events is required. The intricacy of these connections has been highlighted by recent research, which has revealed a dynamic landscape influenced by climate. The effect of extreme weather events on the spread of infectious illnesses is one of the key topics of research **[13]**. A significant rise in the spread of disease both during and following natural disasters such heat waves, floods, and storms has been demonstrated. An increased risk of infectious disease outbreaks is caused by disrupted ecosystems, changing vector habitats, and altered human behaviour during extreme weather events. Several studies have highlighted how susceptible different areas are to diseases spread by vectors, and how changes in climate affect the geographic range of vectors **[14]**. New populations are exposed to diseases like Lyme disease, dengue fever, and malaria due to the spread of mosquitoes, ticks, and other disease vectors. Public health solutions are required to meet these developments and emergent dangers **[15, 16]**.

Severe weather conditions affect the availability of food and water, which in turn affects the frequency of food- and water-borne illnesses. Diseases like cholera and gastrointestinal illnesses occur due to contaminated water sources caused by increased flooding and altered precipitation patterns **[17, 18]**. Changes in humidity and temperature also have an impact on the growth of foodborne bacteria. Extreme weather brought on by climate change can weaken immune systems and put a burden on healthcare services. Extreme heat events are occurring more frequently, which puts vulnerable populations at risk of worse pre-existing medical issues and increased susceptibility to infectious infections. Effective responses to disease outbreaks may be hampered by the stress extreme events place on the healthcare infrastructure **[19]**.

This review focuses on the complex relationships that exist between infectious diseases, extreme weather, and climate change. Comprehending these dynamics is essential for formulating strategies, reducing health hazards, and cultivating durability in the face of climate change. To understand the nuances of this link and develop evidence-based treatments for preserving global health, more multidisciplinary research is necessary.

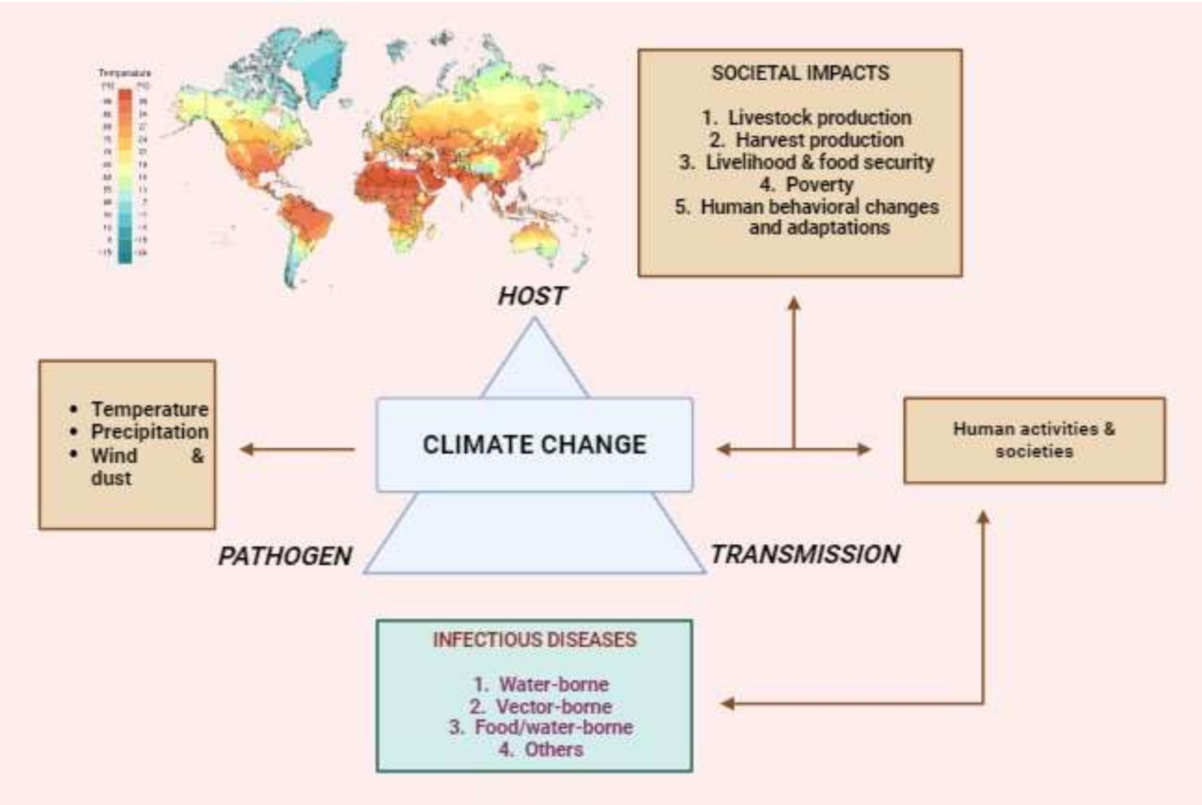


Figure 1: A generalised representation of the relationships and association between the global climate change, human societal implications and infectious diseases. The world map on the top left corner shows the projected future temperatures in different regions of the world (Created using BioRender)

2. Implications of Climate Change-related Migration on Infectious Diseases

The effects of human-caused climate change on migration are now a hotly discussed and crucial issue. Many frameworks, descriptive or analytical often begin by acknowledging that population migration is accelerated by climate change. They go into estimating migratory routes and evaluating possibly impacted populations **[20]**. Climate change is expected to have a number of effects on population movement, including increased severity and frequency of extreme weather events and climate-related disasters, loss of arable and habitable land (e.g., island habitats, coastal or riverine terrestrial land due to sea-level rise), and negative effects on important ecosystems that impact livelihoods **[21]**. The health hazards linked to climate change have been highlighted by epidemiological research. These concerns include temperature changes and extremes, natural disasters connected to climate change, altered food production and water supplies, and changing patterns of infectious diseases **[22]**. These results indicate a breakdown in the fundamental environmental support networks that are essential for maintaining human security and biological health. However, there has not been much focus on how climate change affects health, especially when it comes to effects that arise through indirect causal pathways mediated by social, political, and economic issues, including the health effects of migration and displacement brought on by climate change **[23]**.

Migration affects the risk of infectious diseases dramatically. Both internal and international migration affect the incidence and spread of infectious illnesses **[24]**. While travelling or settling in their new homes, migrants come into contact with new illnesses, act as carriers while travelling, and sometimes they bring infectious agents back with them when they migrate back. The past immunity of a population to particular infectious diseases is a major factor in determining how risks are distributed among host and migrant populations **[25]**. Migration caused by climate change exposes migrants to endemic diseases to which they may not have any social or cultural experience or resistance **[24]**. On the other hand, migratory populations may become infected with diseases including hepatitis B, tuberculosis (TB), and sexually transmitted infections (STIs) **[26]**. Additionally, socioeconomic determinants of living and working situations, as well as health practices in settlement areas, such as access to healthcare for the migrant populations, are linked to the risks of infectious diseases **[26, 27]**.

In order to effectively address the intricate interplay of social, political, economic, and environmental elements in the linkages between migration, health, and climate change, population health approaches must take a multidisciplinary and multi-sectoral approach. Building local resilience, lowering the need for migration from negatively impacted areas, defending the rights and well-being of individuals who face mobility obstacles, and promoting the adaptive potential of migration should be the main goals of development policies that are sensitive to climate change. Global politics, production and consumption patterns, ecosystems, economies, human and environmental studies, and ethical considerations all need to take climate change into serious account **[28, 29]**.

3. Climate Change and Infectious Diseases Framework

Variations in climate refer to changes in one or more of the climatic characteristics, which include wind, sunlight, precipitation, and temperature. These variations have the potential to affect the availability and features of the transmission environment in addition to the survival, reproduction, or dispersal of disease pathogens and their hosts. The ensuing health effects are characterised by observable changes in the seasonal and geographic distribution of infectious human diseases, as well as in the frequency and intensity of outbreaks **[30]**.

A wealth of scholarly literature explores the complex and possible effects of climate change on different types of infectious diseases, including those that are vector-borne, water-borne, air-borne, and food-borne. The complex interaction between climatic conditions and infectious diseases is highlighted by scientific data. Changes in temperature and precipitation patterns, for example, have been shown to affect the distribution and abundance of disease vectors, which in turn affects the dynamics of disease transmission carried by vector-borne illnesses. Furthermore, alterations in host immune responses may modify susceptibility to specific infections due to climate changes **[31]**. In order to develop well-informed policies to reduce the possible health implications of ongoing climate changes, a thorough understanding of these relationships is important **[32]**.

3.1 Climate change and infectious pathogens

Pathogens are a wide range of disease agents that include bacteria, viruses, fungus, parasites, and germs. Both direct and indirect effects of climate change are felt by these diseases. Changes in their habitat, environment, or competition have indirect effects on pathogens, whereas changes in their survival, reproduction, and life cycle have direct consequences. As such, changes may occur not only in the number of diseases but also in their seasonal and geographic distributions **[33]**.

Empirical evidence demonstrates the complex interplay between climate variables and water-borne diseases. Due to sediment disturbance, alterations in precipitation patterns, especially during the rainy season, might increase the number of faecal pathogens in water **[34]**. On the other hand, protracted droughts may cause a rise in infections, which in turn may cause disease epidemics **[35, 36]**. Furthermore, changes in humidity have an impact on airborne infectious diseases like influenza, where the survival and transmission of viruses are influenced by temperature and absolute humidity. Similar difficulties caused by variations in humidity affect the survival of water-borne viruses close to water surfaces **[37]**. Airborne viruses have been found to be transported and to survive in response to wind, a climatic component. Bacterial and viral densities have been linked to dust particles in the atmosphere, especially during occasions such as Asian dust storms. As seen during cholera outbreaks, temperature and sunshine hours work together to create an environment that is conducive to disease growth in aquatic habitats **[38, 39]**.

One of the most important climate variables, temperature has a variety of effects on infections. It affects the survival, development, reproduction, and extrinsic incubation durations of pathogens throughout their life cycle. For example, increasing temperatures can change the kinetics of pathogen transmission by accelerating the extrinsic incubation period **[40]**. Elevated temperatures may also promote an environment that is favourable to the cycles of reproduction for microbes and algal blooms, which could impact the frequency of illnesses such as food-borne salmonellosis. Crucially, variations in temperature can affect pathogen competitiveness as well, giving preference to some bacteria over others based on temperature **[41]**. All things considered, the complex interactions between diseases and climatic variables highlight the necessity for thorough study to clarify these connections and guide mitigation plans for the possible negative effects of climate change on human health **[42]**.

3.2 Climate change and disease transmission

Both direct and indirect methods can spread disease. A disease can be spread directly from one person to another via a variety of techniques, such as physical touch, droplet contact, airborne transmission, or fecal-oral transmission **[43]**. On the other hand, indirect transmission happens when a disease spreads to people through a different species, a vector, or a middle host **[44]**. Research has shown that weather and climatic factors might affect the spread of disease, potentially having an effect on infectious diseases that affect humans **[45]**. Through changes in pathogen viability, climate change can have a direct effect on the spread of illness **[24]**. Indirectly, adaptations to climate change by humans, vectors, and hosts may lead to modifications in transmission pathways. The effects of climate change on human immunity, susceptibility, and environmental degradation may be involved in the higher risk of contracting infectious diseases **[46]**. The complexity of how climate change affects the spread of disease is revealed by scientific evidence. For example, in areas where there is a scarcity of clean surface water, climate change may contribute to the occurrence of water-borne illnesses **[18]**. Variations in temperature, precipitation, and humidity are linked to hospital admissions and malaria transmission patterns in particular areas. Dust storms are one example of a meteorological phenomenon that is closely related to the timing of infectious disease epidemics, such as bird flu **[47]**.

Pathogens are transported by wind and dust storms, which contributes to the spread of airborne illnesses **[48]**. During dust storm seasons, avian influenza outbreaks typically happen in downwind regions **[49]**. Furthermore, the dynamics of disease transmission are impacted by changes in human-pathogen, vector, or host interaction patterns brought about by climate change **[33]**. For instance, open sewers and street flooding have been found to be risk factors for diseases like leptospirosis, which is more common during flood-related incidents. These findings highlight the necessity for thorough investigation to fully understand the complex connections between climatic factors and the spread of illness. This knowledge is crucial for developing adaptable methods to lessen the possible negative effects of climate change on health **[50, 51]**.

3.3 Climate change and vector dynamics

Disease pathogens reside in hosts, which are any living things, such as plants or animals, whereas vectors are the means by which pathogens are transferred from one living thing to another **[52, 53]**. Addressing the relationship between infectious diseases and climate change by examining how disease vectors are affected, with a special emphasis on insects as animal hosts is essential **[54]**. Climate change has the potential to cause changes in the distribution, longevity, and severity of infectious diseases by affecting the populations and geographic locations of disease vectors. Aedes aegypti mosquitoes in Rajasthan, India, have been shown to seek refuge in microenvironments with minimum temperature variations as a means of adapting to climate change **[55]**. Disease vectors may be impacted by modifications in precipitation patterns. Rainfall and vector-borne infectious diseases have been shown to have positive correlations, with mosquito larvae developing more quickly in response to rising temperatures and rain **[56]**. On the other hand, droughts may restrict mosquito breeding grounds, which would lower the number of vectors **[57]**. On the other hand, excessive rain can be detrimental since it might wash away breeding grounds. Due to the accumulation of organic materials in mosquito breeding pools, drought conditions may facilitate the development of the West Nile virus **[58, 59]**.

Variations in humidity have a significant impact on the survival and activity of disease vectors, which is important for the spread of disease **[60]**. Relative humidity affects the spread of malaria, with low humidity reducing the lifespan of mosquitoes that carry the disease **[61, 62]**. On the other hand, warm, rainy weather interspersed with dry spells may force mosquito vectors that spread diseases like Lyme and West Nile into unconventional regions. Low humidity inhibits the growth of associated infectious disorders by making conditions unfavourable for ticks and fleas, especially when combined with high temperatures **[63, 64]**.

Temperature affects the temporal and spatial distribution of disease vectors, which may cause diseases to spread or change geographically. As seen by the Oncomelania hupensis throughout China, rising temperatures have the potential to widen the range of disease vectors **[65, 66]**. The dispersion of disease hosts, as evidenced by the mortality of Aedes aegypti mosquitoes at high air and water temperatures, may be limited by temperature changes **[67]**. Wind affects disease vectors in two ways: it shortens the distance they can fly while also decreasing the likelihood of a bite **[68]**. Sunshine affects disease hosts in concert with temperature. Extended periods of sunshine and higher temperatures have been positively correlated with cases of cholera. The ideal conditions for cholera outbreaks are produced by high temperatures and moderate daylight hours, highlighting the complex link between climatic factors and infectious diseases **[69]**. The above-mentioned parameters have been summarised under **Figure 2**.

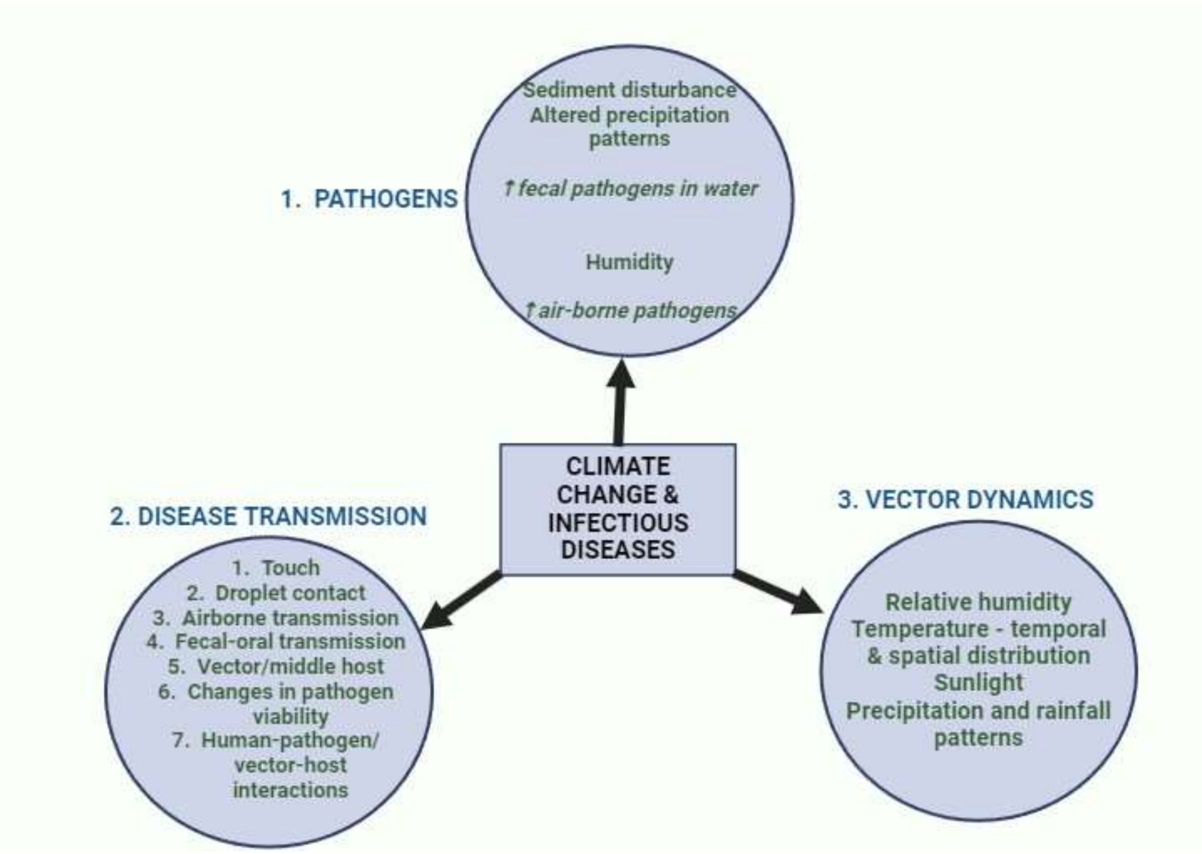


Figure 2: A summarised depiction of the various factors affecting climate change and infectious diseases (Created using BioRender)

4. Extreme Weather Events and Infectious Diseases

In light of global climate change, extreme weather events like hurricanes, floods, heat waves, and droughts have grown more frequent. The complex interactions between extreme weather events and the dynamics of infectious disease transmission are thoroughly examined in this review. We investigate the complex interactions that severe weather has with hosts, disease vectors, and the general epidemiology of infectious diseases. Research suggests that intense downpours might foster ideal mosquito vector breeding conditions, which in turn can enhance malaria transmission in impacted areas **[70]**. The increase of the geographic range of Aedes mosquitoes, the vectors that transmit dengue, has been connected to the intensified and protracted heatwaves due to climate change **[71]**. Water supplies can get contaminated by extreme weather events, especially high rainfall and flooding, which can promote the spread of water-borne diseases such as Vibrio cholerae **[72]**.

Floods have been linked to leptospirosis epidemics, highlighting the need of comprehending the relationship between severe weather and infectious diseases related to water **[73]**. Studies indicate that changes in atmospheric conditions during extreme weather events, like dust storms, could affect how influenza viruses spread and spread **[74]**. Further research into the significance of extreme weather events in pandemics is warranted as preliminary studies suggest possible links between weather patterns and the spread of respiratory viruses, such as SARS-CoV-2 **[75]**. There are research gaps in our knowledge of how simultaneous extreme events, including heatwaves and floods, exacerbate the effects on the dynamics of infectious diseases. Current research emphasises the necessity for interdisciplinary approaches in establishing adaptive methods to reduce the health hazards associated with extreme weather occurrences. **Table 1** shows a summarised version of the key research studies highlighting the association of infectious diseases and extreme weather conditions.

Table 1. A summary of some key studies which highlighted the relationship between infectious diseases and extreme weather events.

Type of Event	**Infectious Disease Type and Study Reference**	**Inferences**
Heatwaves	Vector-borne **[76]**	The West Nile fever outbreak in Israel was

		associated with heatwaves, in 2000.
	Air-borne **[77]**	An increase in the morbidity and mortality rates due to contagious respiratory diseases was found, majorly attributed to heatwaves.
Drought	Vector-borne **[78-81]**	Drought was followed by elevated risks of West Nile virus. Hantavirus pulmonary syndrome (HPS) and drought were found to be related. Research indicated that droughts would raise the possibility of the St. Louis Encephalitis virus spreading. Droughts and Chikungunya disease outbreak may be related.
	Water-borne **[82]**	During droughts, diarrheal illnesses are common, particularly in camps for refugees, as shown by this particular research.
El Nino	Vector-borne **[83-86]**	In Tanzania's Usambara Mountains, the El Nino year had remarkably fewer cases of malaria than the year before. In many areas, there was a favourable correlation between El Nino episodes and malaria outbreaks and epidemics.

		El Nino episodes in the Colorado Plateau have been linked to records of hantavirus cardiopulmonary illness. El Nino events have been associated with an increase in developing disease epidemics.
	Water-borne **[87]**	When exposed to coastal waters during an El Nino winter in southern California, the risk of developing diarrheal symptoms was doubled.
La Nina	Vector-borne **[81, 88]**	La Nina's drought was linked to the chikungunya disease outbreak. West Nile disease and Japanese encephalitis were widespread during the La Nina year.
	Water-borne **[89]**	La Nina winters increased risk throughout symptoms, including diarrhoea.
Quasi-Biennial Oscillation (QBO)	Vector-borne **[87]**	South-eastern Queensland's Ross River virus incidence has been connected to QBO.
Flood	Vector-borne **[86, 90-96]**	Typhoid, cholera, and malaria spread in Mozambique as a result of floods. Ross River fever outbreaks can be caused by heavy rain or flooding.

		Following a flood, instances of diarrheal illnesses like cholera could increase. In 1988, floods in Khartoum, Sudan, were linked to higher rates of malaria and diarrhoea. Increases in lymphatic filariasis have been documented in a few different locations. Following floods, there have also been documented increases in arbovirus diseases. Flooding may cause an increase in hemorrhagic fever and disorders related to renal syndrome. Flooding may potentially lead to an upsurge in HPS illnesses. In certain places, leptospirosis infections may also rise after flooding.
	Water-borne **[97, 98]**	Floods facilitate the spread of water-borne illnesses like Cryptosporidium infection. Deep flooding in the Southern English town of Lewes was found to significantly increase the incidence of gastroenteritis.
Cyclone	Vector-borne **[99]**	Leptospirosis (vector-borne) and cholera (food

	Food and water-borne **[100]**	and water-borne) tend to be more common after a cyclone.
Hurricane	Vector-borne **[101]**	Malaria and dengue fever were reported in Venezuela and Honduras after the hurricane.

5. Impact of Amazon Deforestation on Infectious Diseases

5.1 Habitat depletion and pathogen spread

Wildlife migrates into alternate ecosystems, which include both urbanised and de-urbanized areas, as a result of habitat fragmentation brought on by deforestation and unchecked urbanisation. Human activities within these altered ecosystems bring people and wildlife closer together **[102, 103]**. This increases interactions between people and wild animals, makes classic zoonotic diseases more common, and allows new pathogens to "spillover" between a variety of host species. When a pathogen spreads to new hosts, it must overcome several ecological, molecular, and physical obstacles in order to enter the human population. This process is known as "pathogen spillover." The phylogenetic distance between hosts, the frequency and strength of interspecies encounters, and the genetic makeup of both hosts and diseases are some of the variables that affect this complex process. Despite being a complicated phenomenon, spillover has frequently occurred throughout human history, with pathogens found in wild animals being the source of most infectious diseases **[104-108]**. If favourable conditions are found after spillage, the illness spreads among humans **[109]**.

Some pathogens have a wide host range and are easily adapted to novel environments, including humans; generalist pathogens are more adaptive than specialists. A pathogen's capacity to spread to new hosts and occupy uncharted ecological niches is increased by features such as an RNA genome (high mutation rates) or vector-borne transmission **[110]**. But not all infections continue to spread to humans after spillover, and factors that increase interspecies transmission may not be the same as those that increase human transmissibility. Pathogens generating chronic and non-lethal infections, airborne/respiratory viruses, and non-segmented, non-enveloped, and non-vector-borne viruses all facilitate human-to-human transmission of viral illnesses. Human viral epidemics are maintained by vector-mediated transmission, as demonstrated by the regional endemicity of dengue, malaria, and the Zika virus **[111]**.

Loss of habitat combined with the introduction of wild animals and the fauna connected with them that is vector-borne into cities gives domestic animals like dogs and cats the chance to serve as "bridges" for the spread of pathogens from wildlife to people **[112]**. Close interactions between domestic animals, wildlife, and humans intensify in urban areas near forests, creating conditions that facilitate the spread of pathogens **[112, 113]**. For example, human rabies transmitted by bats is common in the Amazon region; this is probably due to increased wildlife populations, deforestation, and human-wildlife contact **[114, 115]**. The current state of the Amazon is conducive to disease spillover because of the rainforest, environmental deterioration, and increased human-animal contact.

5.2 Rainfall, flooding and water contamination

Climate change and Amazon deforestation are linked to extreme weather events that result in altered precipitation patterns and flooding. Extreme hydrological events linked to climate change are occurring now and in the future in the Amazon region **[116, 117]**. The Amazon region's malaria risk and transmission are greatly influenced by the patterns of rainfall and river water levels **[118]**. The quantity and diversity of pathogens in water are altered by hydrological events, which also affects how much of these pathogens humans are exposed to. Therefore, it is common for infectious diseases—like leptospirosis and gastroenteritis—that present serious public health risks in the Amazon region as well as other parts of Brazil to spread during wet seasons, high river levels, and flooding **[119, 120]**. One of the most common problems in Amazonian cities is the fast population growth combined with poor sanitation and contaminated water **[121]**. This condition aids in the spread of several water-borne illnesses, such as viral hepatitis and gastroenteritis. These diseases not only have an immediate negative effect on the health of those who contract them, but they also put a burden on the public health system and lower productivity because of absenteeism. Problems with water in the Amazon region also encourage the growth of mollusks that are part of the schistosomiasis transmission cycle **[122]**.

5.3 Biodiversity loss

Rich biodiversity environments have the capacity to harbour a multitude of new diseases. In a paradoxical way, protecting these biodiverse ecosystems helps stop infectious diseases from spreading **[123, 124]**. There are many facets to the complex interaction between infectious illnesses and biodiversity, but certain general trends emerge: healthy ecosystems support pathogens in the forest environment, which in turn promotes health **[125]**. On the other hand, perturbations in extremely biodiverse environments may aid in the creation and spread of novel human illnesses. These guiding concepts should be taken into account in future studies, projects, and policy choices concerning the Amazon area **[126]**.

The Amazon Forest is currently facing a serious problem with declining animal species. When there are no predators, the number of species serving as disease reservoirs may increase **[127, 128]**. A particular animal species population growth may encourage the spread of blood-feeding vectors that prey on those animals. Concurrently, habitat fragmentation and the reduction in plant variety are closely related, endangering many animal species and even leading to their extinction in certain cases. The loss of biodiversity in plants and animals together eliminates ecological niches that are home to infections, vectors, and predators. On the other hand, it opens up new niches that different host species, diseases, vectors, and reservoir species could fill. In summary, the dynamics of infection are severely disrupted by the loss of biodiversity **[129, 130]**.

Not only can deforestation and habitat loss negatively affect human populations, but they also cause environmental deterioration that increases stress, hunger, and pollution exposure. These physiological stressors have the potential to weaken the immune system, leading to immunosuppression and increased vulnerability to infections, which can help spread diseases from wildlife to people **[131]**. Conditions that are favourable for the introduction of known and undiscovered infections into the human population are created by the combination of habitat fragmentation, loss of biodiversity, and human interactions with forest regions **[132]**.

6. Strategies for Improvement

6.1 Mitigating the impacts of deforestation

One of the main causes of biodiversity loss, deforestation affects both plants and animals in a variety of environments. As repositories of biodiversity, undamaged forests must be preserved, according to recent studies. Deforestation disturbs biotic interactions, such as the dynamics between predators and prey and plants, highlighting the need for focused conservation efforts. Habitat fragmentation brought on by deforestation isolates populations and lowers genetic diversity. Disease outbreaks and invasive species are more likely to occur in environments that are fragmented. The importance of ecological corridors in reducing the detrimental impacts of fragmentation, promoting species mobility, and preserving genetic connection is being highlighted by ongoing research **[133]**.

The expansion and efficient management of protected areas are critical to maintaining biodiversity in the face of deforestation. According to research, carefully planned and placed reserves can act as hotspots for biodiversity, providing a haven for species that are losing their habitat. Mitigating the effects of deforestation requires integrating agroforestry techniques and encouraging reforestation initiatives **[134]**. Agroforestry systems, according to studies, improve biodiversity, restore ecosystem services, and give local inhabitants sustainable means of subsistence **[135]**. Achieving long-term success in conservation programmes requires involving local communities. Studies highlight the benefits of community-based strategies, like community-managed forests and sustainable resource use, in promoting social well-being and ecological resilience **[136]**.

Achieving a balance between development and conservation objectives requires the implementation of comprehensive land-use planning methods. Research supports a comprehensive strategy that forbids arbitrary deforestation by including ecological factors into national and regional planning. Reducing illicit logging and land conversion requires fortifying legal frameworks and enforcement systems **[137]**. In order to effectively address deforestation, recent studies highlight the necessity of transparent and accountable government institutions. International cooperation is necessary to address the worldwide issue of deforestation. According to research, programmes like REDD (Reducing Emissions from Deforestation and Forest Degradation) can give financial incentives for forest conservation, presenting a viable strategy for reducing the effects of deforestation **[138]**.

6.2 Integrated human and animal surveillance and response systems (iSRS)

The mechanisms of infectious illness transmission demonstrate the convergence of animal and human health **[139]**. The COVID-19 pandemic and other recent zoonotic incidents highlight the necessity of integrated surveillance and response systems for the early detection and management of emerging risks. In order to improve global health security, this study offers a thorough framework that makes use of interdisciplinary cooperation, technology breakthroughs, and policy integration **[140]**. One essential component of using the One Health paradigm to mitigate the effects of climate change is the implementation of Integrated Human and Animal Surveillance and Response Systems (iSRS). While traditional public health surveillance focuses exclusively on humans, an integrated One Health strategy is required to understand the complex dynamics of vector-borne diseases in the context of climate change **[141]**.

The World Bank strongly promotes the deployment of integrated human and animal surveillance (iSRS), highlighting the advantages of early detection and possible cost savings. Estimated to cost between 344 and 360 billion USD over the course of the next century, the expenses of detecting emerging diseases in vectors, cattle, or wildlife before human transmission could be significantly reduced **[142, 143]**. This integrated surveillance's broad application is demonstrated by the fact that it covers vector-transmitted illnesses like dengue fever in addition to zoonoses. Nevertheless, poor communication frequently plagues the public and animal health surveillance systems that are now in place. Digoutte (1999) cites the confusion between yellow fever and Rift Valley disease in Mauritania as an example of the need for improved coordination between veterinary and health services **[144]**. Cases from Mali and the Netherlands highlight the significance of including surveillance systems for illnesses such as Q-fever, brucellosis, and other conditions **[145]**. In a number of scenarios, including the Japanese encephalitis virus in China, borreliosis in Serbia, and West Nile fever in Europe, the efficacy of coupled surveillance systems is demonstrated **[146, 147]**. For thorough coverage, such iSRS programmes ought to include both marine and terrestrial animals **[148]**

Examples such as blood transcriptomes in lemurs showing novel parasite zoonoses in Madagascar highlight the integration of wildlife into iSRS **[149]**. South Korea emphasises the need for a comprehensive strategy, acknowledging the threats related to animal migration, international movement, and the illegal wildlife trade. One Health iSRS systems are being developed in countries such as Mongolia, and ideas for similar systems have been made in other regions **[150, 151]**.

Apart from the integration of surveillance for human and animal diseases, contemporary communication technologies, particularly at the community level, are essential for improving sensitivity and shortening detection times. The discipline of infodemiology is growing as a result of the ease with which real-time data collecting and analysis can be accomplished using mobile technologies, especially smartphones. In order to forecast and track disease outbreaks, this field uses crucial events that are recorded by mobile devices **[152]**. Social media platforms provide useful observational data, but for data scientists and One Health specialists to effectively aggregate and analyse this data, reporting data sources and quality must be standardised **[153]**. Planning sustainable elimination plans and preventing reintroduction are key components of the control and removal of many zoonoses, which require regional coordination. For successful cooperation, bioregional strategies between adjacent nations—such as those between the USA and Mexico or the former USSR are suggested **[154]**. Animal disease surveillance can be connected to global health alert networks through programmes such as the European Early Warning and Response System (EWRS) and the joint FAO-OIE-WHO Global Early Warning System for Health Threats and Emerging Risks (GLEWS) **[155]**. **Table 2** has been attached to enlist the advantages and challenges associated with the implementation of iSRS.

Table 2. A table enlisting the advantages, challenges and mitigation strategies for iSRS.

Advantages	**Challenges & Mitigation Strategies**
Early detection and prevention: More precise and prompt illness diagnosis is made possible by the integration	Data sharing and privacy concerns: Data exchange is essential, yet concerns about

of data on human and animal health. Forecasting epidemics and putting proactive reaction plans into action are made easier by predictive modelling that includes signs from both humans and animals.	confidentiality and privacy still exist. To address these issues, research highlights the necessity of strong ethical frameworks, safe data-sharing procedures, and public involvement tactics.
One health approach: Provides the basis of iSRS and highlights the connection between human, animal, and environmental health. The effectiveness of a comprehensive, multidisciplinary approach in reducing zoonotic risk and improving general public health has been demonstrated by recent studies.	Interdisciplinary collaboration: Effective collaboration amongst various stakeholders is essential for the successful implementation of iSRS. Research shows how crucial it is to develop interdisciplinary collaborations through shared platforms, collaborative research projects, and training activities.
Rapid response and resource optimization: By optimising resource allocation and communication between the veterinary and human health sectors, iSRS enables quick reaction. During outbreaks, the use of integrated data systems makes resource allocation more efficient and well-coordinated.	

6.3 Health education

Interventions must take a comprehensive approach due to the intricate link between infectious illnesses and climate change. A key instrument for strengthening communities, building resilience, and launching preventative actions against health risks brought on by climate change is health education. Studies reveal that temperature variations, precipitation patterns, and extreme weather events have a substantial effect on the spread of infectious diseases. Temperature increases change the dynamics and distribution of disease by fostering conditions that are conducive to vectors. Interventions centred around education are essential for lowering susceptibility to infectious illnesses. Community resilience is increased when people are equipped with information regarding disease transmission, preventive measures, and adaptive tactics.

Research indicates that focused health education programmes result in favourable behavioural adjustments, which enhance community responses to infectious diseases impacted by climate variables. Particularly successful educational initiatives have focused on early symptom recognition, sanitation, and vector control. Cutting-edge technologies provide scalable and easily accessible channels for health education, such as internet platforms and mobile applications. Studies show that internet tools can be used to spread health information related to climate change. Ensuring optimum impact requires tailoring health education to local contexts and cultural subtleties. Research collaborations highlight the value of community engagement in the planning and execution of educational initiatives. A thorough analysis of the policy frameworks underlying health education programmes shows that comprehensive approaches are required. A proactive approach to combating infectious diseases is made easier by the inclusion of climate change considerations in public health plans.

7. Research Efforts: Infectious Disease Spread due to Climate Change

Much of the preliminary work on the relationship between infectious illnesses and climate change highlighted the possibility of increasing disease risk in future climate scenarios. It was widely believed that an increase in global temperature would make people more vulnerable to illness **[156]**. Recent research, on the other hand, offers a more complex viewpoint and introduces the idea of a "two-tailed" reaction. This suggests that changes in the environment could lead to less-than-ideal conditions in some areas and promote the spread of disease in others. It is predicted that pathogens and parasites will adapt to shifting environmental dynamics, which could result in increases in the prevalence of some diseases and decreases or local extinctions of others **[157-159]**.

Researchers face the difficult task of identifying which diseases will have increased prevalence and where and when these changes may occur as they work to grasp the precise outcomes for different diseases. In their work, Jason Rohr and Jeremy Cohen took an ecological stance to examine the variables and processes affecting how illnesses could be affected by climate change in both terrestrial and aquatic systems **[160]**. Jeb Byers studied illnesses in estuaries and near-shore areas using a similar methodology **[161]**. The importance of thermal ecology is emphasised in both publications, which also highlight the significant nonlinear impact that even slight temperature changes can have on ectotherm host-parasite interactions. This point was furthered by Jeremy Burdon and Jiasui Zhan, who highlight the need to improve our understanding of the mechanisms underlying abiotic variables that affect plant pathogens **[162]**. They also draw attention to the differences in patterns that may appear between more complex natural systems and simpler, managed ecosystems like those found in agriculture.

By exploring environmental factors outside biology, Rachel Lowe and her associates broaden the conversation. Their research looked at how vector-borne diseases could become more dangerous due to climate change, but it also looked at the critical actions that must be taken in susceptible areas, like the Caribbean, to build resilient systems and reduce related risks. The combined knowledge gained from these research projects advances our comprehension of the intricate interactions that occur between infectious illnesses and climate change in many ecosystems **[163]**.

8. Invasion Pathways, Expansion and Colonization in Ecological Time

A key component of the dynamics of illness is represented by invasion pathways, which are impacted by changes in vectors and reservoirs brought on by climate change **[164]**. The geographic dispersion of disease vectors is impacted by shifting climatic conditions, such as altered temperature regimes and precipitation patterns, which can have an impact on the start and development of invasion pathways **[165]**. The relevance of comprehending how vectors adapt to novel environments—which may result in unanticipated colonisation events—has been emphasised by recent studies **[166, 167]**.

Infectious diseases that adapt to a changing climate are known for their expansion, which manifests in ecological time as changes in disease prevalence and distribution **[168]**. The number and behaviour of reservoir hosts can change due to climate-induced shifts in ecosystems, which can impact the temporal and spatial patterns of disease expansion. Research findings highlight how important it is to keep an eye on these expansions in order to anticipate and counter new dangers. The emergence of infectious illnesses in newly created ecological niches is reflected in colonisation, which takes place in the context of climate change **[169]**. This phenomenon is closely related to how well hosts, vectors, and diseases adapt to shifting environmental conditions. Formulating effective interventions against the spread of infectious illnesses in new ecosystems requires an understanding of the ecological factors that promote colonisation **[170]**.

The need for a comprehensive strategy that incorporates ecological time into the investigation of invasion routes, expansion, and colonisation is highlighted by recent findings. Extreme weather events have a noticeable impact on infectious diseases in a number of situations, including increased risk of waterborne illnesses during floods, modified vector migratory patterns, and variations in disease prevalence in reaction to temperature changes. Numerous scholarly works underscore the significance of conducting extended ecological surveillance to ascertain the effects of climate change on communicable illnesses **[171]**. Research on the spread of vector-borne illnesses into previously untouched areas is one notable illustration of how ecosystems, climate, and disease dynamics are all intertwined **[172, 173]**. To fully understand the complexities of these systems and forecast future events, integrative models that take ecological subtleties into account are crucial. **Table 3** shows the basics of the different types on infectious agents causing zoonotic infections and their primary pathways of transmission.

Table 3. Tabulated details about the different types on infectious agents causing zoonotic infections and their primary pathways of transmission.

Infectious agent type	**Disease manifestation**	**Transmission pathways**
Bacteria	Leptospirosis	In anthropurgic foci, the primary hosts are canines and livestock, while in natural foci, rodent species. Leptospira spread by water in accordance with the fecal–oral pathway. Usually, human infection occurs when a human comes into touch with animal feces-contaminated water.
	Tularemia	Multiple routes of transmission include oral, airborne, waterborne, direct contact, vector-borne (such as ticks, mosquitoes, and horseflies), etc.
	Borreliosis	Transmitted by Ixodidae tick vectors.
	Q fever	Pets and farm animals serve as the primary reservoirs, while humans are mostly exposed to the disease through inhaling infected aerosols.
Virus	Tick-borne encephalitis (TBE)	Transmitted by Ixodidae tick vectors.
	Pumala (Orthohuntavirus)	Inhalation of rodent excreta which might be infected.

Parasite	Cryptosporidiosis	Ingestion of cryptosporidium oocysts.

9. Conclusion and Way Forward

Studies have revealed spatial and taxonomic biases that require immediate correction by examining current trends in infectious disease and climate change research. Tropical diseases and infections that are directly transferred have received less attention than vector-borne diseases in affluent, temperate settings. This anthropocentric bias highlights the need for a more inclusive, ecosystem-based research paradigm by potentially impeding our knowledge of how climate change affects animal systems. Concerns about global health are also raised by the underrepresentation of some infections, hosts, and modes of transmission because neglected regions may end up serving as hotspots for zoonotic disease outbreaks. Emergencies in underserved areas like Indonesia, Madagascar, and Saudi Arabia highlight the significance of broadening research endeavours. The COVID-19 pandemic highlights the need for more research in this area and highlights the need of examining directly transmitted diseases that are circulating in animals. Addressing biases and promoting fairness also require an awareness of the connections between research funding trends and studies on climate change. Research influence on international policy is vital. Biases in the diseases examined, the research sites, and the author names can be corrected by policy changes that are informed by research. Research on infectious diseases at the interface between humans and wildlife in the context of climate change, minority scientist support, and neglected locations should be given top priority. Furthermore, global programmes like the Global Early Warning System for Health Threats and Emerging Risks and regional coordination are essential. A more robust global health response is achieved through utilising technology, integrating surveillance for both human and animal diseases, and encouraging inclusive collaboration practices. A powerful tactic that enables communities to fight infectious diseases in the face of climate change is health education. The utilisation of digital technologies, community-focused strategies, and culturally aware initiatives improve the efficacy of health education endeavours. To sum up, resolving research biases, promoting policy modifications, and placing a high priority on health education are essential stages in developing a robust global health response to the confluence of infectious diseases and climate change. The report recommends more research, fair partnerships, and improved readiness to protect vulnerable groups from the health effects of climate change in places like India.

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Authors Contribution

The rough draft, revisions, and final draft of the manuscript are all prepared by each author. Cross-referring writers are responsible for designing the study and implementing the plan.

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