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CLIMATE CHANGE, ALTITUDE SHIFT AND VIRUS EMERGENCE: A REVIEW ON *PTEROPUS* BATS IN HIMALAYAN REGION

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Abstract
The potential risk of new infectious diseases to global public health is significant, and climate change has been recognized as a key driver of zoonotic spillover events. The Nipah virus, which has the Pteropus bat (flying fox) as its natural host, is one such disease. The Himalayan region, a biodiversity hotspot and climate change-sensitive area, is a critically understudied region in terms of the ecology of Pteropus bats and the emergence of the Nipah virus. This review aims to compile the knowledge on the distribution and ecology of Pteropus bats in Himalayan region, analyze the expected impact of climate change on the altitudinal distribution of Pteropus bats, and discuss the expected implications of Nipah virus outbreaks. There is very little information available on the ecology of Pteropus bats in the Himalayan region, and only one species-specific distribution modeling study is available from Nepal. Contrary to the expected altitudinal migration pattern in mountainous regions, this study reveals that climate change is not expected to improve the altitudinal distribution of Pteropus medius. Instead, their suitable habitat is expected to be reduced and limited to lower-altitude regions due to their susceptibility to low temperatures. This predicted reduction of range size also overlaps with areas of high human population density and agricultural activity, which could increase the human-bat interface. Among the factors that could play a role in the potential increase in the risk of spillover are the increased viral shedding in the colony because of high population density, stress induced by the disruption of the phenology of fruit tree flowering because of climate change, and the increased opportunities for environmental contamination of date palm sap and food. The interaction of climate change, the unique altitudinal ecology of Pteropus bats, and high human population density in the Himalayan lowlands makes this area a potential perfect storm for the emergence of Nipah virus. A plan to meet this potential risk is to implement immediate, interdisciplinary One Health approaches that include wildlife surveillance, climate modeling, and ecological research to decrease the risk of spillover in this high-risk area.

INTRODUCTION

The past century has witnessed an exponential rise in the number of EIDs that have impacted people across the globe, and evidence suggests that the rate of new infections has risen by more than three times since 1980 (Asokan et al., 2026). The majority of these EIDs are zoonotic, meaning that their origin is pathogens that have jumped species from animals to humans. It has been revealed that of all the known human pathogens, 58% are zoonotic, and what is even more alarming is that three-quarters of emerging pathogens are zoonotic. It is essential to comprehend the intricate relationships between ecological, demographic, and environmental factors including climate change, land use, and habitat destruction to predict and prevent future pandemics (Ortiz-Millan, 2025). Nipah virus is one such virus that helps comprehend these intricate relationships. NiV was first identified in 1998 and caused a severe outbreak of respiratory illness and encephalitis in humans (Epstein et al., 2006; Branda et al., 2025).

The bats from genus *Pteropus*, flying foxes are the natural primary hosts of NiV, which they secrete in their urine, saliva, and feces without any symptoms (Branda et al., 2025; Epstein et al., 2006). These fruit bats are found in massive numbers in the South and Southeast Asian region, including the foothills of the Himalayan region (Deka & Morshed, 2018). The presence of NiV is not a random event but is instead driven by specific human pressures. In general, environmental stressors such as climate change are believed to influence the behavior, population, and viral shedding of bats (Abdu et al., 2025; One Health and Development Initiative, 2025).

The Himalayan environment, a climate change-sensitive biodiversity hotspot, thus provides a unique and relatively unexplored setting for the study of such associations. Predictive modeling analysis has indicated that tropical Asia is a more vulnerable region for zoonotic viral outbreaks (Deka & Morshed, 2018). However, the *Pteropus* bat ecology and the susceptibility of NiV emergence in the Himalayas have been relatively poorly understood until now. Recent habitat suitability analysis in Nepal has indicated that *Pteropus medius* (the Indian Flying Fox) is currently distributed at an altitude of 75 to 1,322 meters, with climate change predictions indicating a range contraction and dominance in the lower-altitude regions, rather than an altitudinal range extension (Thapa et al., 2023). This seemingly contradictory finding has extremely significant implications for virus emergence, suggesting a hotspot for human-bat interface in the densely populated lowland regions.

The intricate dynamics of such challenges require a One Health approach, which identifies the inherent and fundamental unity of humans, animals, and environmental health (Ortiz-Millan, 2025; Branda et al., 2025). This is especially relevant to the development of a NiV and other zoonotic viruses-ready health system. This review combines the existing knowledge based on the ecology of *Pteropus* bats in the Himalayas, the impact of climate change on the distribution of *Pteropus* bats in the Himalayas, and the impact of the change on the emergence of Nipah virus. By identifying the gaps in the existing knowledge base on this topic, we hope to contribute to the research agenda in this affected region in the future.

2. Climatic Warming and Bat Distribution in the Himalayan Region

Rising temperature is expected to be the key factors in future distribution of bats and the emergence of pathogens in Himalayan region in the this century. Few studies have been conducted to explore the effect of climate change on bat populations, particularly *Pteropus* (flying foxes), in this region. Changes in the natural climate including low rainfall and high temperature, has been comprehended by the melting of the Himalayan glaciers and the change in vegetation patterns, which have indirectly and negatively influenced bat habitats (Sigdel et al., 2018).

The mountain forests, which are found in the higher ranges of the Himalayas, are very sensitive to climatic changes, thus making the bat species in these ranges vulnerable due to warming. (Behera et al., 2019). In the case of *Pteropus* bats, which are at present found in the lower ranges of the Himalayas, climate warming creates a complex scenario. Contrary to most species that tend to shift to higher ranges, research studies on *Pteropus medius* have revealed that the future distribution range is expected to shift to higher ranges or towards the northern latitudes. Instead, the range with suitable habitat is expected to witness a slight contraction overall, with any expansion restricted to the lower ranges (Thapa et al., 2023). This is most likely due to the species sensitivity to low temperatures, particularly the minimum temperature during the coldest month and the precipitation in the coldest quarter, which are identified as limiting factors for the colonization of higher ranges (Thapa et al., 2023).

The warming trend has also impacted the plant species in the Himalayas, which in turn impacts frugivorous bats such as *Pteropus*. In the Sikkim Himalayas, warming has resulted in the geographical distribution shift of up to 87% of 124 endemic plant species, resulting in local extinction (Telwala et al., 2013). The distribution and phenology of fruit-producing tree species influence the foraging behavior of *Pteropus* bats. The variety of species and the turnover in species composition have shown sensitivity to climate change (Bhattacharjee et al., 2017), specifically for those inhabiting the treeline ecotone. Certain species, such as *Betula utilis* (Himalayan birch), tend to shift their distribution toward the eastern Himalayas, while their presence declines in the western areas. (Hamid et al., 2018).

Climate warming has resulted in the identification of the phenomenon of change in the phenology of tree species in the Himalayas (Negi et al., 2021). Alterations in the timing of opening of buds, leaf emergence, flowering, and fruit production of tree species in the Himalayas are being caused by rising temperatures (Shrestha et al., 2012). In the case of *Pteropus* bats, which are highly dependent on the fruits and flowers of trees belonging to Moraceae, Fabaceae, and Myrtaceae (Kunz et al., 2011), changes in phenology can cause a mismatch between bat activity and food availability. These mismatches can cause nutritional deficiencies, changes in movement patterns, and potentially increased viral shedding due to immunosuppression (Plowright et al., 2015). There is very little information available on *Pteropus* bats in the Himalayas. Range shift predictions are highly dependent on plant ecology studies, which have not been directly validated by bat behavior studies in the Himalayas.

3. Altitudinal Shifts and Virus Emergence

The co-occurrence of the altitudinal shift of bat genus *Pteropus* due to climate change and the emergence of zoonotic viruses, particularly NiV, is a topic that has been investigated sufficiently in the Himalayan region. *Pteropus* bats are the natural reservoirs of NiV, which is transmitted through their urine, saliva, and feces without any symptoms (Epstein et al., 2020). Environmental factors such as climatic changes and nutritional deficiencies have been associated with increased viral shedding among bat species (Plowright et al., 2016).

With the warming of the Himalayan region, the following factors may have the potential to influence the process of NiV emergence:

3.1 Range Shifts and New Interfaces:

Although *Pteropus* bats are not likely to shift to higher altitudes, their congregation in refugia at lower altitudes may result in increased population density, which could potentially contribute to the transmission of the virus in the population. However, if other bat species shift to higher altitudes, they may establish new sympatric communities with different viral assemblages, which could potentially cause viral spillover among species (Brook and Dobson, 2015).

3.2 Foraging Stress and Viral Shedding:

Range and seasonal extension of fruit trees due to climate change may periodically induce food stress in *Pteropus* bats. Food stress has been linked to increase shedding of NiV in flying foxes (McMichael et al., 2017). In the Himalayan foothills, this may happen if climate change alters the fruiting periods of key forage plants.

3.3 Human-Bat Interface:

Habitat concentration of *Pteropus* bats in low-lying areas corresponds to regions of high human population density and agricultural output (Thapa et al., 2023). Habitat overlap enables the potential of viral spillover by date palm sap contamination, half-eaten fruits, as well as close physical contact with bat feces. Date palm sap collection, a common activity in the Himalayan foothills, has been demonstrated to enable Nipah virus spillover from bats to humans (Luby et al., 2006). The theoretical model of climate change-induced virus emergence is correct in theory but purely theoretical. The key concept overlooks the significance of stochastic processes, immunity, and socio-behavioral factors that enable actual spillover, with non-key information on cave-roosting species that are not relevant to tree-roosting *Pteropus*.

4. Conclusion and Future Directions

Climate change, the specific altitudinal ecology of bats genus *Pteropus*, and the high human population density in the Himalayan lowlands may constitute a potential perfect storm for the appearance of NiV (Thapa et al., 2023; Deka & Morshed, 2018). There is evidence that climate change will not help to migrate these bats to higher altitudes but will instead concentrate them in the very regions where human-bat interactions are most intense (Thapa et al., 2023). A proactive and One Health approach that integrates the surveillance of wild animals, climate modeling, ecological studies, and community engagement is needed to face this new challenge (Ortiz-Millan, 2025; Branda et al., 2025). The time to act is now, before a large-scale outbreak occurs in this high-risk region.

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