International Journal of Plant & Soil Science

Volume 37, Issue 5, Page 516-528, 2025; Article no.IJPSS.136576
ISSN: 2320-7035

Predicting the Effects of Climate Change on the Habitat Suitability of Long-spurred Habenaria in Peninsular India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i55475

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/136576

Original Research Article

Received: 13/03/2025
Accepted: 18/05/2025
Published: 21/05/2025

ABSTRACT

Endemic plant species are increasingly at risk due to global climate change and anthropogenic pressures, making the prediction of suitable habitats essential for their conservation. *Habenaria longicorniculata* is an endemic terrestrial orchid species of Peninsular India, currently facing threats due to climate change and anthropogenic activities. Identifying suitable habitats for these species is crucial for effective conservation planning. In this study, species distribution modeling was performed using MaxEnt to assess the current and future habitat suitability of *H. longicorniculata* under various Shared Socioeconomic Pathways (SSPs). 141 occurrence records were used for the prediction model. The model revealed high predictive accuracy, with an AUC value of 0.927 (±0.037). Results indicate a significant reduction in suitable habitat, projected to decline by 44.41%

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Cite as: *Rout, Yasaswinee, Jeewan Singh Jalal, and J. Jayanthi. 2025. "Predicting the Effects of Climate Change on the Habitat Suitability of Long-Spurred Habenaria in Peninsular India". International Journal of Plant & Soil Science 37 (5):516-28. https://doi.org/10.9734/ijpss/2025/v37i55475.*

to 74.92% under future climate scenarios. Future distributions will likely become restricted to limited regions in Kerala, Tamil Nadu, and Karnataka. The Jackknife test revealed that bioclimatic variables Bio5 (max temperature of the warmest month) and Bio8 (mean temperature of the wettest quarter) are the most influential in determining species distribution. Overall, the study makes a significant contribution to species conservation and provides valuable input for future research and decision-making.

Keywords: Habenaria; MaxEnt; climate change; decline; in-situ conservation.

1. INTRODUCTION

Global climate change has posed a severe threat to biological diversity (Kolanowska et al., 2017; Habibullah et al., 2021). These changes are directly impacting the distribution of plant species, particularly vulnerable and endemic plants with specific habitat needs, especially orchids (Tang et al., 2020). Orchids exhibit a complex lifecycle and are mutually dependent upon other biotic and abiotic factors, like mycorrhizal association, pollinators, and have a very specific habitat requirement for survival (Chandra et al., 2023). As a result, the majority of the species are currently under severe threat. Although various countries have enacted legislation to safeguard these unique species, effective conservation efforts must prioritize the protection and restoration of their microhabitats (Fay, 2018). Habitat suitability modeling serves as a valuable tool in biodiversity conservation, particularly for species with specialized ecological requirements such as orchids. Furthermore, habitat suitability models support in situ conservation planning by highlighting existing habitats that are crucial for the species' persistence, enabling targeted protection and management of those areas. In the face of rapid environmental changes, especially due to climate change, such predictive modeling is critical for developing conservation strategies. A perusal of literature shows that only limited studies are available on the future habitat suitability of orchids either due to their medicinal importance or for their geographical significance viz.: *Anoectochilus elatus* (Patil et al., 2020), *Arundina graminifolia* (Kolanowska & Konowalik, 2014), *Changnienia amoena* (Liu et al., 2024), *Crepidium acuminatum* (Boral & Moktan, 2024), *Crepidium ridleyi* (Usmadi et al., 2023), *Cypripedium calceolus* (Kolanowska & Jakubsha-Busse, 2020; Jakubsha-Busse et al., 2021; Krenova et al., 2023), *Dactylorhiza hatagirea* (Chandra et al., 2021; Wani et al., 2021; Shrestha et al., 2021), *Dactylorhiza fuchsia, Dactylorhiza majalis, Gymnadenia conopsea* and *Platanthera bifolia* (Štípková et al. (2017), *Dendrobium moniliforme* & *Dendrobium nobile* (Tang et al., 2020), *Dendrophylax lindenii* (Kolanowska, 2023), *Epipactis helleborine* (Kolanowska, 2013), *Gymnosia orchidis* (Li et al., 2024), *Habenaria diphylla* (Halagatti et al., 2024), *Listera puberula, Neottianthe cucullata, Herminium monorchis, Cypripedium calceolus, Gymnadenia conopsea,* and *Liparis japonica* (Wan et al. 2014), *Neottia cordata* (Tsiftsis et al., 2020), *Orchis anthropophora, Orchis militaris, Orchis purpurea* and *Orchis simia* (Evans et al., 2020), *Paphiopedilum javanicum* (Romadlon et al., 2021), *Polystachya concreta* (Kolanowska et al., 2020), *Satyrium nepalense* (Boral & Moktan, 2024), *Spiranthes parksii* (Wang et al., 2015), *Traunsteinera globosa* (Kolanowska, 2021), *Vanda bicolor* (Deb et al., 2017) & *Vanilla borneensis* (Deka et al., 2017). However, a few studies have been carried out to investigate the role of climate change in the distribution pattern of threatened/endemic orchids in India. For example, species distribution model was carried out for three *Cypripedium* (*Cypripedium cordigerum*, *Cypripedium elegans* and *Cypripedium himalaicum*), species (Chandra et al., 2023), *Habenaria suaveolens* (Jalal & Singh, 2017; Jalal et al., 2025), *Habenaria longicorniculata* (Sourabh & Uniyal, 2022) which provides current and future potential suitable habitats for the species.

Habenaria longicorniculata J. Graham is an endemic terrestrial orchid, commonly known as "long spurred Habenaria" due to the presence of a 10-15 cm long spur (Fig. 1). The species was first reported from Maharashtra by John Graham in 1839. Later, the species was reported from other parts of the country like Andhra Pradesh, Odisha, Goa, Gujarat, Karnataka, Kerala, Maharashtra, Tamil Nadu, Jharkhand, Chhattishgarh, Madhya Pradesh and Rajasthan (Singh et al., 2019; Jalal, 2018; Purohit et al., 2020; Jalal, 2022). The species can be found growing on lateritic plateaus, grassy slopes, and gravelly soils at an elevation between 1000-1200 m. It is locally abundant in many parts of Peninsular India. According to Kumar et al.

(2001), the overall population size in the Western Ghats exceeds 10,000 mature individuals. Jalal and Singh (2015) reported that the population size in Maharashtra is less than 5,000 mature individuals. Purohit et al. (2020) estimated a population size of less than 1,000 mature individuals in the Mount Abu Wildlife Sanctuary in Rajasthan. Rapid changes in the land use patterns across its habitat due to habitat fragmentation, developmental activities, grazing, rapid urbanization, forest fire, expansion of agricultural land, and anthropogenic activities are posing serious threats to its survival. Additionally, recent shifts in climate patterns, particularly in rainfall distribution and increased frequency of droughts, are adversely impacting its reproductive biology, including pollination efficiency and fruit setting. It is also known for its medicinal importance, leading to the illegal collection of tubers. Therefore, the present study aims at the following objectives: (1) distribution of the species in Peninsular India, (2) key environmental factors that play an important role in the distribution of species, (3) MaxEnt predicted distribution of species in India & (4) measure conservational steps to be taken care of for the protection of the species.

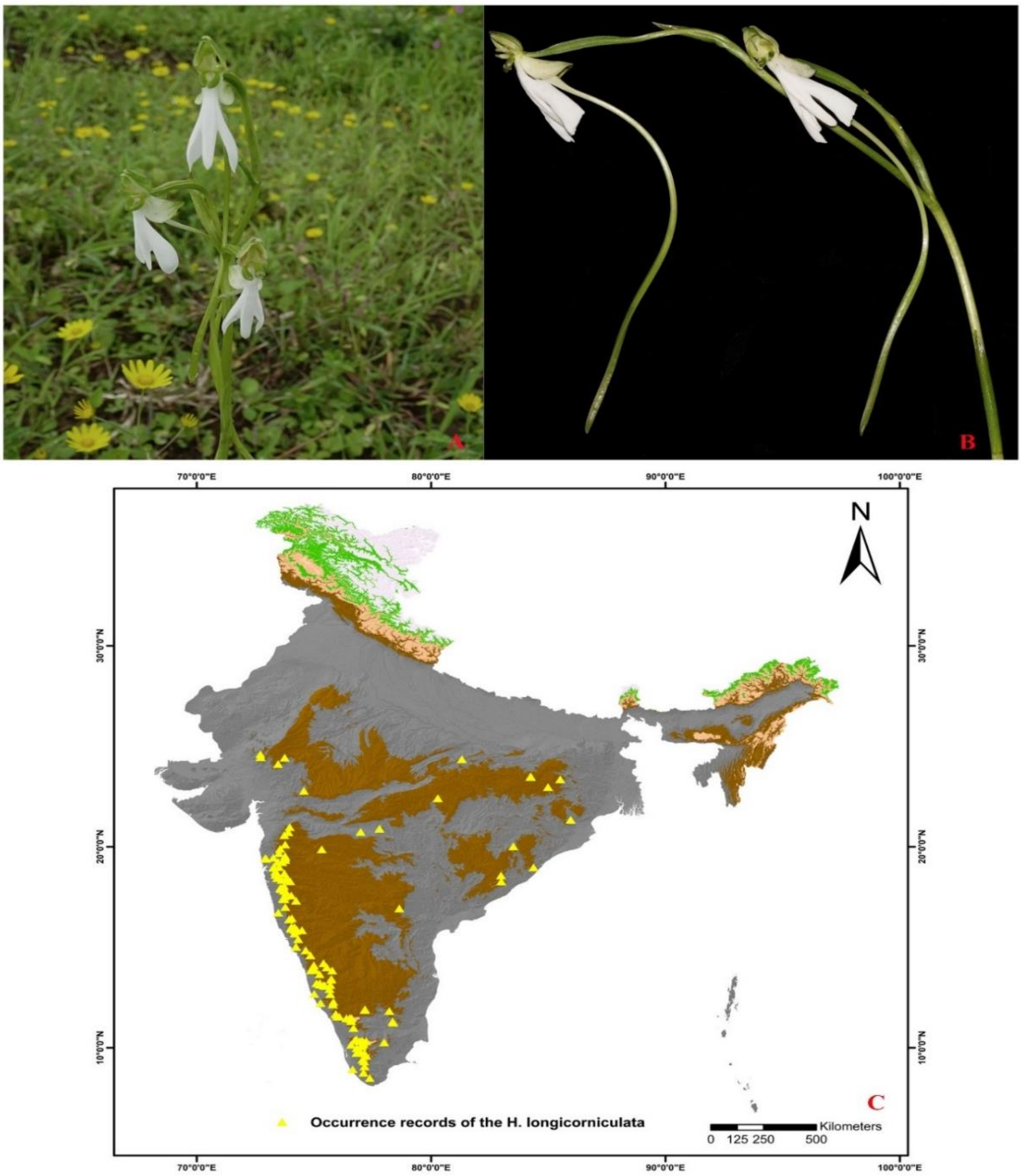

Fig. 1. Habenaria longicorniculata (A) Habitat, (B) Flower & (c) Occurrence records of the species in india

2. MATERIALS AND METHODS

2.1 Species Occurrence Record

The geographical locations of *H. longicorniculata* were obtained from both primary and secondary resources. The primary resources include field surveys from 2012 to 2024, while secondary occurrence records were gathered from different herbaria, viz., Western Regional Centre, Botanical Survey of India (BSI), Central National Herbarium (CAL), Calicut University Herbarium (CALI), Shivaji University, Kolhapur (SUK), Tropical Botanic Garden and Research Institute (TBGT), Kerala Forest Research Institute (KFRI), Southern Regional Centre, BSI (MH), Blatter Herbarium & online resources such as GBIF (GBIF.org (05 May 2025) GBIF Occurrence download https://doi.org/10.15468/dl.9bgrs7), iNaturalists. The geographical coordinates (latitude and longitude) of all recorded occurrences of *H. longicorniculata* were obtained using Google Earth Pro, particularly for locations where direct coordinate data were unavailable in the literature or herbarium records. Each occurrence point was carefully georeferenced based on locality descriptions, ensuring accuracy in spatial representation. The finalized coordinates were compiled and saved in CSV (Comma-Separated Values) format, which included essential fields such as species name, latitude, longitude, altitude (where available), and source reference. This format ensured compatibility with Geographic Information System (GIS) software for further analysis. A species distribution map was created using ArcGIS version 10.5 and the CSV file.

2.2 Bioclimatic Variables

Environmental variables (Bio1-Bio19) were obtained from the global WorldClim dataset version 2.1 (www.worldclim.org) at the spatial resolution of 30 arc seconds (Fick & Hijmans, 2017). The SRTM Digital Elevation Model (DEM) was obtained from the WorldClim archive and utilized to generate slope, aspect, and elevation variables. To identify land cover characteristics of the study area, soil type data and its physio-chemical parameters (pH, organic carbon (OCS) 0-05 cm, clay (0-05cm) were obtained from ISRIC (https://soilgrids.org) version 2.0 and Land Use and Land Cover (LULC) data for the study area were sourced from Copernicus Sentinel-2 imagery (2023) with an original spatial resolution of 10 meters. To ensure compatibility with other environmental predictor layers and to reduce computational complexity, the data were resampled to a 1-kilometer spatial resolution using the nearest neighbor interpolation method. A Pearson's correlation study was conducted to prevent multicollinearity, which could lead to overfitting among environmental variables, and subsequently removed all the variables with a higher correlation (≥0.8) were removed. Subsequently, 16 bioclimatic variables were further used to run the model (Table 1).

Table 1. Dominant environmental and biophysical variables

Code	Variable Description	Percent contribution
Bio5	Max Temperature of Warmest Month	41.7
Bio8	Mean Temperature of Wettest Quarter	14.5
Bio12	Annual Precipitation	12.5
Slope	Slope	8.3
pH	pH	6.9
Bio15	Precipitation Seasonality (Coefficient of variation)	4.9
LULC	Land Use Land Cover	1.7
Bio1	Annual Mean Temperature	1.7
Bio19	Precipitation of Coldest Quarter	1.3
Bio2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	1.2
Bio6	Min Temperature of Coldest Month	1.1
Bio9	Mean Temperature of Driest Quarter	1.1
Bio18	Precipitation of Warmest Quarter	1.1
Bio14	Precipitation of Driest Month	1.1
Bio3	Isothermality (Bio2 / (Bio7 × 100))	0.7
Aspect	Aspect	0.1

For future climate change scenarios, a CMIP6 model, i.e., MIROC6 (Model for Interdisciplinary Research on Climate), was used, as the model performs best in the Indian region (Kumar & Sarathi, 2021; Paul et al., 2023; Konda & Vissa, 2023), which provides the most up-to-date and robust climate projections for future scenarios. Two Shared Socio-Economic Pathways (SSPs), i.e., SSP2-4.5 & SSP5-8.5, were used for the years 2030 (2020-2040), 2050 (2041-2060), 2070 (2061-2080), 2090 (2081-2100). These SSPs play a crucial role in climate change studies, enabling researchers to analyze potential socioeconomic conditions, assess their effects on greenhouse gas emissions, and determine their impact on future climate scenarios (Bhuyan et al., 2025).

2.3 MaxEnt Model Building

The species distribution model was created using MaxEnt (3.4.4) with default settings. It is one of the most widely used models to predict the species distribution especially endangered species (Yuan et al., 2020) by using presence-only data and different environmental variables (Elith et al., 2011). It performs better than other models even when small datasets are applied. We used 10 replicates to cross-validate the model run with 10,000 background points selected randomly from the study area. The regularization multiplier value was set at 0.1 to reduce the model's overfitting and over-prediction with 500 iterations. The occurrence data were divided into 75% for training and 25% for testing, ensuring reliable model validation. A Jack-knife analysis was performed to determine variables that reduce the model reliability when omitted or vice versa (Phillips et al., 2006; Elith et al., 2011). Model performance was evaluated using the Area Under the Receiver Operating Curve (AUC), using the Receiver Operating Characteristic (ROC) analysis. The value of AUC decides the robustness of the model. The model is considered good at AUC (0.7-0.8), excellent at 0.8-1. AUC value close to 1 indicates a higher habitat suitability and a strong correlation between environmental variables and habitat classification, resulting in better model prediction (Elith et al., 2006; Ye et al., 2020; Wei et al., 2024). To create a potential distribution of the species, suitable habitat was manually classified under 4 categories: 0-0.6 means unsuitable, 0.6-0.7 means poorly suitable, 0.7-0.8 means moderately suitable, and 0.8-1 means highly suitable, using ArcGIS 10.5.

3. RESULTS

The current distribution areas of *H. longicorniculata* were predicted using the MaxEnt model. The AUC value for the test and training was 0.944 & 0.946, respectively, along with a mean value of 0.927, with a standard deviation of 0.037 (Fig. 2). This indicates the high performance and reliability of the model (Chandra et al., 2023). 16 bioclimatic factors were used to run the model. As determined by the Jackknife test, the key environmental variables that play an important role in the distribution of the species are Max Temperature of Warmest Month (Bio5), Mean Temperature of Wettest Quarter (Bio8), Annual Precipitation (Bio12), slope, and pH. All together they contribute 83.9% (Table 1).

The MaxEnt model predicted the current suitable habitat for *H. longicorniculata* in Peninsular India, identifying the Western Ghats (WGs) as a significant hotspot for the species. The total area was divided into four categories such as unsuitable, poorly suitable, moderately suitable, and highly suitable. Under current climatic conditions, the total area of suitable habitat comprises approximately 1.26% of the total study region, equating to 21,493 km². The area covers the entire Western Ghats along with some parts of the Aravali Range (Mount Abu, Rajasthan). Specifically, the highly suitable habitat was predicted to occupy 3,654 km², while moderately suitable and poorly suitable areas were estimated to cover 7,410 km² and 10,430 km², respectively (Fig. 3). These results highlight the restricted distribution of the species, emphasizing the importance of preserving these critical areas for its conservation.

On the contrary, under the future climatic conditions, the total suitable area decreases subsequently. Under SSP2-4.5 scenarios, the predicted area decreases from 44.41 to 74.92%; whereas the highly suitable area decreases from 58.18 to 83.44% by 2030-2090 (Fig. 4). In case of SSP5-8.5, the total predicted suitable area and highly suitable area decrease from 50.19% to 88.05%, and 61.16% to 92% by 2030-2090 (Fig. 5). By the end of the century, the highly suitable habitat is expected to be reduced to less than 1,000 km². While the current distribution encompasses 21,493 km², the predicted future distribution will drastically contract to 5,390 km² and 2,567 km² under the SSP2-4.5 and SSP5-8.5 scenarios, respectively (Table 2).

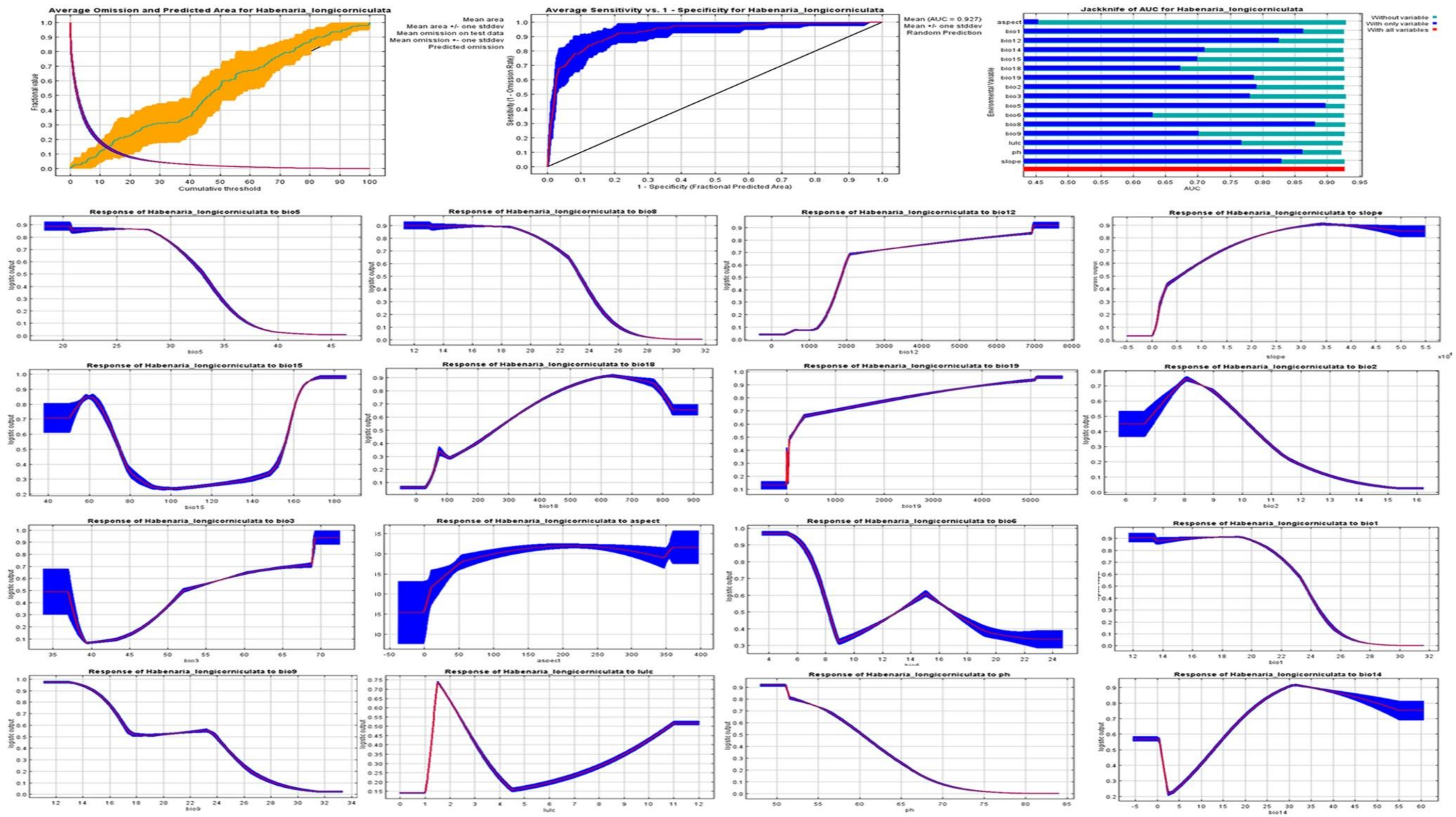

Fig. 2. Omission value of predicated area, AUC value jackknife test and response curves of the environmental variables to distribution probability of *H. longicorniculata*

Consequently, the species' potential distribution range is expected to become highly restricted, with suitable habitats largely confined to the Western Ghats of Kerala and Tamil Nadu in the future. These findings underscore the vulnerability of *H. longicorniculata* to climate change and the need for targeted conservation efforts in these key areas.

Table 2. Predicted Area of suitability of *H. longicorniculata* in Peninsular India under current and future climatic scenarios

Predicted Suitable area	SSP2-4.5					SSP5-8.5			
	Current	2030	2050	2070	2090	2030	2050	2070	2090
Highly Suitable Area (km^2)	3654	1528	994	697	605	1419	462	357	292
Moderately Suitable Area (km^2)	7410	3806	2563	1945	1765	3417	1628	1120	938
Poor Suitable Area (km^2)	10430	6611	4524	3514	3019	5868	3310	1769	1337
Total (km^2)	21493	11946	8081	6156	5390	10704	5399	3245	2567

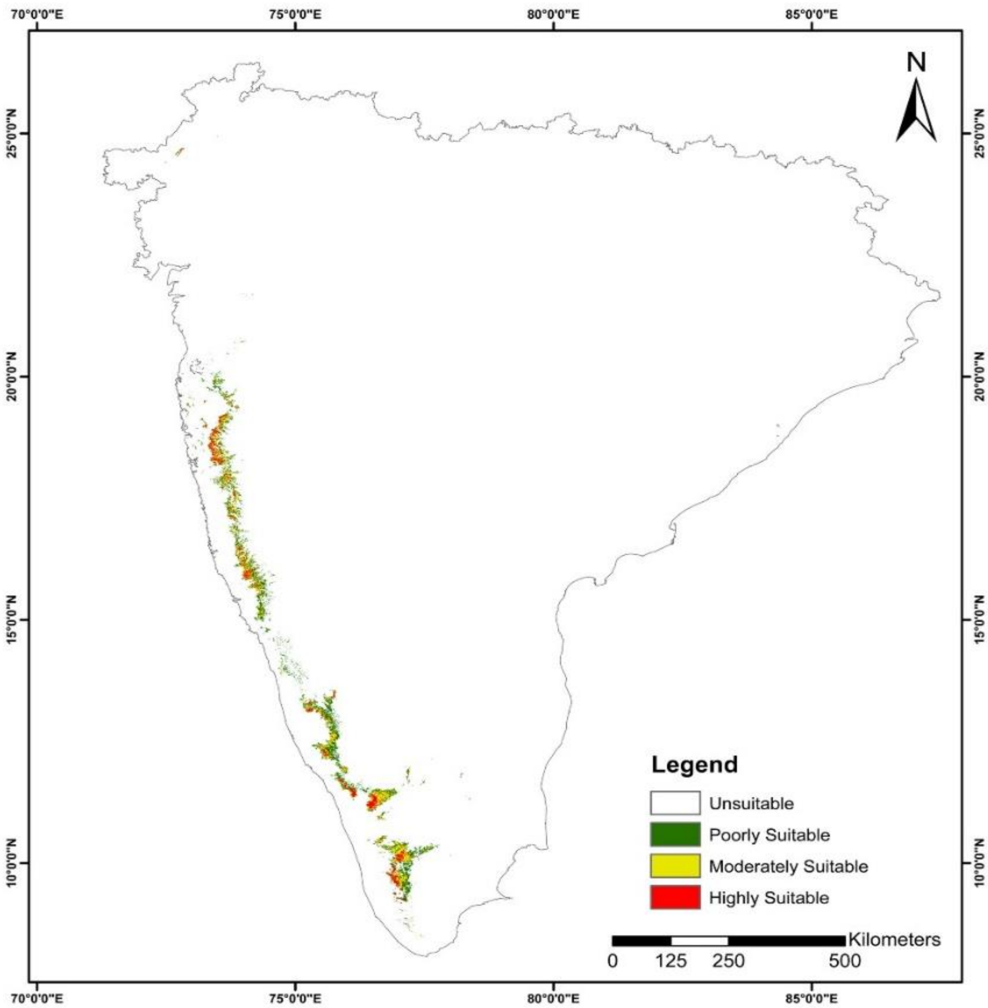

Fig. 3. Current suitable habitat distribution of *H. longicorniculata* in peninsular India

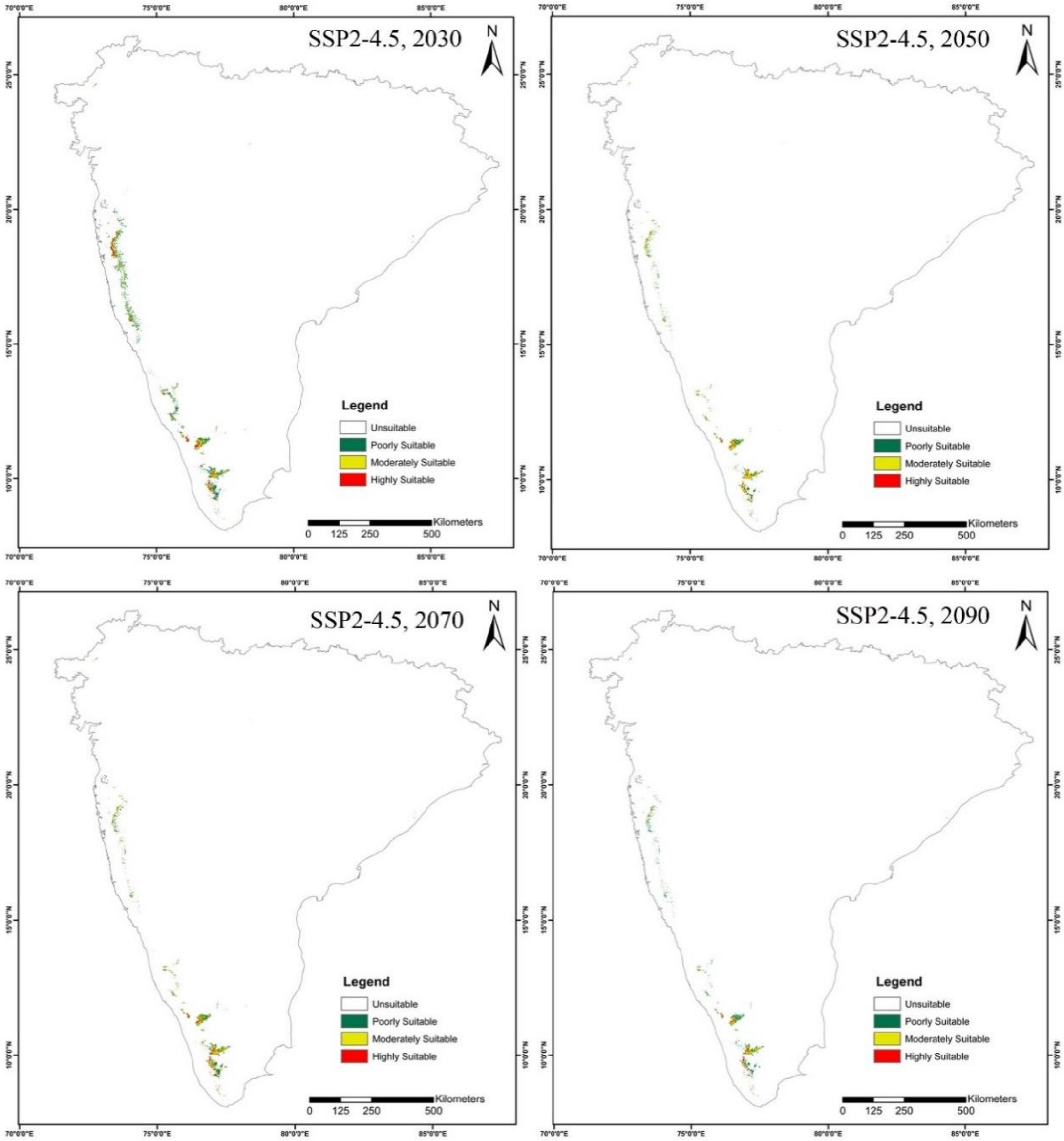

Fig. 4. Predicted suitable area of *H. longicorniculata* under SSP2-4.5

4. DISCUSSION

Habenaria longicorniculata is an endemic orchid distributed throughout Peninsular India; however, the majority of its occurrences are found in WGs. Also, a significant population recorded in the Sirohi of Rajasthan (Purohit, 2020). Belonging to the Orchidaceae family, the species is highly specific to its microhabitat and found growing in the rocky and gravelly areas in grasslands. Known for its distinctive long spur, nocturnal flower opening, and sweet scent emitted for pollination (Dangat & Gaurav, 2020), *H. longicorniculata* relies on *Agrius convolvuli* L. (Hawk Moth) as its primary pollinator (Dangat & Gaurav, 2020). The orchid species is known for its medicinal importance. The tubers are collected from the wild and consumed by the local people. In folk remedies the paste made from the tuber is used externally to cure leukoderma and reducing scrotal enlargement (Subramani & Goraya, 2003; Roy et al., 2007; Purohit et al., 2020). However, these therapeutic uses have contributed to its population decline, compounded by threats such as habitat degradation, fragmentation, developmental activities, grazing, and trampling. Additionally, illegal harvesting of tubers and tourism, particularly in protected areas like the Mount Abu Wildlife Sanctuary, further exacerbate the species' vulnerability (Purohit et al., 2020). Thus, the species is listed in Appendix (https://cites.org/eng/app/index.php) of CITES and the Wildlife Protection Act, 1972, for conservation purposes.

Recent efforts in propagation include successful protocorm development using Knudson C culture media in asymbiotic germination (Patil & Patil, 2017). However, further research is required on aspects such as population dynamics, life cycle studies, and protocol development for ex-situ conservation. Additionally, habitat management and in situ conservation strategies must be prioritized to protect existing populations.

We carried out the study to predict the potential distribution of the species in current and future scenarios using the MaxEnt model. The model was created using 141 occurrence records. Using Pearson's correlation test (0.8), a total of 16 bioclimatic factors were used for the model run. The AUC (0.927) indicates the excellent performance of the model and had a high degree of fit between the actual suitable habitat & climatic variables (Wei et al., 2024). The model

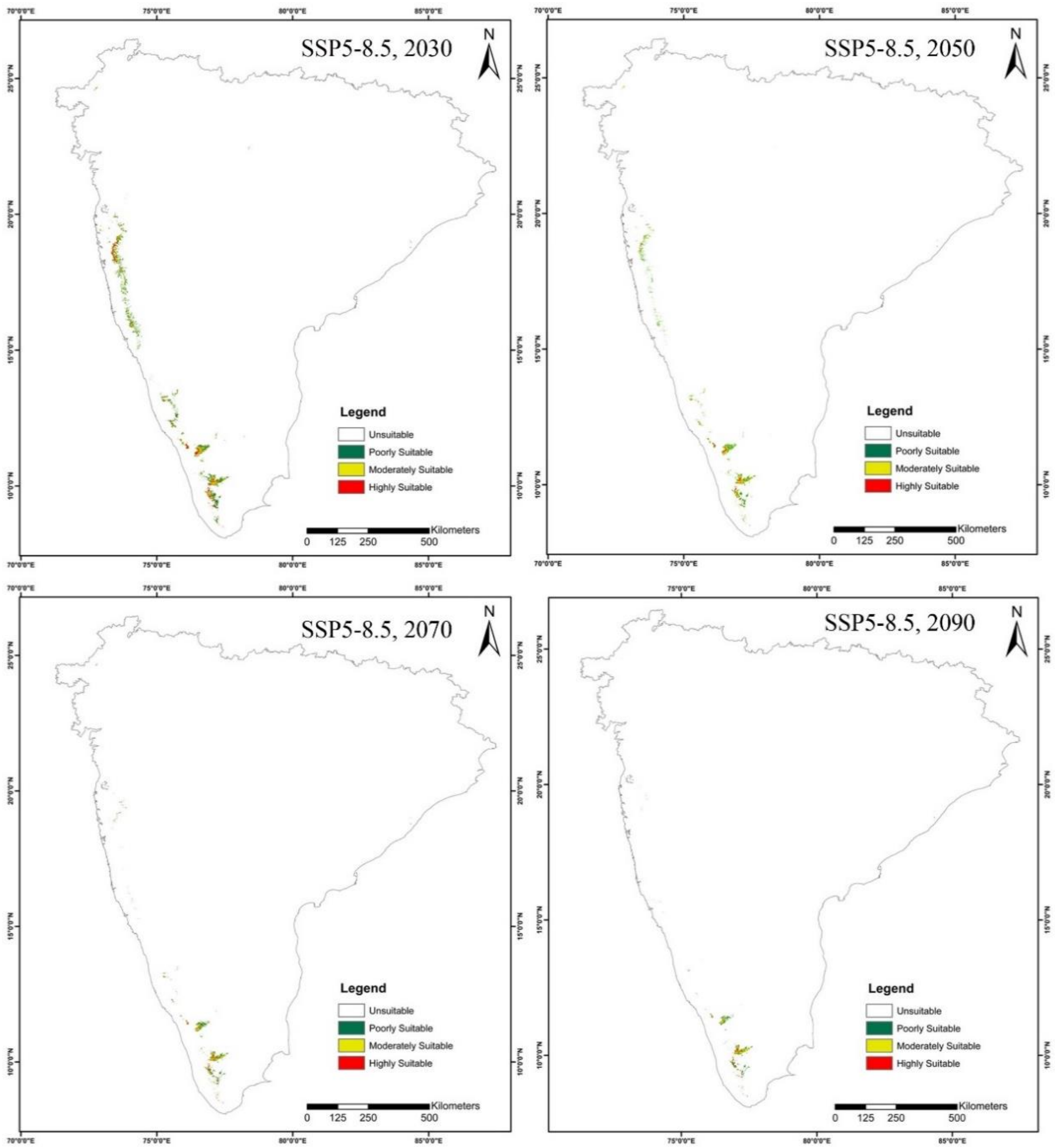

Fig. 5. Predicted suitable area of *H. longicorniculata* under SSP5-8.5 scenario

Jackknife test provides an insight into the key environmental variables that predict the distribution of the species. The results revealed that the Maximum Temperature of Warmest Month (Bio5), Mean Temperature of Wettest Quarter (Bio8), Annual Mean Temperature (Bio1), & pH were the major determining factors that contribute the most to the species distribution.

Under current climatic conditions, the predicted suitable habitat of *H. longicorniculata* spans approximately 21,493 km², which constitutes just 1.2% of the total study area. Of this, the highly suitable habitat is confined to 3,654 km² and is primarily located in Maharashtra (Pune, Raigad, Kolhapur, Sindhudurg), Karnataka (Chikmagalur, Kodagu), Kerala (Wayanad, Kozhikode, Idukki) and Tamil Nadu (Nilgiris). In comparison, Sourabh & Uniyal (2022) estimated the current distribution of *H. longicorniculata* at 20,928 km², which is expected to decrease by 17% (to 17,339 km²) by 2050 under the A2a emission scenario. In our study, under the SSP2-4.5 scenario, the suitable area is predicted to decline from 11,946 km² to 5,390 km², while under the more severe SSP5-8.5 scenario, it is expected to shrink from 10,704 km² to 2,567 km². By 2090, the highly suitable area is predicted to become concentrated primarily in the WGs of Kerala (Idukki, Wayanad, Pathanamthitta) and Tamil Nadu (Nilgiris) under both scenarios, indicating a drastic contraction of the species' suitable habitat. These results highlight the significant impact of climate change on the future distribution of *H. longicorniculata*, with a projected loss of >80% of its suitable habitat under both SSP2-4.5 and SSP5-8.5 scenarios. Its future distribution will likely be confined to less than 1,000 km², predominantly within the Western Ghats of Kerala and Tamil Nadu. This drastic decline in the suitable habitat of *H. longicorniculata* in the future climatic scenarios directly depends upon the climate change along with different anthropogenic pressures (Meza-Joya et al., 2023); which in the future may lead to its endangerment and will increase the risk of extinction (Wiens et al., 2016). Similar findings have been reported for other endemic and vulnerable plant species, where climate change has caused substantial habitat shrinkage. Chandra et al. (2023) documented a decline in suitable habitat for three *Cypripedium* species in the Western Himalayas under RCP 4.5 and RCP 8.5 scenarios, while the endemic species *Habenaria suaveolens* is predicted to experience a dramatic reduction in suitable habitat to less than 1,000 km² in the near future (Jalal et al., 2025). Studies on orchids globally have similarly reported habitat losses due to changing climatic conditions (Tang et al., 2020; Sourav & Uniyal, 2022; Pica et al., 2024). It is crucial to understand that the model was specifically designed to predict the species' fundamental niche, not its realized niche, which represents a significant limitation of the study. The actual niche of the species will likely differ from our model's predictions (Chandra et al., 2023. The distribution of the species depends on both biotic and abiotic factors (Wang et al., 2023). However, while constructing the model, only a few bioclimatic factors were taken into consideration. Since other important factors like mycorrhizal association and pollination behavior were not taken into consideration, it may affect the accuracy in the prediction (Kuo et al., 2014; Xie et al., 2022). Nevertheless, the model provides valuable insights into the potential impacts of climate change on the future distribution of *Habenaria longicorniculata* and emphasizes the urgent need for targeted conservation strategies, including in situ conservation specifically in protected areas like Annamalai Tiger Reserve, Kanyakumari Wildlife Sanctuary, Meghamalai Wildlife Sanctuary, Kodaikanal Wildlife Sanctuary, Nilgiri Biosphere Reserve (Tamil Nadu) Anamudi Shola National Park, Chinar Wildlife Sanctuary, Eravikulam National Park (Kerala) and habitat protection, to mitigate the predicted decline in suitable habitats.

5. CONCLUSION

H. longicorniculata is an endemic, terrestrial orchid species of high medicinal value, found primarily in Peninsular India. Owing to its narrow ecological niche, the species is particularly vulnerable to environmental changes. It exhibits specific habitat preferences, often occurring in rocky and gravelly grasslands with defined microclimatic and edaphic conditions. However, its distribution is increasingly threatened by a combination of biotic and abiotic stresses, including habitat loss, climate variability, overharvesting, grazing, and other anthropogenic pressures. We studied the habitat distribution modelling of the species using MaxEnt and predicted areas suitable for the species. Our analysis identified several key environmental variables influencing the distribution of *H. longicorniculata*, with temperature, precipitation, slope, and soil pH emerging as the most significant predictors. These factors collectively determine the climatic and edaphic suitability for survival and reproduction. The current potential distribution, as predicted by the model, spans the entire Western Ghats (WGs), a global biodiversity hotspot, and extends to parts of the Aravalli Hills in Rajasthan, including Mount Abu. As the climatic scenario changes, the potential area changes drastically. Under both scenarios, suitable habitats are predicted to shrink dramatically and become largely restricted to the southern Western Ghats, particularly in Kerala (districts such as Wayanad, Idukki, and Pathanamthitta) and Tamil Nadu (Nilgiris). This indicates a significant geographic shift and loss of ecological space for the species, reflecting its high vulnerability to climate change. This study can serve as a foundational reference for future research focused on species restoration, propagation protocols, and the integration of climate resilience into conservation strategies.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

ACKNOWLEDGEMENTS

We are grateful to the Director, Botanical Survey of India (BSI), Kolkata, and Head of Office, Central National Herbarium, BSI, Howrah, for facilitating the present research. The authors are also grateful to the curators and in charges of BSI, BLATT, CALI, KFRI, MH, TBGT & SUK for their assistance during the herbarium consultation process.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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