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Current and Future Habitat Suitability of the Endangered Java Slipper Orchid (*Paphiopedilum javanicum*) in Sundaland, Indonesia

Siti Fatimah Hanum[1*], M. Hadi Saputra[2], Ni Kadek Erosi Undaharta[2], M. Bima Atmaja[2], Sutomo[1]

[1] Research Center for Biota Systems, National Research and Innovation Agency, Bogor 16911, Indonesia
[2] Research Center for Ecology, National Research and Innovation Agency, Bogor 16911, Indonesia

Corresponding Author Email: siti046@brin.go.id

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ABSTRACT

The Java Slipper's Orchid (*Paphiopedilum javanicum* (Reinw. ex Lindl.) Pfitzer), a critically endangered species endemic to Sundaland's tropical forests, faces severe threats from climate change, habitat fragmentation, and illegal harvesting. Predicting its spatial distribution under current and future environmental conditions is essential for informing conservation strategies in one of the world's most biodiverse yet vulnerable regions. This study aims to identify the most significant environmental factors influencing the distribution of *P. javanicum*, provide a model distribution of the current probability of occurrence across Sundaland, and project future habitat suitability under mid-century (2040) and late-century (2080) climate. We modelled the potential distribution of *Paphiopedillum javanicum* using MaxEnt species distribution modelling (SDM) with the 19 bioclimatic variables and elevation as predictors. Future projections were generated using the UKESM1-0-LL model under the Shared Socioeconomic Pathway (SSP) 5–8.5. Results indicate that climate change is likely to reduce habitat suitability for *P. javanicum*; both current and projected suitable habitat within protected areas accounts for less than 5% of the total. The most significant environmental factors influencing the distribution are temperature and elevation. The findings highlight the importance of adaptive management strategies to mitigate climate-induced threats to endangered species in Sundaland and identify important refugia for focused conservation efforts.

1. INTRODUCTION

Indonesia's Sundaland region is home to a remarkable variety of indigenous plants and animals, making it one of the world's biodiversity hotspots [1, 2]. The endemicity of flora in Indonesia is more than 22.5% of the total global flora, with more than 5,000 species of orchid spread across the country. One of the most well-known and iconic orchid species is *Paphiopedilum javanicum* (Reinw. ex Lindl) Pfitzer, commonly known as the Java Slipper Orchid. This terrestrial orchid is distinguished by its pouch-like labellum, a floral adaptation that facilitates efficient pollination. The species is native to the Sundaland region, inhabiting montane and lower montane forests of Java, Bali, Lombok, Sumatra, and Kalimantan [3, 4]. It typically grows in shaded microhabitats on steep rocky slopes and forested cliffs, often in leaf litter or moss near rivers and streams [5]. Due to its ornamental appeal, *P. javanicum* has been extensively harvested from the wild, resulting in severe population declines. It is currently listed in Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and is classified as Endangered on the IUCN Red List [6].

The integration of in-situ and ex-situ conservation strategies is essential for the long-term survival of the species [7]. However, effective conservation planning requires robust data on species distribution and environmental preferences. This is especially important for species such as *P. javanicum*, which live in fragmented and declining habitats, often within biodiversity hotspots under intense anthropogenic pressure. In such contexts, Species Distribution Models (SDMs) have emerged as an important tool for predicting suitable habitats under current and future environmental conditions [8-10]. By analyzing climate data and topographical factors, SDMs such as Maximum Entropy Modelling (MaxEnt) can assess habitat suitability and project shifts in species distributions under future climate scenarios [11]. MaxEnt is also effective in predicting species distributions from presence data alone [11]. MaxEnt has been successfully applied to assess habitat suitability for a range of orchid species globally, offering insights into potential refugia and introduction sites under climate change scenarios [12, 13]. In Indonesia, researcher [14] applied MaxEnt to model the distribution of *P. javanicum* on Mount Lawu in Central Java, highlighting areas of high conservation value. Their study recommends extending this modelling approach to other parts of Java and surrounding islands to support more comprehensive conservation strategies. Furthermore, the dynamic nature of climate projections underscores the need to integrate future climate scenarios into SDM analyses to anticipate range shifts and inform adaptive conservation planning [15]. This study represents the first comprehensive SDM assessment for *P. javanicum* across multiple islands in the Sundaland region under current and future climate scenarios, providing spatially explicit guidance for its conservation.

2. METHODOLOGY

2.1 Study area

This study was conducted across the Sundaland region of Indonesia, focusing on the islands of Java, Bali, and Lombok. The study area extends approximately from 105° to 116° E longitude and 6° to 9° S latitude, encompassing a wide range of climatic, topographic, and ecological conditions. Elevation ranges from coastal lowlands to montane environments exceeding 3,500 m above sea level, particularly in the volcanic mountain system of Java and Bali.

The climate of the region is tropical monsoonal, characterized by distinct wet and dry seasons, with mean annual temperatures ranging from approximately 20–30℃ and annual precipitation varying from 1,500 to over 4,000 mm depending on elevation and exposure. Vegetation types include lowland tropical rainforests, montane forests, subalpine vegetation, and fragmented secondary forests, reflecting strong environmental gradients across the islands.

The study area encompasses numerous protected areas, including national parks, nature reserves, and wildlife sanctuaries, that serve as critical refugia for biodiversity conservation in Sundaland.

2.2 Study species

Paphiopedilum javanicum is a terrestrial plant. Leaves up to 30 × 5 cm, tessellate; dark green spots often coalesce. Inflorescences consisting of a single flower held on a ± 40 cm long peduncle, which is usually longer in the wild than when the plant is cultivated. Flowers up to 10 cm broad across the petals; dorsal sepal ovate, acute, green with white margins, longitudinally striped dark brown. Petals long-oblong held nearly horizontal but sometimes drooping, greenish, finely spotted reddish brown in the lower two-thirds, white or pink in the apical third, lip dull brownish green [3].

2.3 Species occurrence data

Species occurrence records of *Paphiopedilum javanicum* were compiled from herbarium collections of Bali Botanic Garden and Bogor Botanic Garden and supplemented with records from the Global Biodiversity Information Facility (GBIF). All records were carefully cleaned prior to modelling. Duplicate records and points with identical geographic coordinates were removed. To minimize the effect of spatial sampling bias and spatial autocorrelation, spatial thinning was applied using a minimum distance threshold of 5 km between occurrence points. Records collected before 1970 were excluded to ensure consistency with contemporary climate data. After the data cleaning process, a total of 48 high-quality occurrence points were retained and used in the final modelling.

2.4 Environmental variables

The environmental variables used in the analysis were derived from WorldClim 2.1 (https://www.worldclim.org/) at a spatial resolution of 30 arcseconds (~1 km). The dataset included 19 bioclimatic variables (BIO1-BIO19), which represent annual trends, seasonality, and extreme or limiting environmental factors. Additionally, elevation data from WorldClim 2.1 were incorporated to account for topographic influences on species distribution.

Prior to model construction, multicollinearity among environmental variables was assessed using Pearson correlation analysis. When pairs of variables showed high correlation ($|r| > 0.7$), only the variable considered more ecologically relevant to the species was retained in the model to reduce redundancy and overfitting. This procedure ensured that the final set of predictor variables provided independent and robust contributions to model performance.

To project future habitat suitability, we utilized downscaled and bias-corrected climate projections from WorldClim 2.1. Future climate scenarios were based on the UKESM1-0-LL model under the Shared Socioeconomic Pathway (SSP) 5-8.5. The selected time periods included (1) 2041-2060 (UKESM1-0-LL SSP5-8.5, 30 arcseconds), (2) 2061-2080 (UKESM1-0-LL SSP5-8.5, 30 arcseconds), and (3) 2081-2100 (UKESM1-0-LL SSP5-8.5, 30 arcseconds).

2.5 Data analysis

All analyses were performed using Ecocommons (https//www.ecocommons.org.au/), a web-based ecological modelling platform that integrates the Biodiversity and Climate Change Virtual Laboratory (BCCVL). The modelling was conducted using the Maximum Entropy (MaxEnt) algorithm, which is widely used for species distribution modelling due to its ability to predict suitable habitats based on presence-only data. In this study, 60 percent of the species presence points were randomly selected for modelling, and the remaining 40 percent were used to evaluate the model. The jackknifing method was used to evaluate the contribution of the various bioclimatic variables to the model. The response curves demonstrating the relationships between the probability of plant presence and the environmental variables were evaluated [16]. Model outputs were exported from EcoCommons and mapped in ArcGIS 10.4. The ROC curve evaluates model performance by plotting sensitivity (true positive rate) against 1-specificity (false positive rate). Higher AUC values indicate better discrimination; AUC values greater than 0.7 are commonly interpreted as acceptable, greater than 0.8 as good, and greater than 0.9 as excellent.

The distribution analysis was divided into five classes based on the probability of the suitable area ranging from 0 to 1. The classification that is used here is not suitable (0-0.2) and currently not suitable (0.2-0.4), low suitable (0.4-0.6), high suitable (0.6-0.8), and very high suitable (0.8-1) [17]. The current and predicted analyses were calculated for each island based on the appropriate classification and presented as percentages of the total area. Thus, the changes were calculated using Excel to provide the changes in areas that increase or decrease between the current and future prediction [17].

3. RESULT

3.1 Model performance evaluation

Overall, the AUC value of the current, 2040, 2060, and 2080 model performances is 0.963, which belongs to good model performance (Figure 1). The high AUC values across all time periods suggest that the model effectively differentiates suitable habitats for *P. javanicum*, supporting its use for forecasting future distribution trends under climate change scenarios. However, further validation using independent datasets would enhance confidence in the model's predictive capacity.

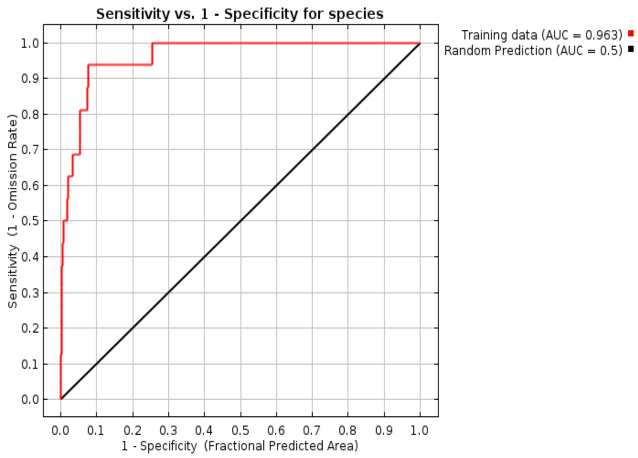

Figure 1. Modeling accuracy using the Receiver Operating Characteristic (ROC) plot for *P. Javanicum* in the current year, year 2040, year 2060, year 2080

3.2 Key environmental variables and their influence

The result of the jackknife method shows that the most important environmental variables in determining the habitat of *P. javanicum* are the maximum temperature of the warmest month (Bio 5) and elevation, which contribute 56.4% and 21.15% to the current distribution model, respectively. Meanwhile, the projected model also shows the maximum temperature of the warmest month (Bio5) as the most important environmental variable (Table 1).

Table 1. Percentage contribution of the predictor variables

Variable	Percent Contribution			
	Current Year	Year 2040	Year 2060	Year 2080
Bio8 (Mean temperature of wettest quarter)	5.30	3.66	0	24.31
Bio5 (Max temperature of warmest month)	56.42	62.56	55.34	58.24
Bio10 (Mean temperature of warmest quarter)	0	22.09	19.85	4.5
Elevation	21.15	21.15	21.15	21.15

However, according to the response curve, for the current year, higher probabilities of *P. javanicum* presence are obtained when the maximum temperature of the warmest month is below 15°C, and located at an elevation above 500 m a.s.l. But this condition shifts for 2040 and 2060, which show the maximum temperature of the warmest month below 25°C, and for 2080, the maximum temperature of the warmest month is below 30°C (Figure 2).

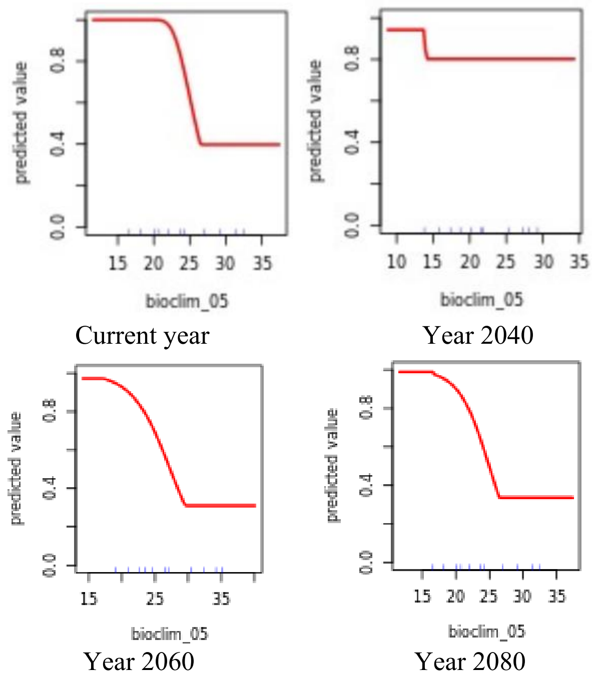

Figure 2. Response curve for the maximum temperature of the warmest month to *P. javanicum* distribution in different years (current, 2040, 2060, 2080)

3.3 Current potential distribution pattern

The species distribution modelling results for *Paphiopedilum javanicum* across Java, Bali, and Lombok indicate variations in habitat suitability under different time periods (Figure 3). The maps display the current distribution and projected habitat suitability for the years 2040, 2060, and 2080 under the UKESM1-0-LL SSP5-8.5 climate scenario.

In the current climate, highly suitable habitats (red areas) are concentrated in certain regions of West Java, Central Java, East Java, Bali, and Nusa Tenggara Barat, particularly in high-altitude areas where environmental conditions support the species' growth. Areas with moderate suitability (yellow and orange) are scattered across the three islands, while unsuitable regions (green) dominate the lowland areas (Figure 4).

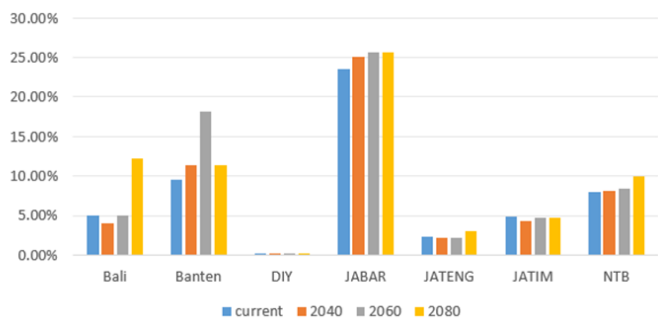

Figure 3. The percentage area of *P. javanicum* suitable habitat modelling based on the province

However, the estimated area of *P. javanicum* in protected areas occupied by potentially suitable habitats under current conditions is 301,872.51 ha, which represents 3.99% of the total area analysed. With regard to the suitability of habitats for the species, the high suitability area covers 141,242.41 ha, the moderate suitability areas cover 77,427.13 ha, and the low suitability area covers 83,202.97 ha, respectively representing 24.81%, 13.60%, 14.62% of the total area. Finally, the area with habitats that are potentially unsuitable for the species is 267,408.18 ha (46.97%) (Table 2 and Figure 5).

- West Java (JABAR) consistently exhibits the highest proportion of suitable habitat, with approximately 23-25% of its area being classified as suitable across all time periods. This indicates a relatively stable habitat for the species despite climate change.
- Banten shows a moderate percentage of suitable habitat under current conditions, but a notable increase is observed in 2040, followed by stabilization in later periods. This suggests that future climatic conditions may initially enhance habitat suitability in this region.
- Bali and NTB (West Nusa Tenggara) maintain a relatively stable proportion of suitable habitat, with only slight variations across different time periods. This implies that the species may persist in these areas with minimal impact from climate change.
- Central Java (JATENG) and East Java (JATIM) have a lower percentage of suitable habitat, with slight increases projected over time. This suggests that while these areas may not be primary habitats, they could still support some populations of *P. javanicum* in the future.
- The special region of Yogyakarta (DIY) has the smallest percentage of suitable habitat, remaining consistently below 1% across all scenarios. This suggests that the region is not a significant habitat for *P. javanicum*, and climate change is unlikely to improve its suitability.

Table 2. Classification of habitat suitability of *P. javanicum* in the protected area obtained from the MaxEnt model

Time	Scenario	Unit	Total Suitable	Unsuitability	Low Suitability	Moderate Suitability	High Suitability
Present		ha	301,872.51	267,408.18	83,202.97	77,427.13	141,242.41
		%	53.03	46.97	14.62	13.60	24.81
		% total	3.99				
2040	SSP5-8.5	ha	317,447.52	251,833.14	111,292.22	75,812.54	130,342.76
		%	55.76	44.24	19.55	13.32	22.90
		% total	4.2				
2060		ha	314,297.76	254,982.87	89,084.63	91,160.94	134,052.19
		%	55.21	44.79	15.65	16.01	23.55
		% total	4.16				
2080		ha	309,129.02	260,151.61	91,125.69	81,700.36	136,302.96
		%	54.30	45.70	16.01	14.35	23.94
		% total	4.09				

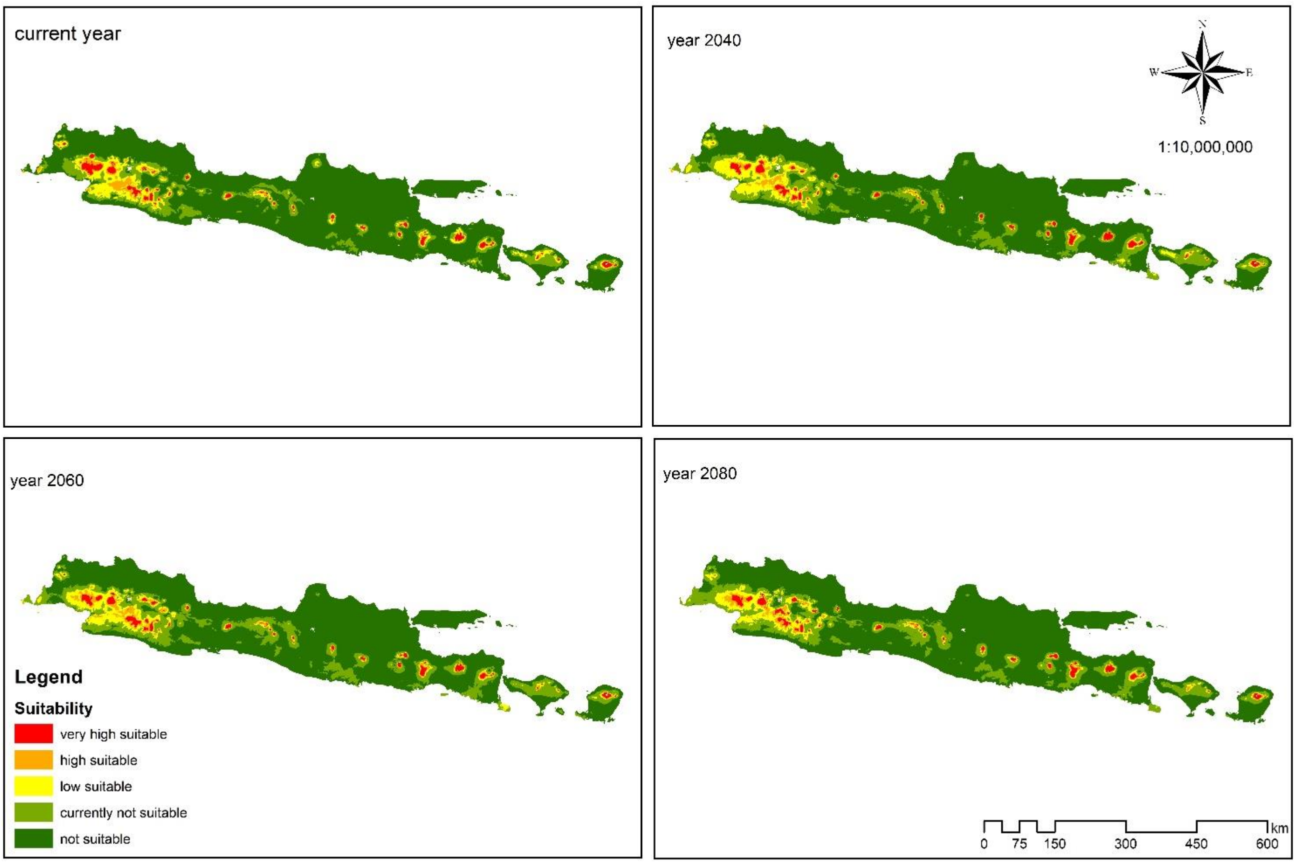

Figure 4. Current and projected habitat suitability for *Paphiopedilum javanicum* in Sundaland under present conditions and future climate scenarios (2040, 2060, and 2080)

Note: Red colour determines a very high suitability while green colour determines an unsuitable area.

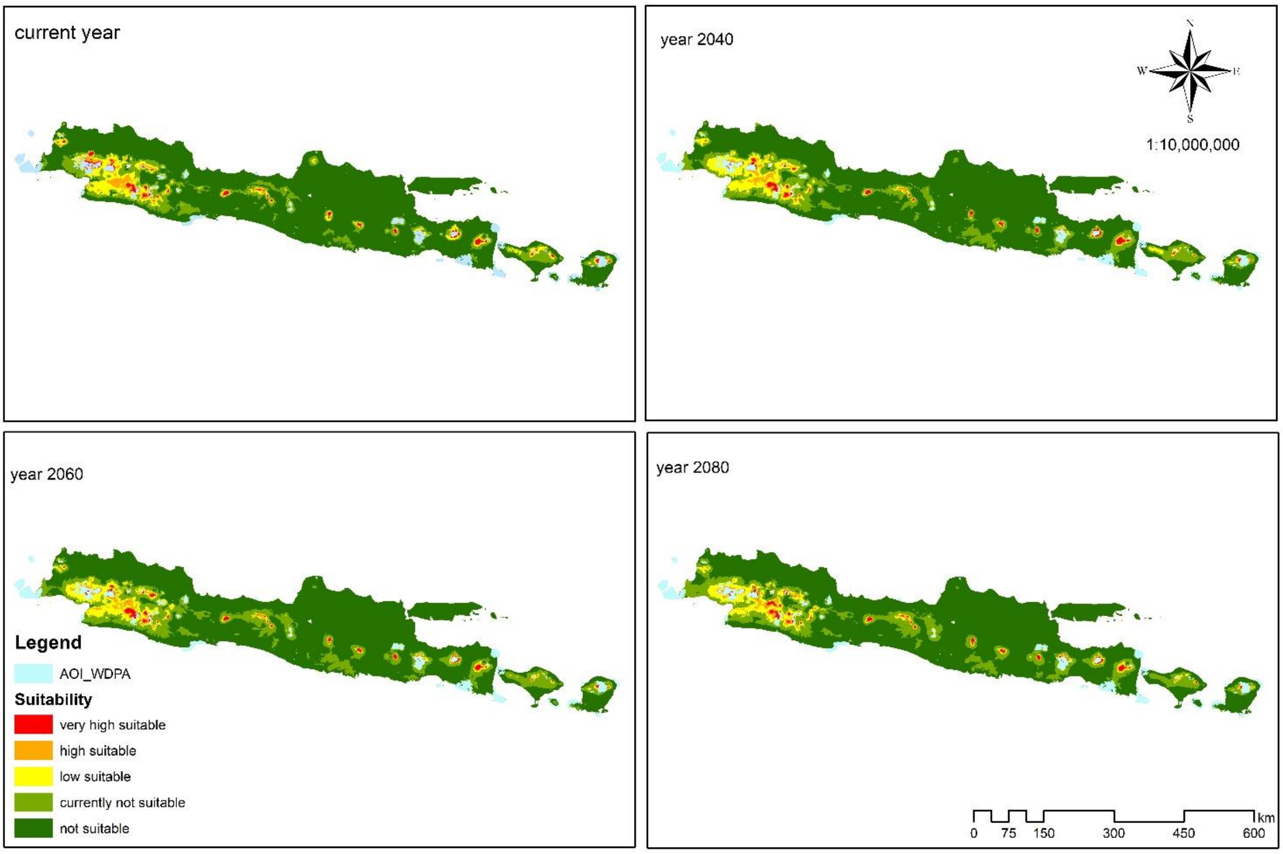

Figure 5. Current and projected habitat suitability for *Paphiopedilum javanicum* in the protected area of Sundaland under present conditions and future climate scenarios (2040, 2060, and 2080)

Note: The light blue outlined polygon indicates the protected areas in the Sundaland region. Red colour determines a very high suitability while green colour determines an unsuitable area.

3.4 Future distribution change projections

Under future climate scenarios, habitat suitability shows a shifting trend. By 2040, the distribution of highly suitable areas remains relatively stable but exhibits minor expansions in some regions of West Java and Bali. However, by 2060 and 2080, a noticeable decline in suitable habitats is observed in parts of Central Java and eastern Java, indicating the potential impact of climate change on the species' distribution. A significant expansion of suitable habitat is projected in West Java, with an increase of approximately 23–25% is expected across all future time periods. Conversely, in the Special Region of Yogyakarta (DIY), suitable habitat remains extremely limited, consistently occupying less than 1% of the total area across all scenarios (Figure 3).

Overall, these findings indicate that while climate change may lead to localized increases or decreases in habitat suitability, West Java remains the most critical region for *P. javanicum* conservation. Efforts to protect this species should prioritize areas with high and stable habitat suitability while monitoring regions that may experience shifts in habitat conditions. Conservation efforts should focus on protecting and monitoring these areas, because *P. javanicum* is found in protected areas below than 5% (Table 2).

4. DISCUSSION

Our findings revealed that the AUC value for the training data is 0.963 in both the current and future scenarios. This result is lower compared with research [14], which has an AUC training value of 0.973. Overall, the high AUC values across all time periods suggest that the model effectively differentiates suitable habitats for *P. javanicum*, supporting its use for forecasting future distribution trends under climate change scenarios. The AUC value will be higher for species with a narrow distribution range [11].

The environmental variables influencing the distribution of species are derived from the jackknife test. The higher the contribution, the greater the variable's influence on the final prediction [16]. The determining factor in habitat modelling is species-specific. In selecting variables used to build a Maxent model, it is necessary to consider ecological relevance and data suitability [14]. Our findings revealed that temperature and elevation appear to have a strong influence on the habitat suitability of *P. javanicum* in Java, Bali, and Lombok. The result is similar to the findings of a previous study conducted on the same species in Mount Lawu, which highlighted the importance of temperature-related variables [14].

The dominance of Bio5 is closely linked to the physiological characteristics of *Paphiopedilum* orchids. Many species in this genus are adapted to shaded, moist, and thermally stable forest understories. Their leaves are relatively thin and not structurally adapted to withstand prolonged heat or intense radiation. In addition, successful germination and early development depend on symbiotic fungi, which are themselves sensitive to soil temperature and moisture fluctuations. High maximum temperatures during the warmest month may therefore limit not only adult plant survival but also recruitment processes. These physiological constraints explain why *P. javanicum* is rarely found in lowland or seasonally hot environments and instead concentrates in montane habitats with moderated thermal extremes [18]. Meanwhile, *P. javanicum* was also found in Mount Lawu with a temperature of 21.8-29.7°C and an elevation of 1,231 – 1,825 m a.s.l. [14].

Elevation also contributed substantially to the model, reinforcing the role of montane environments as thermal refuges. Elevation gradients integrate multiple environmental factors, including lower temperatures, higher humidity, frequent cloud cover, and reduced thermal amplitude. These conditions create microclimates that buffer organisms from regional warming. Studies on other *Paphiopedilum* species similarly report strong associations with mid- to high-elevation forest zones where temperature extremes are limited and canopy cover maintains stable humidity [19].

The current potential distribution pattern shows that highly suitable habitats are concentrated in mountainous regions of West Java, Central Java, East Java, Bali, and Lombok. This is consistent with field observations indicating that *P. javanicum* typically occurs between approximately 1,200 and 2,500 m a.s.l. [14]. Although research [3] reported occurrences as low as 750 m, most populations are associated with cooler montane forest. The preference for such elevations reflects the species' sensitivity to heat stress and its dependence on shaded, moist habitats.

Importantly, several mountain complexes were identified as remaining suitable across all time periods: Mount Rinjani, the mountain areas around Ulun Danu Beratan, Mount Raung, Mount Argopuro, Bromo Tengger Semeru National Park, Mount Arjuna, Mount Kawi, Mount Liman, Mount Lawu, Mount Merbabu National Park, Mount Merapi National Park, Mount Sumbing, Mount Sindoro, Mount Prau, Mount Slamet, Mount Ceremai National Park, Mount Halimun Salak National Park, Mount Gede-Pangrango National Park, Mount Cikuray, and Mount Karang. These areas can be considered long-term climate refugia for several reasons.

First, these mountain systems possess high elevation ranges, allowing upward shifts of suitable thermal zones as regional temperatures increase. Species such as *P. javanicum* can persist by moving to higher altitudes where maximum temperatures remain within physiological tolerance. Second, many of these areas have complex topography, producing diverse microhabitats with varying slope aspects, canopy cover, and moisture regimes. Such heterogeneity increases the probability that localized cool and humid pockets will persist even under broader climatic warming. Third, most of these mountains are located within protected areas or forest reserves, where land-use change is relatively limited compared to the surrounding lowlands. Reduced anthropogenic disturbance enhances their role as stable refuges for temperature-sensitive species.

The persistence of suitability in these montane landscapes highlights their importance as conservation priorities. Protecting forest integrity in these areas will not only conserve existing populations but also provide future habitat as climate envelopes shift. Conservation strategies should therefore focus on preventing habitat degradation, controlling illegal collection, and maintaining canopy cover and watershed functions that regulate local microclimates. In addition, these refugial zones may serve as priority sites for population reinforcement or assisted migration if low-elevation populations decline.

Species distribution modeling (SDM) represent a valuable tool to develop predictions to understand the future distribution of plant and evaluate appropriateness of the habitat for a particular species [16]. Our findings also revealed that under future climate scenarios, habitat suitability shows a shifting trend. By 2040, the distribution of highly suitable areas remains relatively stable, but shows minor expansion in some regions of West Java and Bali. However, by 2060 and 2080, a noticeable decline in suitable habitats is observed in parts of Central Java and eastern Java, indicating the potential impact of climate change on the species' distribution.

The contrasting trends in habitat suitability among regions reflect underlying differences in topography and regional climate sensitivity. West Java consistently retains the highest proportion of suitable habitat across all time periods, which can be attributed to its extensive mountainous terrain and complex topography, which create persistent cool, moist microclimates. These conditions are less vulnerable to surface warming and provide climatic refugia for montane species under future climate change.

In contrast, Central Java and East Java exhibit more pronounced declines in habitat suitability, particularly in later projections (2060–2080). These regions are dominated by lower elevations and broader lowland areas, where increasing temperatures and changes in precipitation patterns under the SSP5-8.5 high-emission scenario intensify thermal stress and reduce habitat suitability for temperature-sensitive species such as *P. javanicum*. This spatial divergence highlights the buffering effect of topographic complexity in West Java and underscores the importance of high-elevation landscapes as long-term refugia for conservation planning.

The percentage area of *P. javanicum* suitable habitat shows that West Java remains the most critical region for *P. javanicum* conservation. West Java has many mountains and hills, and the topography influences the environmental conditions in the region. Several studies reported the occurrence of *P. javanicum* in Gede-Pangrango National Park [20], Cakrabuana Mountain, Majalengka [21], and Jambu Mountain, Sumedang [22].

The identification of priority sites for species conservation is a crucial concern in plant conservation management. The application of SDM helps us to identify with a high predictive accuracy. Thus, we predict the potential distribution of *Paphiopedilum javanicum* based on bioclimatic variables, which allow us to highlight areas that could be transformed. The establishment of protected areas and/or the extension of the existing ones is surely the first step towards effective protection for these species [23]. The model indicates that the current total suitability area of *P. javanicum* habitat in the protected area is 301,872.51 Ha (3.99%) of the total area, while the projected area shows an increase in the year 2040 and 2060, but then a decrease in the year 2080. The suitable habitat is a high-altitude area that has suitable environmental conditions to support the *P. javanicum* growth. Policymakers should consider the influence of anthropogenic activities in the conservation management design of *P. javanicum*, because this plant has economic value, even though it grows in mountain areas and not inside protected areas, but many people take it from nature, so the number is limited.

In this study, the model primarily relies on bioclimatic variables and elevation, while other potentially important factors, such as soil properties, vegetation structure, canopy cover, and biotic interactions, were not explicitly incorporated due to data limitations at the regional scale. Nevertheless, climate remains the dominant driver of large-scale species distributions, particularly under future climate change scenarios. The use of spatially filtered occurrence data and variable selection procedures helped minimize model uncertainty. Future studies integrating edaphic variables, land cover, and species interactions would further improve the ecological realism of the predictions.

5. CONCLUSION

This study shows that *Paphiopedilum javanicum* is extremely susceptible to current and anticipated climate change, with temperature and elevation having a significant impact on future habitat suitability. A robust and efficient framework for identifying present and future conservation priority areas for this endangered orchid across Sundaland, which was enabled by MaxEnt.

Our findings demonstrate the importance of montane areas as long-term climate refugia in high-emission scenarios, especially in West Java. These results highlight the importance of safeguarding high-elevation habitats that could protect species from future climate stress and offer spatially specific guidelines for conservation strategy.

Nevertheless, this study is subject to certain limitations. The model primarily relies on climatic and topographic variables and does not explicitly incorporate non-climatic factors such as soil properties, vegetation structure, land-use change, biotic interactions, and dispersal constraints, which may further influence species persistence at local scales. Future studies integrating these factors, along with population-level and genetic data, would enhance the ecological realism of predictions and strengthen conservation strategies for *P. javanicum* and other climate-sensitive orchid species.

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