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New record and potential spatial distribution of *Curcuma sumatrana* (Zingiberaceae): An endemic wild turmeric in Sumatra, Indonesia

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Abstract. *Syafira F, Nurainas, Syamsuardi. 2024. New record and potential spatial distribution of* Curcuma sumatrana *(Zingiberaceae): An endemic wild turmeric in Sumatra, Indonesia. Biodiversitas 25: 4127-4138. Curcuma sumatrana* Miq. is a Sumatran turmeric species with medicinal potential. However, it remains underutilized and is classified as vulnerable by the IUCN. Its vulnerability is aggravated by limited knowledge of its distribution, a need for more data on habitat preferences, and habitat degradation. Field observations revealed significant morphological variations among populations, likely influenced by environmental factors. This study assessed the morphology, microhabitat preferences, and spatial distribution of *C. sumatrana* in West Sumatra, Indonesia. Surveys and laboratory observations highlighted morphological traits, such as leaf and ligule length and width, significantly contribute to these observed variations. Notably, the leaf shape differed between open and shaded areas, being narrowly elliptic in open areas and broadly elliptic in shaded areas. Populations in Koto Malintang and Lubuk Minturun showed distinct differences, separated by six morphological traits. The *C. sumatrana* prefers habitats with fertile soils, moderate plant diversity, and open land cover, often coexisting with species like *Dendrocnide stimulans* (L.fil.) Chew, *Macaranga tanarius* (L.) Müll.Arg., and *Diplazium* sp. Maximum Entropy modeling (AUC 0.944) predicted a highly suitable habitat of 918 hectares in the western Bukit Barisan range. The model suggests distribution is influenced by soil type and precipitation patterns during the seasonal, warmest, and coldest quarters, as well as land cover. New records from West Sumatra extend the species' known range, reaffirming its vulnerable status with a potential risk of becoming endangered.

Keywords: Koenih rimbo, maximum entropy, principal component analysis, species distribution model

INTRODUCTION

The Zingiberaceae family, commonly known as the ginger family, is a prominent group of plants within the order Zingiberales, widely distributed across tropical regions, including Thailand, Sumatra, and the Malay Peninsula (Larsen et al. 1999; Newman et al. 2004). The family comprises a considerable diversity, both in wild and cultivated forms, reflecting its extensive adaptation and domestication. Zingiberaceae is recognized as one of the largest plant families, encompassing approximately 115 genera and over 3,000 species worldwide (WFO Plant List 2024). In Sumatra, 76 species were documented by Newman et al. (2004), while recent studies report 100 species identified in West Sumatra (Rahmi et al. 2023). Among these, *Curcuma sumatrana* Miq., an endemic species to Sumatra with vulnerable conservation status, stands out as a species of significant concern (Nurainas and Ardiyani 2019).

Since its rediscovery in 2011, *C. sumatrana* has been the focus of intensive scientific research, particularly regarding its utility in food and medicine (Ardiyani et al. 2011). The species is famous for its medicinal properties; its rhizomes contain secondary metabolites that have been proven to prevent brain degeneration, enhance cognitive function, and improve brain histological structure and concentration (Nawawi 2021). Additionally, its rhizomes exhibit antibacterial and anticancer properties, making *C. sumatrana* a species of considerable pharmacological interest (Wulansari et al. 2020; Rahman et al. 2022; Alamsjah et al. 2023). More and more research research underscores the need for conservation efforts to ensure the survival of this valuable plant.

Field observations reveal significant intraspecific variation in *C. sumatrana*, particularly in individual size across different populations. Ardiyani et al. (2011) reported a wide range of sizes in leaves, pseudostem, peduncles, and spikes. Morphometric studies were carried out using methods that measure and analyze morphological characters in taxa to measure and analyze this morphological variation. Understanding these variations is crucial for identifying populations that may be more vulnerable and require targeted conservation efforts.

Preliminary observations at the Herbarium of Universitas Andalas, Padang, Indonesia, identified 19 voucher specimens of *C. sumatrana* collected from various regions in West Sumatra. Both herbarium specimens and fresh samples were measured to enhance the accuracy of morphometric calculations. Environmental adaptations often influence morphological variation in plants. However, current information on the habitat of *C. sumatrana* has not been provided (Nurainas and Ardiyani 2019). Therefore, to address this gap, field observations of the species' microhabitats were carried out in two locations with contrasting land cover types: an open area in Koto

Malintang, as documented by Ardiyani et al. (2011), and a shaded area in Lubuk Minturun identified through preliminary field survey. Understanding these microhabitats provides insights into the species' specific environmental adaptations and helps identify habitat preferences that support optimal growth and larger populations.

The limited distribution range and intense human activities have contributed to the degradation of *C. sumatrana*'s habitat, potentially elevating its conservation status from vulnerable to endangered in the near future (Nurainas and Ardiyani 2019). Conservation strategies for endemic species like *C. sumatrana* are crucial, particularly when their spatial distribution is well understood. Comprehensive field surveys for species distribution require significant costs and time. Technological advances have led to the development of distribution modeling tools like MaxEnt, BIOCLIM, and DOMAIN, which help predict species distributions based on geographical data. Compared to other modeling tools, MaxEnt produces more accurate models with limited occurrences (Yudaputra et al. 2019). Combining phytogeographic studies with Geographic Information Systems (GIS) and remote sensing can predict and analyze the potential distribution areas, aiding in effective conservation planning. Determining the potential distribution of *C. sumatrana* is essential for developing conservation strategies and contributing valuable data for assessing the species' conservation status.

This study aims to assess morphological character, analyze habitat preference, determine the potential of spatial distribution, and understand key environmental variables responsible for the distribution of *C. sumatrana*.

MATERIALS AND METHODS

Study area

We conducted field surveys in six localities in West Sumatra, Indonesia: Lubuk Minturun in Padang (13 August 2023), Rimbo Panti Nature Reserve in Pasaman (7 September 2023), Batu Busuk in Padang (9 September 2023), Lembah Anai Nature Reserve in Tanah Datar (22 September 2023), Koto Malintang in Agam (6 January 2024), and Lubuk Kilangan in Padang (11 August 2024). A total of 24 occurrences were collected from field observation, ANDA Herbarium specimens (Voucher Code: ANDA 0043553-0043585), and the Global Biodiversity Information Facility (Cubey 2022; Takahashi 2023). Koto Malintang and Lubuk Minturun were chosen as locations for microhabitat observation based on land cover, open area, and shaded area, respectively. All coordinates were converted to decimal degrees, imported into Microsoft Excel, and then saved in CSV format, and are used as input data for habitat suitability modeling using MaxEnt.

Procedure

Morphological measurements

Observations were made on 16 fresh adult individuals of *C. sumatrana* collected from Lubuk Minturun and Koto Malintang, as well as 17 specimen sheets stored at the ANDA Herbarium. We followed the morphological measurements by Ardiyani et al. (2011) to identify the specimens as *C. sumatrana*. The characteristics are as follows: leaf length and width, petiole length, pseudostem length, ligule length, spike length, pedunculus length, and inflorescence length. All specimens were deposited in the ANDA Herbarium, Universitas Andalas Padang, West Sumatra.

Recording microhabitat data

Microhabitat data collection consists of biotic and abiotic components. Environmental factors, both biotic and abiotic, were observed using field surveys with modified transect-based plots from Mueller-Dombois and Ellenberg (1974). The total plot size was 100 m², consisting of 10×10 m for trees (DBH ≥10 cm), saplings (2 cm<DBH<10 cm, height ≥2 m), and seedlings (height <2 m). Data collected included collection number, species name (local or scientific), DBH, and number of individuals that may experience post-conservation declines, such as organ and sap color. A 5×5 m plot was used for saplings and 2×2 m for understory plants. DBH was measured at 1.3 m above ground level. Tree species at each life stage (trees, saplings, understory) were identified in the field. For unidentified species, samples of leaves, bark, fruit, and flowers (if available) were collected and identified at the ANDA Herbarium, Universitas Andalas. Soil samples were taken to analyze physical and chemical properties at both sites.

Species distribution modeling

We used a total of 8 occurrences recorded from field survey, herbarium specimen, presented coordinates by Ardiyani et al. (2011), and GBIF records. The following spatial variables were included as predictors in the model: elevation, land cover, soil type, and bioclimatic variables. Elevation and bioclimatic variables were downloaded from the Global Climate Database (https://www.worldclim.org/, accessed on 1 June 2024). for the recent period (1970-2000). Land cover was downloaded from (indonesia-geospasial.com). Soil type was downloaded from the Food and Agriculture Organization (https://www.fao.org/soils-portal/data-hub/). The spatial resolution was 2.5 arcminute for elevation and bioclimatic variables. Processing of the raster file, including cropping to the extent of the study region, and conversion of the bioclimatic raster into ASCII format for use in MaxEnt were conducted using Quantum Gis ver 3.28 (Setyawan et al. 2020).

In our predictive models, we applied the default settings for the convergence threshold ($<10^{-6}$) and a maximum of 500 iterations in the MaxEnt model (Harapan et al. 2020). To identify optimal species locations, ten replicated models and background sample functions were employed, which account for environmental conditions influencing species presence across different spatial scales (Gunawan et al. 2023).

Data analysis

Morphometrics analysis

The results of morphometric characterization were analyzed using Principal Component Analysis (PCA). This method is employed to assess statistical variation within a species and to identify groupings within a taxon based on principal components. The PCA was conducted using

Paleontological Statistic (PAST) software version 4.03, following the guidelines provided by Hammer et al. (2001). The core concept of PCA is to reduce the number of variables by transforming the original variables into a new, smaller set of variables called Principal Components (PCs). These PCs represent new combinations of the original quantitative variables measured in the study. The proportion of variation in the data explained by each principal component is indicated by its eigenvalue, with PCs having eigenvalues greater than 1 kept for analysis (Xiao and Yang 2024). The contribution of each variable (in this study, the measured morphological characters) is represented by the loading value, where loadings >0.6 or <-0.6 are considered significant contributors to the PCA (Idrees et al. 2021). The analysis output is visualized through scatter plots. Additionally, the Kruskal-Wallis test was performed to identify characters showing significant differentiation among individuals, with significance indicated by a p-value ≤0.05. The Mann-Whitney test was subsequently used to examine significant differences between individuals from different locations, providing insight into the grouping patterns (Hammer et al. 2001).

Microhabitat analysis

The biotic data is analyzed through the Importance Value Index (IVI) and Shannon-Wiener Diversity Index (H'). The analysis follows the formula established by Mueller-Dombois and Ellenberg (1974):

$$IVI = RDi + RF + RDo$$

Where:

Relative Density (RDi) : The density of a species relative to the total density of all species

Relative Frequency (RF) : The frequency of a species relative to the total frequency of all species

Relative Dominance (RDo) : The basal area of a species relative to the total basal area of all species

The Diversity Index according to Shannon-Wiener (H') was used in this study to compare the species diversity of plants between the two research locations and calculated using the following formula (Odum and Barrett 1971):

$$H' = - \sum \{(ni/N) \log (ni/N)\}$$

Where:

H' : Shannon-Wiener Diversity Index
ni : Important value of each species
N : Total important value

The abiotic data consists of soil data, which, in its analysis, involves determining the status of each parameter according to the criteria for soil chemical properties and assessing soil fertility status based on the soil fertility classification criteria (Teapon and Hadun 2018).

Accuracy and habitat suitability analysis

The significance and contribution of each environmental variable to the habitat suitability model for *C. sumatrana* were evaluated using the Jackknife test (Wei et al. 2018), and the model's performance was assessed with the Area Under Curve (AUC). AUC values range from 0 to 1. An AUC value below 0.5 indicates that the model's prediction is no better than random, while a value close to 1 reflects a highly accurate and informative model (Silva et al. 2022). Additionally, a Jackknife analysis was performed to determine the contribution of each variable to the model's prediction and to identify the dominant factors influencing the potential distribution of species (Ali et al. 2023).

The results were then imported into Quantum GIS version 3.28 for further visualization and analysis. The habitat suitability on the Maxent-generated model map was categorized into four classes: highly suitable (0.7≤P≤1.0), moderate suitability (0.5≤P<0.7), low suitability (0.2≤P<0.5), and not suitable (0.0≤P<0.2) (Huang et al. 2022).

After producing a prediction map for *C. sumatrana*, we validated the species distribution model on the ground by conducting additional sampling at four locations predicted to be within the species' suitable range: Batu Busuk and Lubuk Kilangan in Padang City, Rimbo Panti NR in Pasaman District, and Sungai Suko in Dharmasraya District. We employed the GeoCat Redlisting tool (Bachman et al. 2011) to evaluate the extinction risk of *C. sumatrana* using our combined field survey data. The analysis focused on two key aspects of the species' geographic range: the Extent of Occurrence (EOO) and the Area of Occupancy (AOO). The AOO was calculated using the default IUCN grid cell size of 2 km².

RESULTS AND DISCUSSION

Morphometric study of *Curcuma sumatrana*

Morphological assessments of *C. sumatrana* were conducted on living material and herbarium specimens from Universitas Andalas. Key morphological characters measured included leave length, width, and ratio, along with pseudostem, petiole, ligule, inflorescence, peduncle, and spike lengths. Principal Component Analysis (PCA) revealed that leave length and width, pseudostem, ligula, and inflorescence length contributed most to PC1. In contrast, the leave length-to-width ratio and ligula and peduncle lengths influenced PC2. The scatter plot showed significant overlap among populations, indicating limited morphometric differentiation (Figure 1, Table 1).

A Kruskal-Wallis test identified significant differences in leave length, width, and ligule length among *C. sumatrana* populations (Table 2). A Mann-Whitney test revealed Koto Malintang and Lubuk Minturun were the most distinct, differing in six characters: leave length and width, pseudostem, petiole, ligula, and inflorescence lengths (p-value 0.0004, 0.0229, 0.0286, 0.0389, 0.0186, and 0.0380 respectively). Koto Malintang also differed significantly from Sipisang and Kambang in leave length (0.0015 and 0.0372, respectively), while Lubuk Minturun differed from other populations in ligula (Asam Pulau 0.015, Sianok 0.041, and Kambang 0.015), inflorescence (Asam Pulau 0.037, Lembah Anai 0.016, and Kambang 0.037), and spike lengths (Sipisang 0.023, Asam Pulau 0.016, Lembah Anai 0.016, and Kambang 0.016).

Variation in the leave length-to-width ratio was examined by locality. Specimens from Koto Malintang, Sianok, Asam Pulau, Batu Busuk, Ulu Gadut, and Kambang had higher ratios, resulting in narrowly elliptic leaves. In contrast, those from Lubuk Minturun, Lembah Anai, and Sipisang had lower ratios, leading to broadly elliptic leaves (Figure 2). According to Ardiyani et al. (2011), the leaves of *C. sumatrana* are described as elliptic. The term "elliptic," as defined by the Systematics Association Committee for Descriptive Biological Terminology (1962) in The Kew Plant Glossary: An Illustrated Dictionary of Plant Terms (Beentje 2016), refers to a leave shape with a length-to-width ratio ranging from 1.5 to 2, which can be either narrowly or broadly elliptic.

Microhabitat study of *Curcuma sumatrana*

Our field surveys showed that Lubuk Minturun was more shaded than Koto Malintang, with richer plant diversity. In Lubuk Minturun, the tree was more dominant than sapling and understorey in all values testes (Rdi (%), Rdo (%), and IVI (%)) except for RF (%). *Macaranga tanarius* (L.) Müll.Arg. was the dominant tree, reflecting its adaptability as a pioneer in secondary forests; *Dendrocnide stimulans* (L.fil.) Chew dominated saplings, while *Diplazium* sp. ferns dominated the understorey. In comparison, *D. stimulans* also dominated *C. sumatrana's* habitat in Koto Malintang, suggesting frequent co-occurrence. *Coffea canephora* Pierre ex A.Froehner, a commercially cultivated plant, was dominant from seedling to sapling stages at Koto Malintang (Table 3).

Field observations revealed a significant range in plant diversity at both locations, from 1.29 to 2.65, indicating a moderate level of diversity (Figure 3). Notably, Lubuk Minturun boasts a higher diversity (H' = 2.20) than Koto Malintang (H' = 1.66), a finding that could be attributed to the conversion of forest to agriculture in Koto Malintang. The lower diversity in Koto Malintang, which indicates reduced competition for resources, provides an ideal environment for *C. sumatrana* to thrive. This suggests specific adaptations that enable efficient growth and regeneration. The population and individual size of *C. sumatrana* is greater in Koto Malintang than in Lubuk Minturun. Our analysis of soil composition, a crucial aspect of *C. sumatrana*'s habitat preferences, revealed that the soil in Koto Malintang has a higher silt content (39.38%) compared to Lubuk Minturun (34.20%), which may contribute to a comparatively more fertile and silty soil texture. In comparison, the soil in Lubuk Minturun is more sandy and less fertile (Table 4). These findings have significant implications for our understanding of plant diversity and habitat preferences in these regions.

Table 1. Loading value to the principal component in fresh samples and specimens of *Curcuma sumatrana*

Morphological characters	PC 1 Eigenvalue = 3.30 variability = 36.69%	PC 2 Eigenvalue = 2.39 variability = 26.59%
Leave length	0.83*	0.07
Leave width	0.66*	-0.60
Length-to-width ratio of the leave	0.21	0.82*
Pseudostem length	0.78*	0.13
Petiole length	0.57	0.12
Ligula length	0.61*	-0.64*
Inflorescence length	0.61*	0.47
Pedunculus length	0.53	0.61*
Spike length	0.41	-0.55

Note: *: Significantly different

Table 2. Significance values of morphological character variation in *Curcuma sumatrana* using Kruskal-Wallis analysis

Morphological characters	P-value
Leave length	0.00*
Leave width	0.02*
Length-to-width ratio of the leave	0.53
Pseudostem length	0.24
Petiole length	0.13
Ligula length	0.04*
Inflorescence length	0.16
Pedunculus length	0.41
Spike length	0.11

Note: *: Significantly different

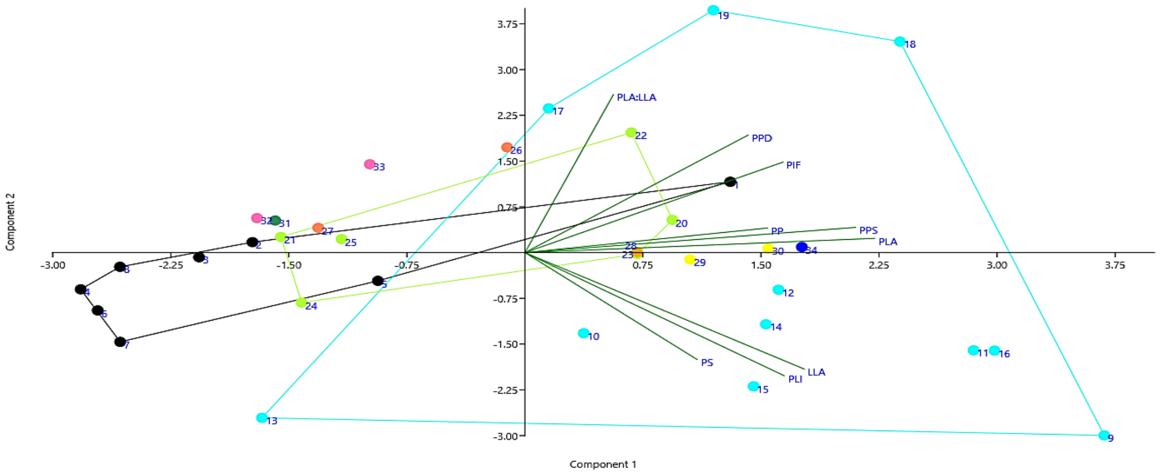

Figure 1. Scatter plot of the quantitative character values of *Curcuma sumatrana* from living materials and specimens in West Sumatra, Indonesia. The numbers indicate individual numbers. Number of 1-8: Lubuk Minturun; 9-19: Koto Malintang; 20-25: Sipisang; 26-27: Asam Pulau; 28: Ulu Gadut; 29-30: Lembah Anai; 31: Sianok; 32-33: Kambang; 34: Batu Busuk

Table 3. Relative density, relative frequency, relative dominance, and importance value index of the most important species around *Curcuma sumatrana* in Lubuk Minturun and Koto Malintang in West Sumatra, Indonesia

Location site	Habit	Species	RDi (%)	RF (%)	RDo (%)	IVI (%)
Lubuk Minturun	Tree	*Macaranga tanarius*	28.57	25.00	57.64	111.21
	Sapling	*Dendrocnide stimulans*	26.25	8.33	15.31	49.90
	Understorey	*Diplazium* sp.	25.14	25.81		50.94
Koto Malintang	Tree	*Dendrocnide stimulans*	21.74	23.53	4.08	49.35
	Sapling	*Coffea canephora*	60.87	33.33	41.38	135.58
	Understorey	*Coffea canephora*	26.88	15.38		42.27

Table 4. The physical and chemical properties of the soil from Lubuk Minturun and Koto Malintang in West Sumatra, Indonesia

Parameter	Unit	Lubuk Minturun	Koto Malintang
Fraction : Sand	%	40.01	31.79
Silt	%	34.20	39.38
Clay	%	25.79	28.82
pH - H_2O		6.25 (sa)	6.36 (sa)
pH - KCl		5.51 (sa)	5.69 (sa)
C-organic	%	4.89 (h)	7.49 (vh)
N-Kjeldahl	%	0.34 (m)	0.56 (h)
P_2O_5 (Bray)	ppm	36.49 (vh)	19.20 (m)
KTK	cmol/kg	16.04 (l)	25.79 (h)
K	cmol/kg	0.46 (m)	1.22 (vh)
Na	cmol/kg	0.20 (l)	0.18 (l)
Ca	ppm	5.17 (l)	7.62 (m)
Mg	ppm	0.94 (l)	2.70 (h)

Note: sa: slightly acid; vh: very high; h: high; m: moderate; l: low

Potential spatial distribution and environmental factors influencing *Curcuma sumatrana*

The MaxEnt model predicts *C. sumatrana*'s potential habitat, mainly in the western Bukit Barisan range, West Sumatra, covering about 918 hectares (Figure 4). This limited distribution highlights the species' vulnerability and the need for targeted conservation efforts, as *C. sumatrana* may be sensitive to environmental changes and habitat disturbances. The model's performance, evaluated using occurrences and selected environmental variables, is classified as excellent, with an Area Under the Curve (AUC) of 0.944 for training data and 0.883 for test data (Figure 5). This high level of accuracy was further validated during field surveys, where *C. sumatrana* was discovered, demonstrating the robustness of the research process. The performance of the model is considered very high, supported by its strong AUC value. Field surveys in areas with high-probability predictions further validated the model's accuracy.

In this study, a rapid red list assessment classified *C. sumatrana* as vulnerable, with the potential to be reclassified as endangered. The assessment estimated an Extent of Occurrence (EOO) of 14,690 km² and an Area of Occupancy (AOO) of 52 km² (Appendix 5). This EOO shows a significant increase of about 12,000 km² compared to the previous report by Nurainas and Ardiyani (2019), highlighting the need for continued monitoring and conservation efforts.

The Jackknife test analysis identified five key environmental variables influencing *C. sumatrana* distribution: soil type (Soil), seasonal precipitation (Bio15), precipitation during the warmest quarter (Bio18), precipitation during the coldest quarter (Bio19), and land cover (Landcov) (Figure 6). Soil type is the most influential, contributing 77.9%, followed by seasonal precipitation at 11.2%, warmest quarter precipitation at 4.8%, coldest quarter precipitation at 4.3%, and land cover at 1.7% (Table 5).

Permutation importance assesses the significance of each variable in the model's accuracy. Variables with high permutation importance result in the greatest decline in accuracy when their values are randomized, indicating their crucial role. In this study, soil type emerged as the most important environmental factor, followed by precipitation during the coldest and warmest quarters, seasonal precipitation, and land cover, underscoring the model's reliance on these variables for accurate predictions.

The model outputs include response curves that illustrate how various environmental factors influence plant distribution. These curves represent the average response from 10 repetitions of the MaxEnt program. The response curve for soil type shows that *C. sumatrana* is optimally distributed on acrisol soils, followed by areas near water bodies (Figure 7.A). For seasonal precipitation, the curve indicates that optimal conditions for *C. sumatrana* occur between 15-35 mm, with the highest suitability at approximately 27 mm (Figure 7.B). The response to precipitation during the warmest three-month period reveals that *C. sumatrana* thrives in environments with 500-800 mm of precipitation (Figure 7.C).

Additionally, the curve for precipitation during the coldest quarter shows an optimal range of 200-1,000 mm for *C. sumatrana* (Figure 7.D). The most suitable land cover for this species includes areas near water bodies, shrublands, and human settlements. Field surveys indicate that *C. sumatrana* populations in Batu Busuk and Koto Malintang are located close to water bodies and settlements, while in Lubuk Minturun, the species is found around rivers in agricultural areas adjacent to shrubland (Figure 7.E).

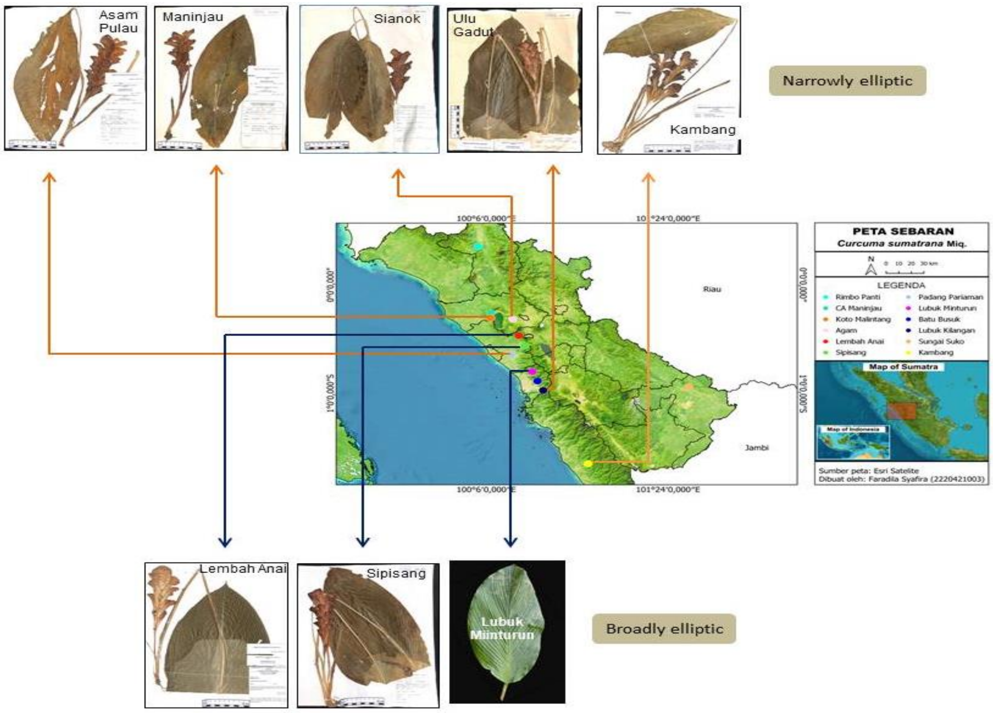

Figure 2. Variation in leaves shapes of *Curcuma sumatrana* based on specimen collection locations

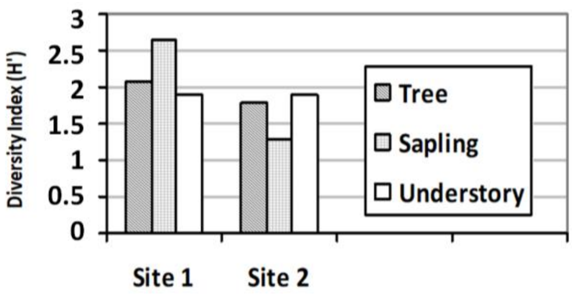

Figure 3. Diversity index of vegetation around *Curcuma sumatrana* in Lubuk Minturun (Site 1) and Koto Malintang (Site 2) in West Sumatra, Indonesia

Field validation

Subsequently, field validation, a crucial step in our research, was conducted to verify the accuracy of the potential distribution model of *C. sumatrana*. New locations were identified that align with the model's predicted distribution. These additional sites include Batu Busuk and Lubuk Kilangan (Padang), Sungai Suko (Dharmasraya), and Rimbo Panti Nature Reserve. All four locations are within areas predicted to have low to high suitability for *C. sumatrana*. Batu Busuk, Lubuk Kilangan, and Rimbo Panti NR were found to be highly suitable, suggesting that these areas are suitable for the species' growth and development. However, Sungai Suko was found to be less suitable due to its low habitat suitability and environmental conditions that are less supportive, as it is located near oil palm plantations. The number of individuals observed at Sungai Suko was approximately 10 individual, which is a relatively low population. Voucher specimens were deposited in Herbarium ANDA.

According to Harapan et al. (2022), for endangered taxa, field surveys in areas with a probability ≥80% have a high potential for locating the targeted taxa. This suggests that areas with high probability predictions in the model are indeed likely to be suitable habitats for the species in question.

Discussion

We provide photographs of *C. sumatrana*, including the sheathing bract and detailed part of the inflorescence, fruit, and seed (Figure 8), updated from a previous study by Ardiyani et al. (2011). Our findings align with the previous description, but we assess the color of the fruit to be white-red (young-ripe).

The variations observed in *C. sumatrana* is assumed to be influenced by differences in land cover. The locations where this species was found in Koto Malintang, and Kambang are agricultural areas, while Lubuk Minturun and Lembah Anai are shrubby areas adjacent to secondary forests. Field observations indicate *that C. sumatrana* grows more abundantly and with larger individuals in open areas (Koto Malintang). Agricultural areas generally have lower diversity than shrublands or secondary forests (Fan et al. 2024). Open areas, such as agricultural fields, support fewer species, resulting in reduced competition. This allows *C. sumatrana* to absorb more resources for growth. The morphological variation observed in this study is also assumed to result from differing growth environments. Adaptation of plants to their environment can lead to the development of distinct morphological variations. Environments with richer nutrients can increase species growth (Syofiani et al. 2020).

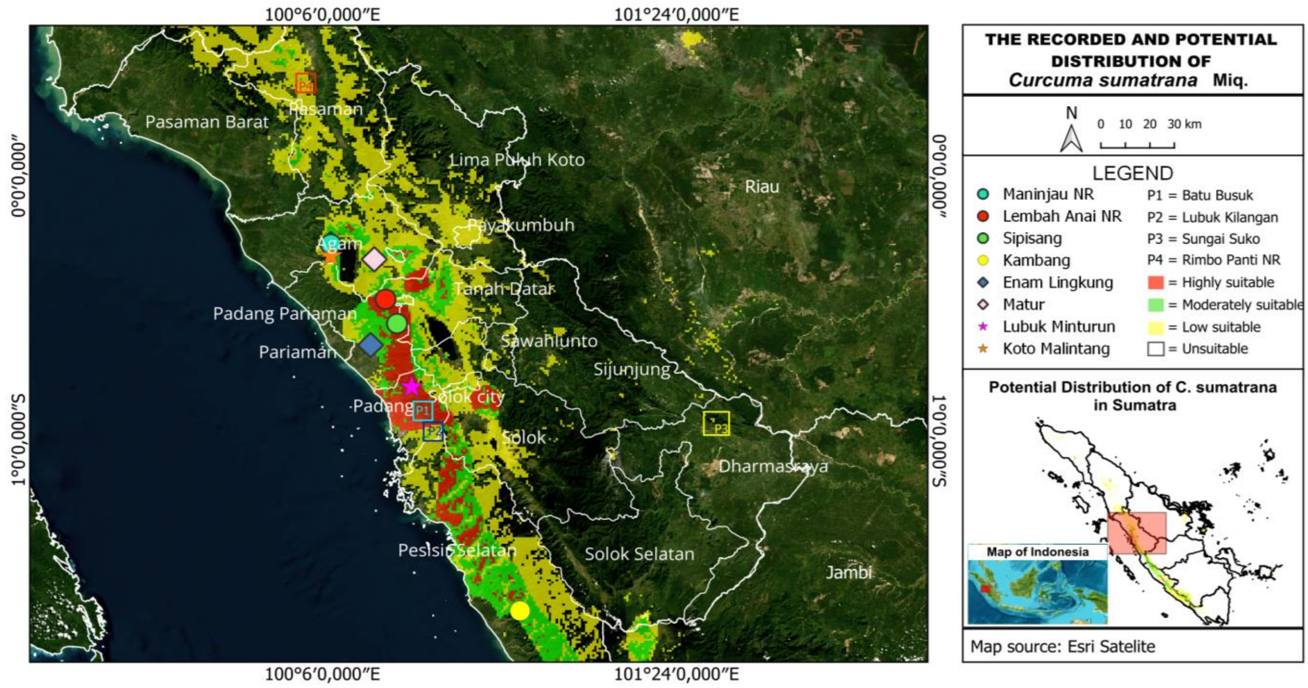

Figure 4. Map of the recorded and potential distribution of *Curcuma sumatrana*. The Inset map shows the potential distribution of the species on Sumatra Island, Indonesia. Symbols indicate collection sites: circles and diamonds are previously known sites (coordinate from IUCN and GBIF); stars are recorded occurrences from field surveys. Sites indicated by the circles and stars were used to generate the SDM model. The SDM-generated habitat suitability is provided in red, green, and yellow areas. Open rectangles represent areas that were sampled based on the prediction map: P1: Batu Busuk; P2: Lubuk Kilangan; P3: Sungai Suko; P4: Rimbo Panti Nature Reserve

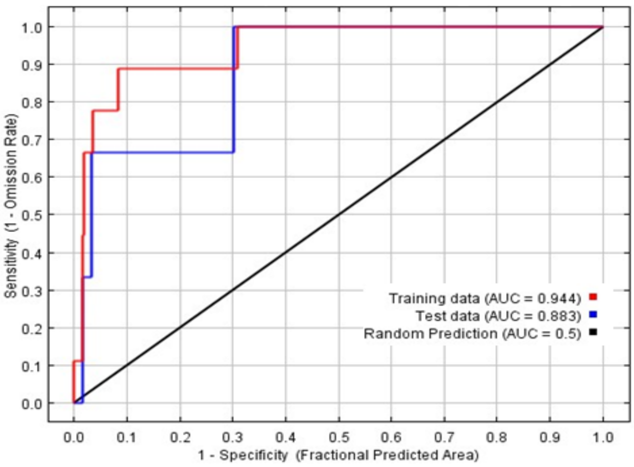

Figure 5. The area under the curve value of the maxent model of the potential distribution of *Curcuma sumatrana*

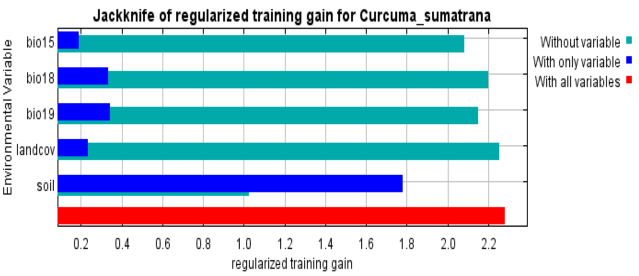

Figure 6. Jackknife analysis to potential distribution model of *Curcuma sumatrana*

Our findings showed a high Importance Value Index (IVI) for *M. tanarius*, indicating its significant role in ecosystem stability and forest recovery (Utama et al. 2012; Lee et al. 2020). The high IVI value of *C. canephora* in the *C. sumatrana* habitat indicates its ecological dominance, especially at the sapling stage. This is likely due to its deliberate commercial cultivation and its resilience in tropical soils, which enables it to compete effectively with native vegetation (Asigbaase et al. 2019). The habitat of *C. sumatrana* was also dominated by *D. stimulans*, which was the most abundant species, consistent with Ardiyani et al. (2011), noting the prevalence of *Laportea* (now *Dendrocnide*) at collection sites. The dominance of *Diplazium* sp. is linked to moist soils near water bodies (Juliasih and Adnyana 2023) and its use as a vegetable and in traditional medicine (Halimatussakdiah et al. 2020; Semwal et al. 2021). Dominant species typically adapt well to environmental conditions, as evidenced by their higher IVI (Smith 1977; Rambey et al. 2021). A higher IVI indicates greater stability and a better chance for species persistence and sustainability.

Our results indicate that the organic matter content in Lubuk Minturun is lower than in Koto Malintang, consistent with previous studies showing that sandy soils typically have lower organic matter than silty soils and exhibit poor nutrient retention ability (Ho et al. 2019; Spohn and Stendahl 2024). Soil pH is crucial for nutrient availability, as certain nutrients depend on pH levels (Wang and Kuzyakov 2024). Both research locations had slightly acidic soils within the optimal pH range for plant growth, with pH H_2O values of 6.25-6.36 and pH KCl values of 5.51-5.69. Healthy soils typically exhibit near-neutral pH, which maximizes nutrient availability (Syofiani et al. 2020). The pH values at both sites are characteristic of acrisol soils, classified as slightly acidic (Fathia et al. 2019).

Our findings from the soil samples collected from both research locations have significant implications. The chemical composition in Koto Malintang was generally higher compared to Lubuk Minturun. However, the available Phosphorus (P) content in Koto Malintang was lower than in Lubuk Minturun. Carbon (C) content was classified as high, with higher levels in Koto Malintang compared to Lubuk Minturun. Soils at a depth of 0-20 cm contain the highest levels of organic carbon, which decreases with increasing soil depth (Fathia et al. 2019; Spohn and Stendahl 2024).

In addition to carbon, nitrogen, and phosphorus, other essential macronutrients include cations such as Ca, Mg, K, and Na. These macronutrients are required by plants in large quantities. The Cation Exchange Capacity (CEC) in Lubuk Minturun is classified as low, while in Maninjau, it is considered moderate. Soils with high CEC indicate that they are capable of effectively absorbing and utilizing nutrients from fertilizers to support plant growth (Nhunda et al. 2024).

Another species from the Zingiberaceae family, *Z. macradenium* K.Schum. and Bilongkiang (*Zingiber* sp.), has been reported to thrive in environments rich in carbon (organic-C), which aligns with our research findings. The presence of Bilongkiang is highly influenced by soil pH, altitude, and moisture levels. This species grows well in environments with slightly acidic pH (Muharani 2022; Hermansah et al. 2023).

Koto Malintang is more exposed than Lubuk Minturun, aligning with previous research on *Curcuma* species, which thrive in partially shaded areas with light intensities of 59-73% (Hossain et al. 2009). We suggest that *C. sumatrana* is more adaptable to environments dominated by a few species, indicating a preference for habitats with lower biodiversity. The Shannon-Wiener Diversity Index (H') is commonly used to assess environmental conditions based on biological diversity (Haq et al. 2024), suggesting that species diversity at each growth stage is relatively stable. A plant community with higher values of species diversity is considered healthy and indicates greater community stability (Tan et al. 2024). Previous research found *C. sumatrana* in secondary forests at elevations of 100-500 masl (Ardiyani et al. 2011), which have moderate to high diversity indices (Solfiyeni et al. 2022). Environmental factors like precipitation, temperature, and soil type in low-diversity habitats may better support *C. sumatrana*'s growth. Other Zingiberaceae species, such as *Bilongkiang* (*Zingiber* sp.), also prefer habitats with lower diversity (Muharani et al. 2022).

Table 5. Contribution percentage permutation importance of key environmental factors of potential distribution model of *C. sumatrana*

Code	Variable	Contribution (%)	Permutation importance (%)	Value
Soil	Soil type in Sumatera	77.90	83.80	Acrisol and water body
Bio15	Seasonal precipitation	11.20	1.90	15-35
Bio18	Precipitation of the warmest quarter	4.80	2.60	500-800
Bio19	Precipitation of the coldest quarter	4.30	12.10	200-1000
Landcov	Land cover in Sumatra	1.70	0.50	Waterbody, shrubland, settlement

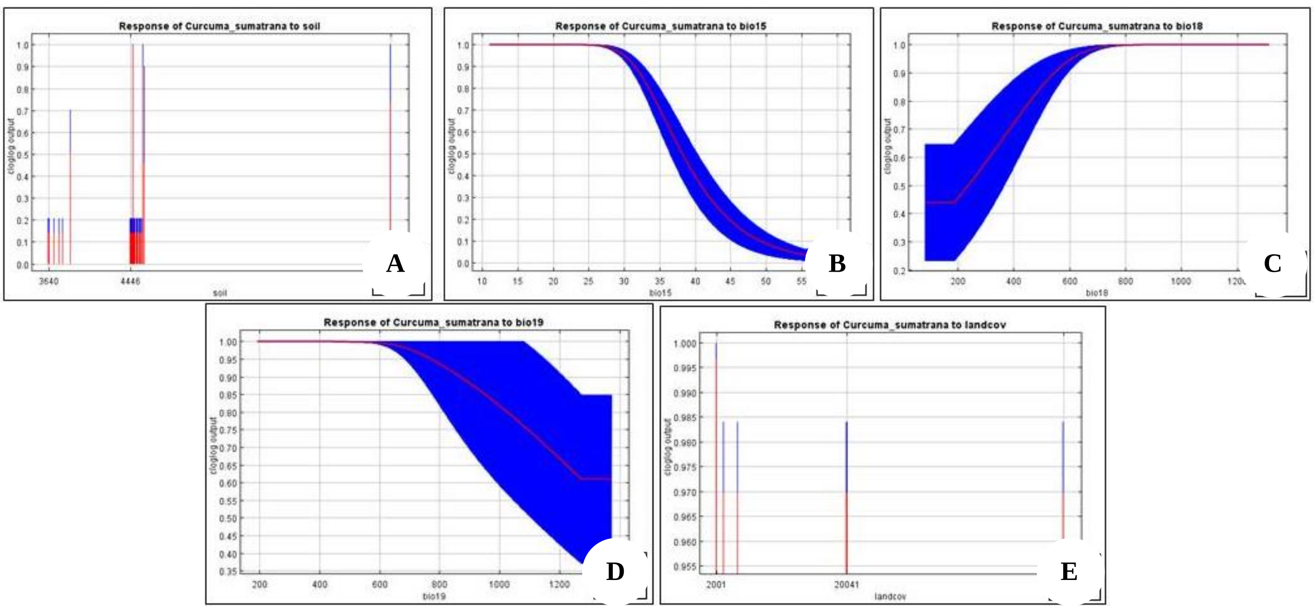

Figure 7. Response of *Curcuma sumatrana* to five key environmental factors: A. Soil type; B. Seasonal precipitation; C. Precipitation of warmest quarter; D. Precipitation of coldest quarter; E. Land cover. Average value

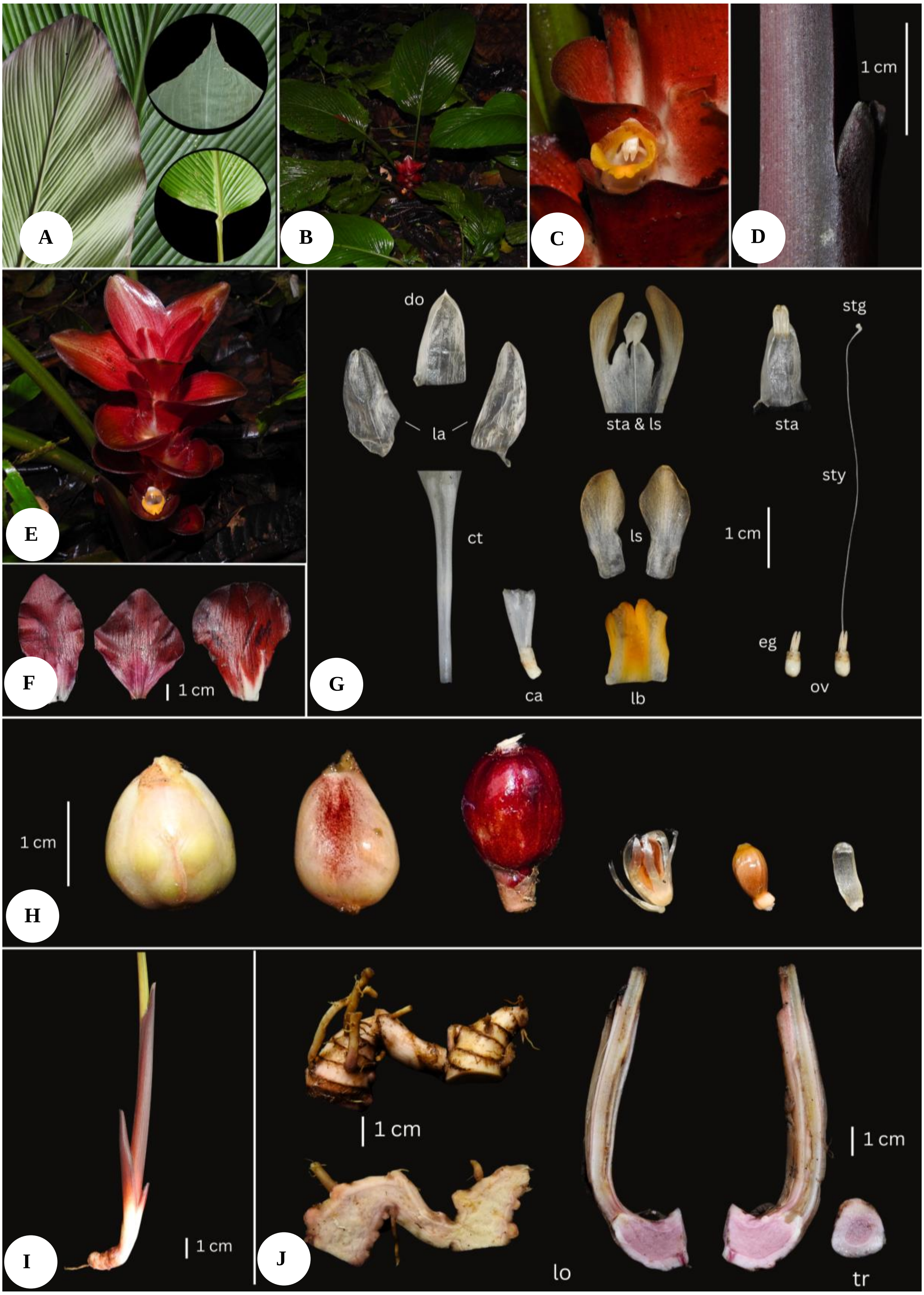

Figure 8. Morphological photograph of *Curcuma sumatrana*. A. Adaxial and abaxial side, apex, and base of leaves; B. Habit; C. Flower in bract; D. Ligule; E. Inflorescence; F. Coma bract and fertile bract; G. Flower dissection: do = dorsal corolla lobe, la = lateral corolla lobe, ct = corolla tube, ca = calyx, sta = stamen, ls = lateral staminodes, lb = labellum, stg = stigma, sty = style, eg = epigynous gland, ov = ovary; H. Fruit from young to ripe, seed, and aril; I. Sheathing bracts; J. Rhizome: lo = longitudinal section, tr = transverse section. Photos: Faradila Syafira; Firham Yasra (B,C,E)

The MaxEnt model demonstrates good performance in predicting the potential distribution of *C. sumatrana*. An AUC value between 0.90 and 0.95 indicates a good model, while values between 0.95 and 1.00 suggest excellence, reflecting a close approximation to real-world conditions (Harapan et al. 2022). The IUCN assessment indicates that *C. sumatrana* is facing habitat decline due to human activities and is likely to be classified as endangered in the future (Nurainas and Ardiyani 2019). Deforestation and agricultural expansion are identified as primary threats to many species in Indonesia, and reducing human activities is critical for the protection of rare taxa (Santoro et al. 2023; Suwardi et al. 2023a). The findings confirm that the distribution model's performance is accurate and reliable, significantly influenced by environmental factors, including climatic (light, temperature, precipitation), edaphic (soil properties, nutrient content, moisture, pH, slope), and biological factors (surrounding flora and fauna) (Zhang et al. 2018; Ali et al. 2023; Wang et al. 2023).

Our model shows that soil and precipitation significantly limits the distribution of *C. sumatrana*. Soil properties, in particular, have been shown to influence the habitat suitability of endangered species (Harapan et al. 2022). Previous studies on various taxa have indicated that precipitation is a more crucial factor for plant distribution than temperature (Song et al. 2016; Chen et al. 2017; He et al. 2021; Harapan et al. 2022; Mkala et al. 2023; Shi et al. 2024; Solfiyeni et al. 2024; Song et al. 2024; Wang and Wang 2024). Additionally, land cover is also a major factor affecting *C. sumatrana*'s distribution, consistent with earlier findings that emphasize its importance (Daï et al. 2023; Li et al. 2024). Beyond these variables, plant modeling and distribution are influenced by temperature and solar radiation (Pradhan 2015; Gunawan et al. 2021; Fitriani et al. 2022; Gong et al. 2022; Gufi et al. 2023; Gunawan et al. 2023; Hou et al. 2023). Slope can also affect the distribution of some plant species (Yi et al. 2016; Abolmaali et al. 2018).

This study presents, for the first time, the potential distribution of *C. sumatrana* in suitable habitats based on current climatic data. Understanding the distribution and habitat suitability of a species is crucial for informed management and effective conservation strategies (Suwardi et al. 2023b). These findings may improve *C. sumatrana* conservation efforts in Sumatra, with in situ conservation planning and increasing individual populations identified as the most effective approaches. Special attention should be directed towards the species' native habitat, particularly the Lembah Anai Nature Reserve, where recent field surveys have reported the absence of this species. This habitat loss is most likely caused by habitat degradation due to forest conversion into tourist areas and changes in land use caused by the local community's limited conservation of understanding (BKSDA 2012). Additionally, infrastructure development near forest areas and natural disasters have negatively impacted the Lembah Anai Nature Reserve. The increasing dominance of invasive species also raises concerns about the potential decline of native and rare species diversity in the area (Solfiyeni et al. 2016).

It can be concluded that morphometric characterization of the *C. sumatrana* population needs to show a clear separation. However, leave length, width, and ligule length differed significantly among individuals. The Koto Malintang population was significantly different from Lubuk Minturun, with a tendency for lamina to be narrowly elliptic or broadly elliptic. The *C. sumatrana* grows better in fertile soils with fewer surrounding plants and moderate diversity, thriving in more open areas. The potential spatial distribution in the western Bukit Barisan, modeled using Maximum Entropy, demonstrates high performance, enhancing the reliability of our research. The main environmental factors influencing distribution include soil type, seasonal precipitation, precipitation during the warmest and coldest quarters, and land cover type.

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