Accuracy Assessment of Andaliman (*Zanthoxylum acanthopodium* DC) Growth Suitability using Google Earth Engine and Presence Data

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Abstract: *Andaliman (Zanthoxylum acanthopodium DC.), known as Batak pepper, is a spice plant found in the highlands around Lake Toba in North Sumatra, Indonesia. Despite its ecological and economic importance, Andaliman is losing its habitat due to land conversion, climate change, and limited farming methods. The lack of detailed information on suitable habitats makes conservation and sustainable management challenging. Remote sensing and species distribution modeling can address this issue through cloud-based platforms. This study used the Maximum Entropy (MaxEnt) model to predict the suitability of Andaliman's habitat. It included Sentinel-2A NDVI (2025), elevation from the DEM (2025), and average rainfall data from 2024 to 2025 within the Google Earth Engine (GEE) framework. Presence-only data were collected from 158 GPS points surveyed in the field in 2025, with spatial thinning applied to reduce autocorrelation. To ensure reliable predictions, the study employed 5-fold spatial block cross-validation and assessed model accuracy using AUC. The MaxEnt model displayed high predictive accuracy, achieving an AUC of 0.898. The DEM proved to be the most important predictor, accounting for 81%, while NDVI accounted for 18% and rainfall for 1.1%. This study provides the first spatially validated habitat suitability map for Andaliman, utilizing GEE and MaxEnt. It also shows how effective cloud-based remote sensing can be for modeling local crops. The results indicate key areas for conservation and cultivation, creating a framework that supports Nature-Based Solutions in the Lake Toba region. Overall, this study demonstrates the potential of combining Sentinel-2A imagery, climate data, and spatial validation to model species distributions in tropical mountain ecosystems.*

Keywords: Andaliman suitability, Google Earth Engine, MaxEnt modeling, Sentinel-2A, Zanthoxylum acanthopodium

Introduction

Andaliman (*Zanthoxylum acanthopodium*), known locally as "Batak pepper," is a spice plant native to the highlands of North Sumatra in Indonesia. It plays an important role in traditional agroforestry systems and provides significant benefits to local communities. However, Andaliman habitats are increasingly under threat due to land conversion, climate change, and a lack of organized cultivation and conservation efforts. Thus, identifying suitable areas for Andaliman growth is crucial for its long-term sustainability and conservation.

Worldwide, the use of species distribution modeling (SDM) has grown rapidly to predict the habitat suitability of crops and native species. However, few studies focus on native spice plants in Asia, particularly those with narrow ecological ranges, such as Andaliman. While SDM methods, such as MaxEnt, have been widely used for cash crops and invasive species, there is a noticeable gap in the literature on the systematic use of cloud-based remote sensing tools, such as Google Earth Engine (GEE), to model the suitability of lesser-known tropical spice plants.

Using GEE and Sentinel-2A imagery adds value not only for ecological insights but also for improving remote sensing methods. Sentinel-2A, with its high spatial resolution and red-edge bands, enables accurate calculation of vegetation indices. GEE facilitates large-scale, reproducible, and efficient modeling workflows. By combining NDVI, topographic factors (elevation), and climatic data (rainfall), SDM for Andaliman can illustrate the potential of cloud-based geospatial platforms for scalable, adaptable, and accessible methods that extend beyond local conservation, thereby contributing to wider geospatial modeling practices (Kass et al., 2021; Lasaponara et al., 2022).

In Indonesia, most research on Andaliman focuses on ethnobotany and postharvest studies, with limited exploration of spatial habitat modeling. Therefore, this study addresses both local and global research gaps: (1) the urgent need for an accurate habitat suitability assessment of an endemic threatened species, and (2) the demonstration of a cloud-based, replicable SDM framework relevant to the global geospatial community. Specifically, this study aimed to evaluate (i) environmental and vegetation variables influencing Andaliman distribution, (ii) the accuracy of the MaxEnt model using presence-only data, and (iii) spatial patterns of suitability across North Sumatra, with an emphasis on methodological rigor in spatial validation and transferability.

Literature Review

Remote sensing-based suitability modeling now relies on a combination of Sentinel-2A (10–20 m resolution, red-edge channel) and Google Earth Engine (GEE) for large-scale pre-processing, making workflows (such as cloud masking and annual composites) replicable and efficient. Recent studies have shown that the Sentinel-2 NDVI series in GEE is sensitive to pixel-level vegetation changes and conditions, which is relevant for extracting the habitat gradients of target species. Thus, GEE serves as more than a data processing tool; it enables a transparent, auditable, cloud-native workflow for human resources, offering methodological value that extends beyond local conservation through its emphasis on scalability, reproducibility, and open access (Lasaponara et al., 2022).

In general, NDVI has been proven to be a strong predictor of canopy vigor and land cover conditions. However, there is still a lack of research on endemic spice species such as Andaliman, which have narrow niches and depend on humid highlands. Recent syntheses have emphasized that accuracy improves when NDVI is combined with topography (elevation) and climate (rainfall) at similar spatial resolutions. However, specific applications of mountain spice commodities have rarely been reported. This study addresses this gap using an NDVI-DEM-rainfall predictor configuration within the GEE framework. In this way, the contribution extends beyond producing habitat maps to demonstrating best practices in integrating biophysical variables within cloud-based SDM (Lasaponara et al., 2022).

For climate, CHIRPS provides stable high-resolution precipitation for the 2024–2025 aggregation, capturing the latest conditions in Andaliman. In contrast, DEM (elevation) controls microclimate, drainage, and erosion potential, which influence growth performance in the mountains of North Sumatra. The combined NDVI, rainfall, elevation consistently improved model discrimination compared to a single predictor. Thus, this set of variables is both ecologically and practically relevant for landscape-scale modeling (Bolvin et al., 2020).

In the presence of only SDM, MaxEnt remains the de facto standard; however, its performance is strongly influenced by the selection of appropriate background, feature class, and regularization parameters to avoid overfitting. Current best practices require systematic tuning (ENMeval 2.0) and spatial block-based evaluation to mitigate the bias caused by autocorrelation. This approach enhances both reliability and transferability to new locations, which is essential when maps are applied for survey prioritization and the designation of cultivation areas. In other words, the methodological contribution of this study lies in the adoption of a spatially tuned and validated MaxEnt pipeline on cloud-native data (Fielding & Bell, 1997; Kass et al., 2021).

Accuracy assessment should go beyond AUC, incorporating threshold analysis to convert probabilities into operational classes (highly suitable versus unsuitable). Standardized and auditable SDM reporting protocols are also recommended to ensure a clear data–method–evaluation flow for replication and review. This is in line with the 2020–2024 SDM methodological trend that emphasizes spatial validation as a mandatory component (Zurell et al., 2020).

Recent studies have shown that point sampling bias, which tends to concentrate in easily accessible locations, can artificially increase model performance when the background is poorly designed. Two recommended solutions are using file/strata bias to form a background comparable to the sampling process and implementing spatial blocking during the validation. This design shifts the focus from the mere goodness-of-fit to the ability to generalize. Consequently, suitability maps are more reliable for predicting new locations than for those that have been extensively sampled (Broussin et al., 2024).

For Andaliman, the latest literature confirms a preference for humid highlands, identifying elevation, rainfall, and canopy conditions (NDVI) as the primary determinants of suitability. Beyond ecology, bioactivity studies highlight the conservation-economic value of Andaliman, making methodologically robust suitability mapping a strategic necessity. By combining NDVI (2025), DEM (20250, and average rainfall (2024-2025) within a spatially tuned and validated MaxEnt framework, this study utilized state-of-the-art SDM for endemic spice species. This context connects remote sensing science with conservation and cultivation decision-making for Andaliman (Bald et al., 2023; Nurlaeni et al., 2024).

Methodology

a. Data dan Citra

This study utilizes Sentinel-2A imagery with a spatial resolution of 10–20 m, accessed through GEE, for the period from January to December 2025. The red and near-infrared channels were used to calculate the Normalized Difference Vegetation Index (NDVI), a proxy for canopy conditions. In addition, the 2025 Digital Elevation Model (DEM) was used to create the elevation maps. Average rainfall data for 2024-2025 were obtained from global satellite datasets, such as CHIRPS, to capture the latest climate conditions. This combination of biophysical variables was chosen because it has been proven to be relevant in modeling species distribution in tropical mountain ecosystems (Drusch et al., 2012; Funk et al., 2015).

Presence-only data for Andaliman were collected through field surveys conducted in February and March 2025, using high-precision GPS in the Lake Toba region of North Sumatra. Sampling points were distributed across several key locations representing diverse ecological conditions, including Ronggur Nihuta Village, Salaon Dolok Village, Janji Maria Village, Dairi, Taman Eden, Lumban Julu Village, Silaen Village, and Sibaganding Village (Figure 1). These presence points (158) represented the actual locations of the species and served as the primary input to the MaxEnt model. Because MaxEnt works optimally with presence-only data, selecting representative training points is crucial for reducing spatial bias. To strengthen the model, these data were split into a test set (70%) and a training set (30%). This strategy aligns with contemporary species distribution modeling practices, which utilize presence-only data (Vollering et al., 2019). The distribution of the sampling points is shown in Figure 1.

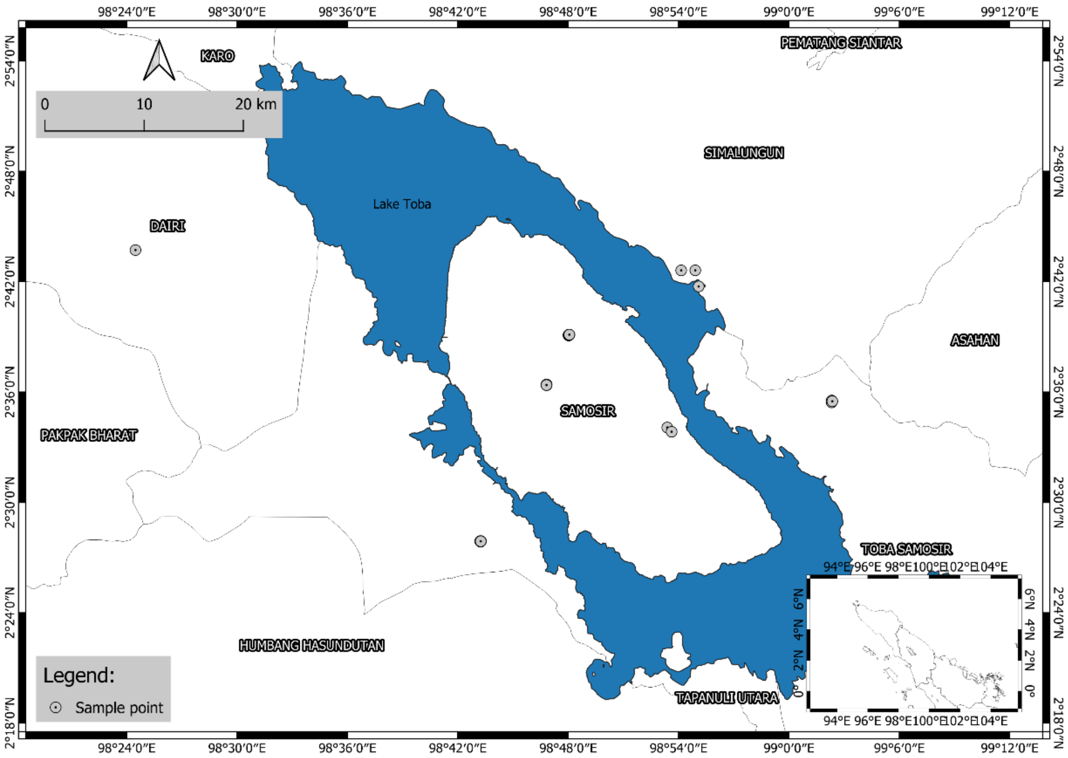

Figure 1. Distribution of reliable sampling points taken from February to March 2025 in the Lake Toba area.

c. Data Pre-processing dan Variable Extract

Image pre-processing in GEE was carried out in the following stages: cloud masking with the s2cloudless algorithm, creation of a 2025 median composite, and calculation of NDVI using the formula (B8 – B4)/(B8 + B4). From the DEM, elevation maps were derived using GEE spatial operators, and rainfall data were calculated as a two-year average (2024-2025) to obtain stable spatial values. Next, all variables were projected to a uniform spatial resolution of 10 m and extracted to determine the presence and background points. This combined dataset was used as the input for the classification model. Similar steps have been applied to model the suitability of forest tree growth and agricultural yields in various landscapes (Lasaponara et al., 2022).

d. Modeling and Accuracy Assessment

Modeling was performed using MaxEnt 3.4.4 with 158 background points and an initial regularization multiplier of 1.0. To avoid overfitting, simple tuning was performed on the feature class combinations (linear, quadratic, and hinge). Accuracy validation was performed using 5-fold spatial block cross-validation, in which the study area was divided into five spatial blocks with a proportional distribution of the presence and background. This method produced a more conservative accuracy estimate and reduced spatial bias, in accordance with the latest literature.

The model was replicated 5 times, with a maximum of 1,000 iterations per run. The replication process reduces the influence of random variation, enhances the robustness of the results, and enables the estimation of variability across different runs. Increasing the number of iterations to 1,000 ensured that the optimization algorithm converged properly, particularly when using complex feature combinations or when the dataset involved heterogeneous environmental variables. These settings are widely recommended for enhancing the reliability and stability of habitat suitability predictions. The use of MaxEnt in ecology has proven effective in mapping the habitats of endemic and threatened plants with high accuracy (An et al., 2021).

Model performance was evaluated using the Area Under the Curve (AUC), which provides information on discrimination and the balance of sensitivity and specificity. In addition, MaxEnt produces variable-contribution analyses and response curves to identify the relative influence of NDVI, elevation, and rainfall on Andaliman's suitability. The analysis pipeline consists of five stages: (1) data input (Sentinel-2, DEM, CHIRPS, presence GPS), (2) image pre-processing in GEE, (3) variable extraction to presence-background points, (4) MaxEnt modeling with 5-fold spatial validation, and (5) output in the form of probability maps, suitability classes, and variable analysis. This multi-stage approach aligns with modern SDM trends that emphasize workflow transparency and reproducibility (Bald et al., 2023).

Results and Discussion

a. Prediction distribution

A total of 158 Andaliman locations were collected in 2025 from various land cover types, including plantation forests, shrublands, dryland agriculture, mixed agriculture, and rice fields in North Sumatra (**Figure 1**). This distribution pattern confirms Andaliman's ecological preference for humid mountainous environments. According to Siahaan et al. (2019), this species is commonly found in secondary forests and open land with temperatures of 15-18 °C, an altitude of approximately 1,300 m above sea level, acidic soil (pH 3.0-4.5), annual rainfall of 1,600-1,850 mm, and sandy loam texture with good drainage. This study also found distributions of andaliman presence in a DEM range of 1000 to 2000 m above sea level (Figure 2), NDVI values of 0.3 to 1 (Figure 3), and rainfall of 1200 to 1600 mm/year (**Figure 4**). This basic information is important for developing an ecological framework for remote sensing-based suitability modeling.

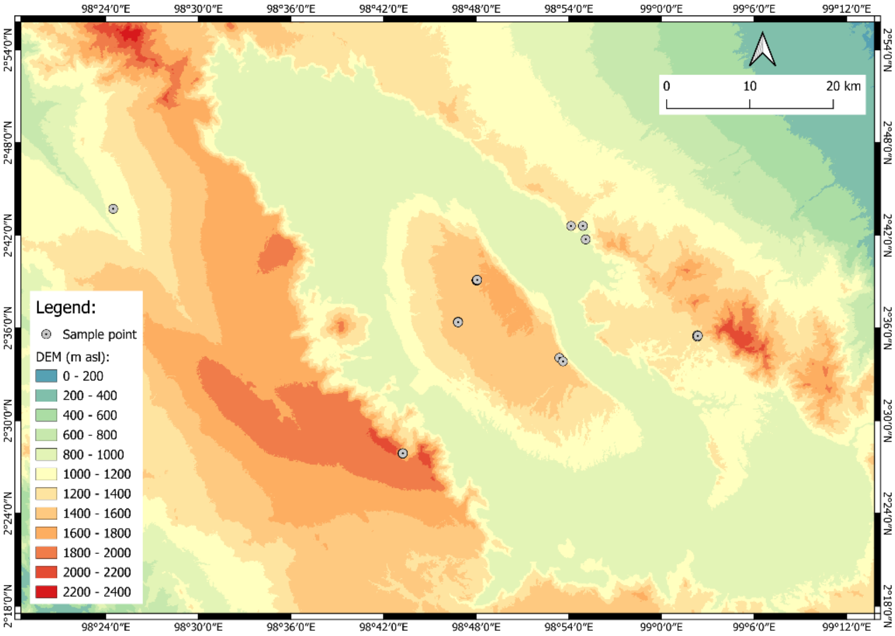

Figure 2. Distribution of andaliman locations based on the DEM of the Lake Toba area, North Sumatra

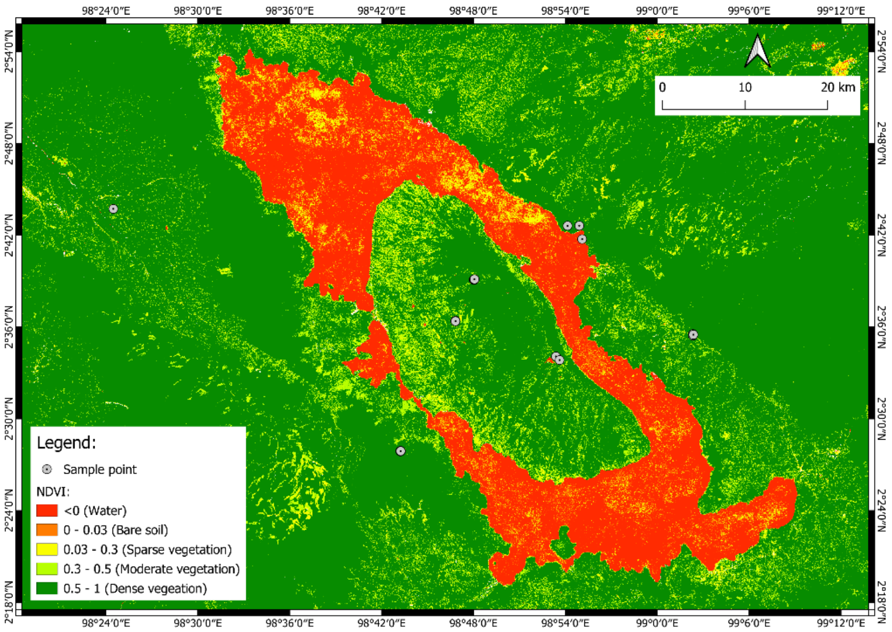

Figure 3. Distribution of andaliman locations based on NDVI on the Lake Toba area, North Sumatra

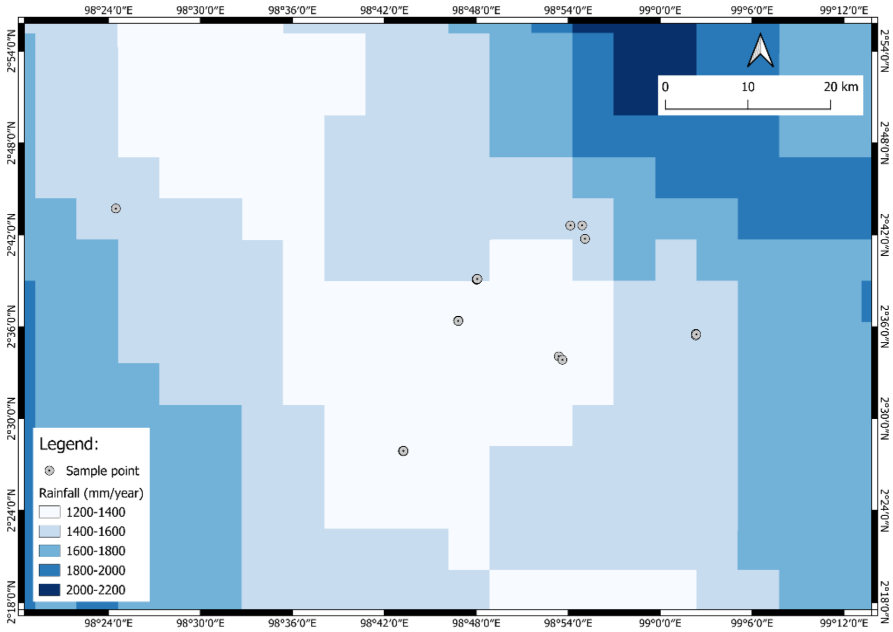

Figure 4. Distribution of andaliman locations by rainfall in the Lake Toba area, North Sumatra.

b. Contribution of Environmental Variable

The uneven distribution of points makes the use of pseudo-absence and block-based spatial validation crucial steps in reducing bias (Condro et al., 2020; Rahman et al., 2022). With this approach, the MaxEnt model produced high performance, as indicated by an AUC of 0.898 ± 0.02 (**Figure 5**). An AUC value above 0.8 indicates excellent discrimination between suitable and unsuitable habitats, indicating that the model can reliably separate areas with high and low probabilities of Andaliman occurrence. However, the high AUC value in these results may also be due to the narrow distribution of occurrence points sampled during the study. Taken together, these metrics show that the Andaliman suitability map is both statistically sound and ecologically interpretable, making it a reliable tool for guiding conservation strategies and cultivation planning in highland ecosystems in Indonesia.

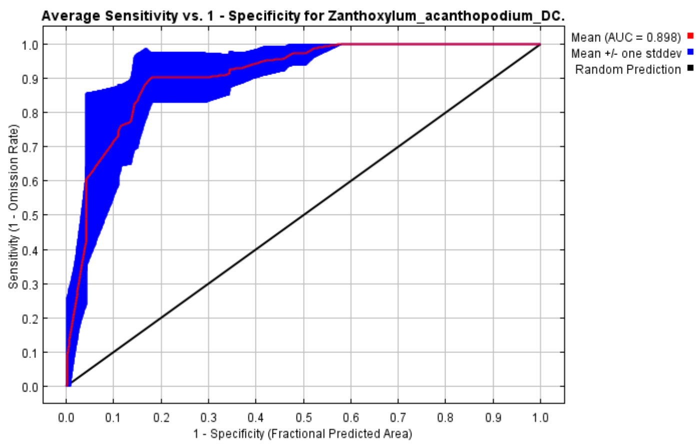

Figure 5. AUC graph in the habitat suitability modeling of Andaliman.

Compared with similar studies, this research's results demonstrate model performance comparable to or slightly higher than that for other endemic or economically significant species in tropical montane ecosystems. The AUC value of 0.898 achieved in this study indicates excellent model discrimination and reliability in predicting the suitability of Andaliman habitats. This level of accuracy aligns closely with findings from (Wardatutthoyyibah et al., 2019) who reported an AUC of 0.88 in modeling the distribution of Proboscis monkeys using bioclimatic predictors in North Sumatra. Such consistency confirms that integrating remote sensing and environmental variables into MaxEnt modeling effectively captures the ecological gradients that govern species distributions in complex mountainous landscapes.

The environmental factors utilized to forecast the habitat suitability of Andaliman in this research consisted of (1) DEM, (2) NDVI, and (3) rainfall. Their impact on the MaxEnt prediction is demonstrated in the response curves (Figure 6), which show the likelihood of species occurrence as a function of the resemblance of environmental traits among the selected variables. In this context, MaxEnt produced results indicating anticipated shifts in occurrence likelihood due to changes in each environmental factor. The model was run with 5 replicates, and the variable with the highest correlation with Andaliman presence was elevation (DEM).

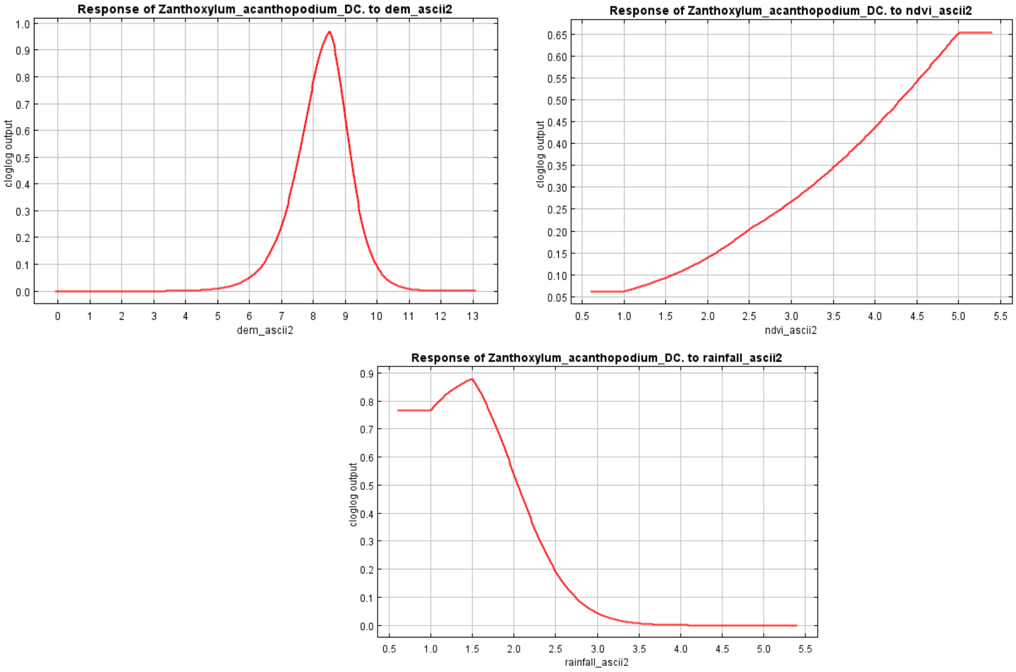

Figure 6. Response curves of *Zanthoxylum acanthopodium* generated by the MaxEnt model showing the relationship between species presence probability and environmental variables: (a) elevation (DEM), (b) vegetation index (NDVI), and (c) rainfall.

The examination of variable impacts showed that elevation (DEM) was the most influential factor in forecasting habitat suitability, with a percent contribution (PC) of 80.0% and permutation importance (PI) of 68.8% (**Table 1**). The elevated values of both parameters suggest that elevation offers the strongest explanatory power for distinguishing between suitable and unsuitable regions. This discovery suggests that topography, as illustrated by the DEM, significantly impacts the distribution of Andaliman by altering essential environmental gradients, including temperature, soil type, and microclimatic conditions. In MaxEnt modeling, this high contribution indicates that the DEM significantly improves model performance. Even when shuffled, it results in a notable drop in predictive accuracy, affirming that elevation provides distinct and non-redundant information that is not offset by other factors.

Table 1. Analysis of the contribution of environmental variables to the growth habitat of Andaliman.

Variable	Percent contribution (PC)	Permutation important (PI)
DEM	80.0	68.8
NDVI	18.1	30.2
Rainfall	1.1	0.9

The role of NDVI (PC 18.1%; PI 30.2%) further underscores the significance of vegetation cover in influencing the probability of Andaliman presence. Although NDVI has a smaller impact on overall model performance during training, its notable permutation importance suggests that it provides additional insights beyond elevation. NDVI indicates canopy density and plant vitality, which are essential for preserving soil moisture, managing microclimate, and ensuring ecological stability, elements recognized for affecting the growth and survival of andaliman. This suggests that within the suitable elevation range, regions with higher NDVI values are more likely to provide conducive microhabitats that support robust Andaliman populations, underscoring the combined influence of topography and vegetation structure in defining its ecological niche.

Conversely, rainfall had a slight effect, with a PC of 1.1% and a PI of 0.9%, suggesting that precipitation fluctuations have a minimal impact on the model's overall predictive capability. This finding suggests that rainfall may not limit Andaliman distribution in the study area, likely because precipitation patterns are consistent across the Lake Toba highlands. Additionally, rainfall may be indirectly reflected in other factors, such as the NDVI, which combines long-term moisture levels and vegetation responses. Collectively, these findings indicate that elevation is the primary factor determining the suitability of the Andaliman habitat. In contrast, NDVI enhanced the prediction by integrating vegetation-related ecological details, and rainfall had only a minor impact on shaping the spatial distribution of this highland-endemic species. These results reinforce the findings of Siahaan et al. (2019), who reported that andaliman is commonly found in highland areas with rainfall of approximately 1, 600 mm/year, where sandy clay soil with good drainage allows for ideal water distribution. Thus, rainfall not only determines soil water availability but also acts as a microclimate controller that supports Andaliman productivity in its natural habitat.

The jackknife test of the AUC for *Zanthoxylum acanthopodium* (**Figure 7**) provides a clear visualization of the relative importance and unique contribution of each environmental variable to the model's predictive performance. When used independently, the elevation variable (DEM) yielded the highest AUC value among all predictors, indicating that it contained the most relevant information for species' distribution. In contrast, NDVI and rainfall produced markedly lower AUC values when used alone, signifying weaker explanatory power. The substantial decrease in AUC when DEM was excluded from the model further reinforces the conclusion that topography is indispensable for determining Andaliman's habitat suitability. This pattern supports the interpretation that the DEM not only defines the fundamental ecological envelope of Andaliman but also serves as a proxy for several biophysical gradients, such as temperature and soil moisture, that directly influence the species' growth and reproduction.

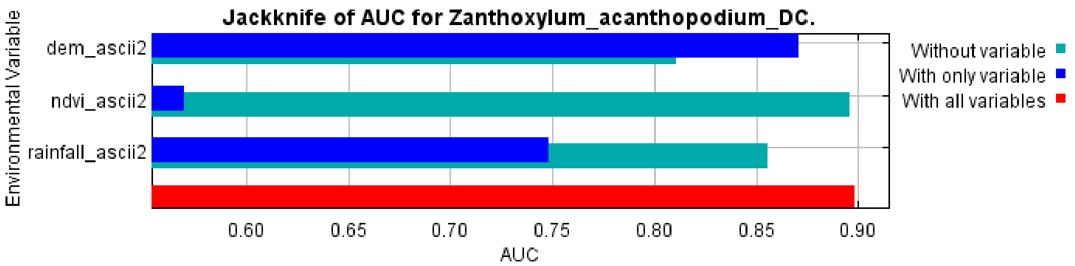

Figure 7. Graph showing the effect of environmental variables on Andaliman using Jackknife analysis.

From an ecological and management perspective, our results emphasize that elevation delineates the broad environmental limits of Andaliman. Simultaneously, NDVI refines predictions within these elevational zones by considering vegetation health and canopy stability. The jackknife output suggests a hierarchical relationship among the predictors, with

DEM establishing the spatial extent of suitable habitats and NDVI differentiating between degraded and stable forest patches. This finding has practical implications for conservation and cultivation: mid- to high-elevation areas with high NDVI values should be prioritized for field validation, protection, and potential cultivation trials. Furthermore, the strong dependence on DEM highlights the need to include additional topographic and microclimatic variables, such as slope, aspect, or insolation, in future model iterations to reduce proxy bias and enhance ecological realism.

c. Spatial Patterns of Suitability

The habitat suitability map generated by the MaxEnt model (**Figure 8**) illustrates the spatial probability of Andaliman occurrence across the Lake Toba landscape, ranging from low suitability (0.0–0.3, indicated by blue tones) to very high suitability (0.77–0.92, indicated by red). Warmer colors indicate areas with environmental conditions most favorable for Andaliman growth, primarily in the mid- to high-elevation zones surrounding the lake, particularly in the western, southern, and central highland regions. These high-suitability areas correspond to elevations typically between 1,200 and 1,500 m above sea level, where cooler temperatures, well-drained volcanic soils, and dense vegetation canopy create ideal microclimatic conditions for andaliman development. Moderate-suitability zones (0.38–0.69, green–yellow) extend into transitional slopes, where environmental gradients, such as temperature and vegetation structure, begin to shift. Conversely, the low-suitability regions (0.0–0.23, blue) dominated the lower-elevation and lakeshore zones, where higher temperatures and anthropogenic disturbance likely limit Andaliman establishment and regeneration.

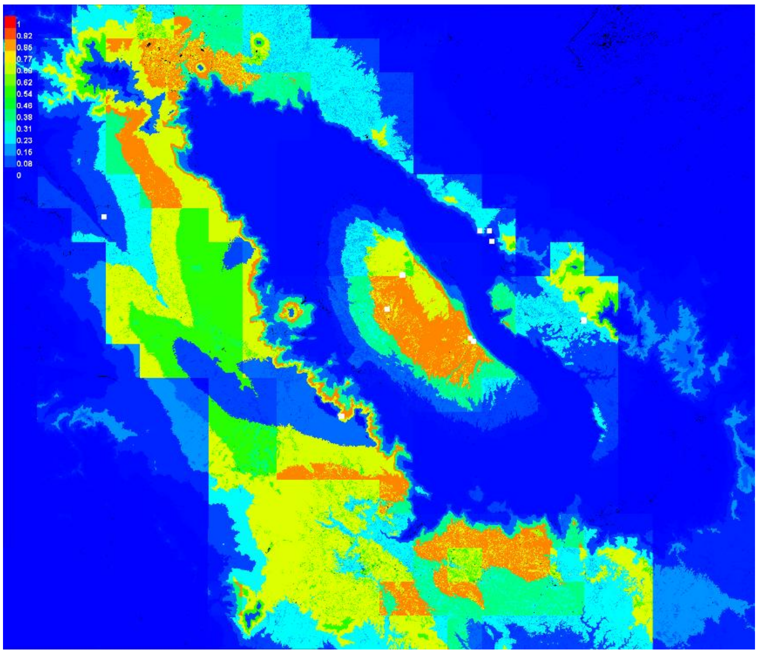

Figure 8. Habitat suitability map for *Zanthoxylum acanthopodium* in the Lake Toba region generated using the MaxEnt model, showing probability values ranging from low (blue, <0.3) to very high suitability (red, >0.8).

The spatial alignment between the model predictions and occurrence data, represented by white (training points) and violet (testing points) dots, demonstrates a high degree of model reliability. Most observed presences occurred in areas predicted to be highly suitable, indicating that the MaxEnt model effectively captured the key ecological gradients shaping Andaliman's distribution. This strong agreement suggests that elevation (DEM) is the dominant controlling factor, with NDVI serving as an indicator of vegetation stability and canopy density. This pattern is ecologically consistent with other highland aromatic species that exhibit similar topographic dependencies, such as *Zanthoxylum armatum*, which thrives in humid montane environments with moderate rainfall and fertile volcanic soils (Tian et al., 2022; Zheng et al., 2022). The concentration of high-suitability areas along the caldera rim suggests that Andaliman is strongly associated with the Lake Toba highland ecosystem, characterized by rich biodiversity and complex terrain. These findings reinforce the importance of topography-driven niche differentiation (Allouche et al., 2006) and highlight the potential for identifying new conservation and cultivation zones, particularly within intact highland forest corridors that maintain stable canopy cover and minimal human disturbance.

According to Chen et al. (2021), this spatial pattern underscores that Andaliman has a restricted ecological niche, unlike other highland commodities that are more resilient to environmental changes. These findings confirm the role of humid mountain zones as micro-refugia that must be protected by adaptive agroforestry, forest cover protection, and reforestation. Examination of variations between folds revealed that the transition zone between the "suitable" and "marginal" categories exhibited greater prediction uncertainty, attributed to biophysical diversity that cannot be fully accounted for by just three primary predictors. Conversely, the "highly suitable" and "unsuitable" regions generally remained consistent with minimal deviations. This uncertainty data is crucial for decision-makers, as it helps identify areas that require further field verification before being prioritized for conservation (Múrria et al., 2020). This difference can be explained by Andaliman's more specific niche, which environmental predictors capture more easily. This demonstrates the significant potential of MaxEnt-GEE-based modeling for endemic spice commodities, which have rarely been the focus of global studies.

Only a small portion of the region is truly suitable for andaliman, and the threat of land conversion could further narrow this area. Therefore, the results of this map are important for establishing protection zones and supporting both in-situ and ex-situ conservation strategies (Zhang et al., 2022). Conversely, areas with high suitability can be designated as Andaliman cultivation centers to strengthen the economic resilience of mountain communities. With this approach, remote sensing-based modeling contributes not only to the conservation of endemic species but also to the development of sustainable agriculture (Branco et al., 2021)

Conclusion and Recommendation

This study demonstrates that integrating MaxEnt modeling with Google Earth Engine provides a powerful and reliable approach for mapping the habitat suitability of Andaliman in the Lake Toba highlands. The model achieved high predictive accuracy (AUC ≈ 0.90) and revealed that elevation is the dominant factor controlling Andaliman distribution. At the same time, vegetation condition (NDVI) serves as an important secondary factor refining habitat prediction within the suitable elevation range. Rainfall had only a minor effect, suggesting that topography and canopy structure play a greater role in shaping Andaliman's ecological niche. The most suitable areas were identified between 1,200 and 1,500 m above sea level along the caldera rim, where the model's predictions aligned closely with field observations. Based on these findings, conservation and cultivation efforts should focus on mid- to high-elevation zones with healthy canopy cover to ensure ecological sustainability and economic benefits for local communities. Future research should incorporate additional variables, such as slope, aspect, and temperature, to improve model precision and reduce proxy effects. Regular updates using Sentinel-2 time-series data are also recommended to monitor habitat changes, refine predictions, and support adaptive management for the conservation and sustainable cultivation of Andaliman in North Sumatra.

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