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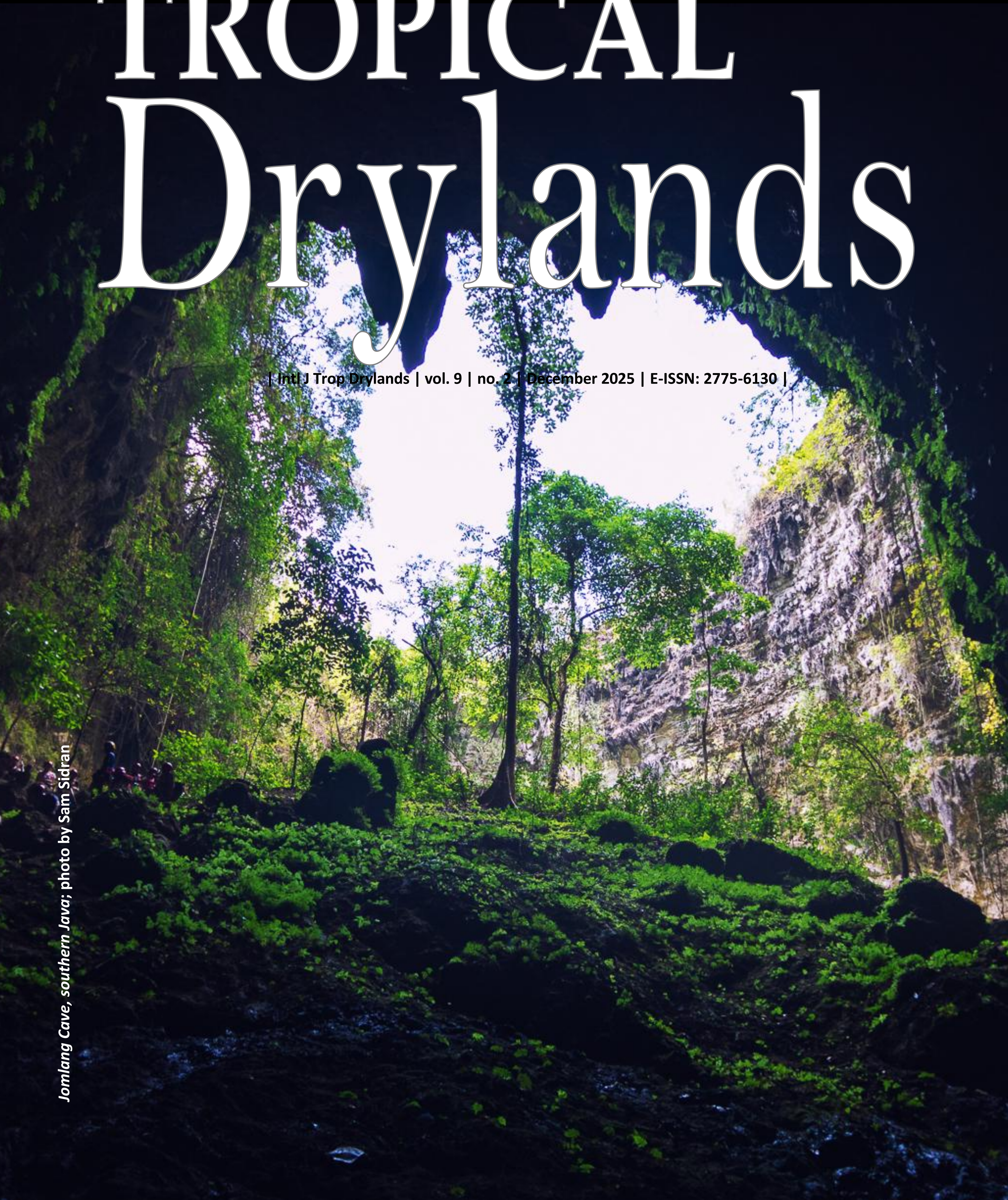

Jomlang Cave, southern Java; photo by Sam Sidran

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Introduction is about 600 words, covering the aims of the research and provide an adequate background, avoiding a detailed literature survey or a summary of the results. **Materials and Methods** should emphasize on the procedures and data analysis. **Results and Discussion** should be written as a series of connecting sentences, however, for a manuscript with long discussion should be divided into subtitles. Thorough discussion represents the causal effect mainly explains why and how the results of the research were taken place, and do not only re-express the mentioned results in the form of sentences. **Concluding** sentence should be given at the end of the discussion. **Acknowledgements** are expressed in a brief; all sources of institutional, private and corporate financial support for the work must be fully acknowledged, and any potential conflicts of interest are noted.

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Journal:

Saharjo BH, Nurhayati AD. 2006. Domination and composition structure change at hemic peat natural regeneration following burning; a case study in Pelalawan, Riau Province. Biodiversitas 7: 154-158. DOI: 10.13057/biodiv/d070213.

The usage of "et al." in long author lists will also be accepted:

Smith J, Jones M Jr, Houghton L et al. 1999. Future of health insurance. N Engl J Med 965: 325-329. DOI: 10.10007/s002149800025.

Book:

Rai MK, Carpinella C. 2006. Naturally Occurring Bioactive Compounds. Elsevier, Amsterdam.

Chapter in the book:

Webb CO, Cannon CH, Davies SJ. 2008. Ecological organization, biogeography, and the phylogenetic structure of rainforest tree communities. In: Carson W, Schnitzer S (eds.). Tropical Forest Community Ecology. Wiley-Blackwell, New York.

Abstract:

Assaeed AM. 2007. Seed production and dispersal of *Rhazya stricta*. 50th annual symposium of the International Association for Vegetation Science, Swansea, UK, 23-27 July 2007.

Proceeding:

Alikodra HS. 2000. Biodiversity for development of local autonomous government. In: Setyawan AD, Sutarno (eds.). Toward Mount Lawu National Park; Proceeding of National Seminary and Workshop on Biodiversity Conservation to Protect and Save Germplasm in Java Island. Universitas Sebelas Maret, Surakarta, 17-20 July 2000. [Indonesian]

Thesis, Dissertation:

Sugiyarto. 2004. Soil Macro-invertebrates Diversity and Inter-Cropping Plants Productivity in Agroforestry System based on Sengon. [Dissertation]. Universitas Brawijaya, Malang. [Indonesian]

Information from the internet:

Balagadde FK, Song H, Ozaki J, Collins CH, Barnet M, Arnold FH, Quake SR, You L. 2008. A synthetic *Escherichia coli* predator-prey ecosystem. Mol Syst Biol 4: 187. DOI: 10.1038/msb.2008.24. www.molecularsystembiology.com.

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Modelling drought-tolerant *Sorghum bicolor* distributions in Eastern Indonesia using machine learning approaches

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Abstract. *Utomo SW, Wibowo AA, Lestari F. 2025. Modelling drought-tolerant* Sorghum bicolor *distributions in Eastern Indonesia using machine learning approaches. Intl J Trop Drylands 9: 99-110.* Tropical arid ecosystems require alternative species that are drought-tolerant. *Sorghum bicolor* (L.) Moench has been considered an alternative, drought-tolerant species. Despite its resistance to drought, information on the potential distribution of sorghum is very limited. This information is very important, especially in arid eastern Indonesia, where sorghum is nominated as an alternative species to sustain food security. This study aims to model the potential distribution of *S. bicolor* using machine learning (random forest), geoclimate (Bioclim), and statistical methods (GAM/GLM) on five arid islands, including Lombok, Sumba, Sumbawa, Flores, and the Timor Islands, Indonesia. Area Under Curve (AUC) was used to evaluate model performance. In general, all the models confirm that Timor, followed by Sumbawa and the Flores Islands, have large, suitable areas for sorghum. It is estimated that up to 99.71% of arid island ecosystems in eastern Indonesia are suitable for sorghum. The geoclimate and machine learning models generated the highest values for AUC in comparison to statistical methods in which the Domain model is 0.962, SVM is 0.903, and both GLM and GAM are 0.894. It is important for plant cultivation planning to consider species distribution modeling and not rely on any single modeling method. The plant cultivation should evaluate the performance of all available models for their crops and area of interest, and select the best representative methods to develop an accurate and representative sorghum crop distribution model.

Keywords: Arid, AUC, machine learning, model, sorghum

INTRODUCTION

The region in eastern Indonesia, which includes the five islands of Lombok, Sumbawa, Sumba, Flores, and Timor Islands, is distinguished by a dry climate and a predominance of desert habitats. Grasslands and shrublands predominate in these tropical habitats. El Nino has extended the dry seasons in this area and risked the supply of crops, particularly rice, when combined with the region's arid environment. 8,400 hectares of rice fields were impacted by the last El Nino, indicating that rice is a crop that is sensitive because of the dry circumstances on Lombok Island (Yasin et al. 2004). Six rivers, water catchment regions, and irrigation systems of Timor Island had water shortfalls as a result of El Nino, leaving insufficient acreage for rice growing.

The circumstances that eastern Indonesia went through between 1980 and 2020—roughly 13 extremely dry seasons—are what caused this susceptibility (Yanti et al. 2022). In eastern Indonesia, 25.46% of all natural disasters have been caused by drought. Low rainfall seasons that last for four months have put agricultural operations in general and rice cultivation in particular at risk. Annual rainfall rates in the region have dropped as low as 1,900 mm, compared to the 2,702 mm national average. One significant abiotic stressor that reduces agricultural production and output is drought. It regularly affects all major crops and occurs in large parts of the planet. Severe droughts severely reduce agricultural yields and quality, and in food-insecure areas, they can cause famine (Akbar et al. 2021). One of the potential alternative crops to replace conventional drought-sensitive rice is sorghum (*Sorghum bicolor* (L.) Moench).

The semi-arid and desert regions are home to about 500 million people who live in impoverished nations and have made sorghum (*S. bicolor*) their main species to be cultivated. Sorghum has a high fiber and protein content and is devoid of gluten (McCann et al. 2015; Impa et al. 2019). Scientific data indicates that sorghum possesses nutrients comparable to those of rice. In addition to providing nutrients for human consumption, sorghum is also collected and used as a feedstock for the production of bioethanol (Mathur et al. 2017).

Sorghum has been harvested recently and is now grown all over the world. Most sorghum is planted in dry, semi-arid areas with limited water supplies. For instance, according to Hadebe et al. (2017), 60% of the land in Sub-Saharan Africa used to grow sorghum is thought to be susceptible to recurrent droughts. Similarly, 80% of sorghum grown in the United States is grown without irrigation, where water is a major limiting factor and yields are significantly lower. Sorghum's advantages were linked to its decreased water needs. In a location with low annual rainfall rates of 300 mm, sorghum is expected to require merely a minimal water input of 350/400 mm/yr (Ruiz-Giralt et al. 2023). In spite of the fact that sorghum resistant to drought, nutrient mobilization and transport as well as nitrogen uptake in the soil were affected by drought stress (Yu et al. 2015; Sarshad et al. 2021).

A technique to simulate and ascertain the possible geographical distributions of sorghum is necessary for its development as an alternative crop. A popular method for simulating a species' possible geographic ranges is to combine statistical, geoclimate, and machine learning models. This model has been frequently used to predict possible ranges of a wide range of creatures, including crop species (Fitzgibbon et al. 2022; Lin et al. 2022; Li et al. 2023), floral species, faunal species (Stephenson et al. 2022), including ticks (Sánchez et al. 2023), and even vegetation (Khanum et al. 2013). At the moment, an increasing number of methods are being used to estimate habitat suitability and species distribution regions. These methods range from general additive/linear models (GAM, GLM) that emphasize statistical methods to Bioclim, Domain, and Biomapper that emphasize geoclimatical methods. In addition, there are Artificial Neural Networks (ANN) that emphasize deep learning techniques and MaxEnt, Random Forest, Support Vector Machines (SVM) that emphasize machine learning-based techniques. Every strategy is different and has pros and cons of its own. According to Marcer et al. (2013), machine learning is seen to be one of the modeling approaches with benefits when compared to other ways. As a result, it is the method that is most commonly used in habitat suitability modeling research. According to Fois et al. (2018), there are several benefits to using machine learning, including the requirement for only species occurrence records, the method's ability to be applied with a limited amount of data, and its capacity to produce prediction models and estimations with high accuracy, high reproducibility, and the capacity to discern the most distinct environmental variables. In an arid region in KwaZulu-Natal, South Africa, MaxEnt informed that sorghum suitability was following the west-to-east trend, with areas in the west being more suitable than the east (Mugiyo et al. 2022). Sorghum has been proposed as an alternative to rice as the main crop in Indonesia (Paesal et al. 2021). The Indonesian government intends to set aside 115,000 hectares in 2023 and an extra 154,000 hectares in 2024 for the cultivation of sorghum in eastern Indonesia. Despite these advancements, nothing is known about the possible range of sorghum, which is mostly found in the dry eastern part of Indonesia. This information is needed in advance to ensure and continue sorghum cultivation. The general purpose of this study is to identify possible sorghum growing locations in dry environments on five specific eastern Indonesian islands. The particular purposes of this study are (i) to predict habitat suitability of drought-tolerant sorghum, (ii) to identify key environmental drivers, and (iii) to generate a suitability map for Eastern Indonesia. The information on possible sorghum growing locations is required by the Indonesian government to support its policy in promoting sorghum cultivation. This research is new in that it uses statistical modeling, geoclimate, and machine learning to attain precision in possible distributions. The outcomes of this study will benefit food safety in the particular arid environment of eastern Indonesia.

MATERIALS AND METHODS

The research was conducted on several islands in eastern Indonesia. The study methodology followed methods developed by Semu et al. (2021), including species occurrence, environmental variables, and model evaluation.

Study area

This research was conducted on several islands located in the eastern Indonesia regions, consisting of Lombok, Sumba, Sumbawa, Flores, and Timor Islands, Indonesia, within the geocoordinates of 8°-10° South latitude and 116°-126° East longitude (Figure 1). These regions are characterized by low rainfall and high temperatures (Table 1), and each island has different areas. The smallest island was Lombok Island, followed by Sumba Island. The most arid islands were Flores, Sumbawa, and the Timor Islands. Those islands have the lowest rainfall, reaching only 5 mm. Among other islands, Sumbawa Island has the hottest temperature, ranging from 32.0 to 36.6°C.

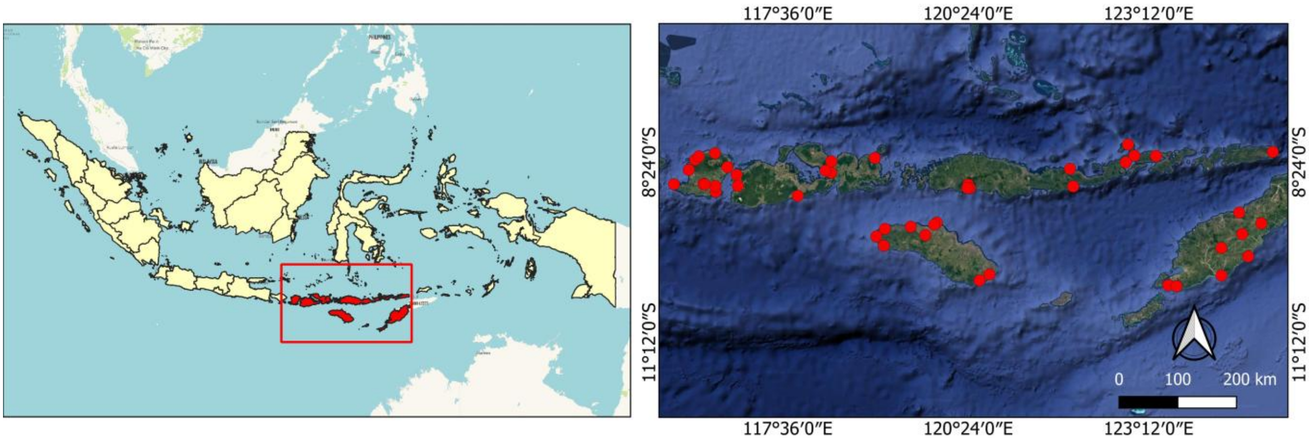

Figure 1. Spatial distribution of presence locations of sorghum (red dots) in Lombok, Sumba, Sumbawa, Flores, and Timor Islands, Indonesia

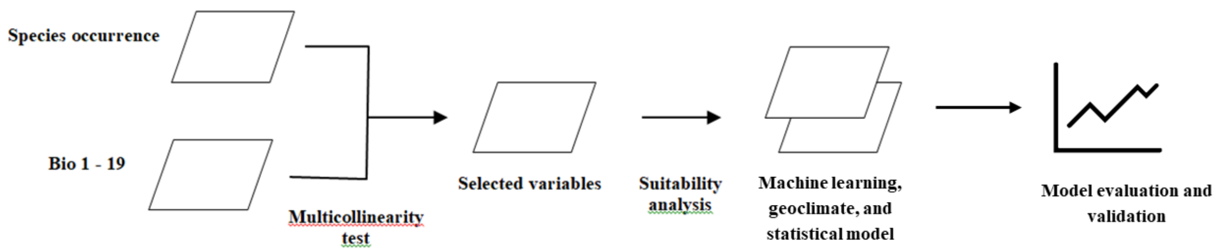

Figure 2. Schematic flowchart showing the potential distribution analysis pipeline

Table 1. Climatic variables in Lombok, Sumba, Sumbawa, Flores, and Timor Islands, Indonesia.

Islands	Area (km^2)	Rainfall (mm)	Temperature (°C)
Lombok	4,739	77-489	23.9 -31.9
Sumba	11,006	15-162	25.0-32
Sumbawa	15,414	10-446	32.0-36.6
Flores	15,531	5-483	16-30
Timor	30,777	10-667	27-31

Because of the dry temperature and arid ecosystems, the ecosystems of those islands are dominated by savanna and grassland ecosystems, which are patchy and fragmented, and range from lowland tropical rainforests to upland tropical forests to sub-alpine vegetation (Sutomo et al. 2021). There are numerous meadows and shrublands on the island (Sapta et al. 2015).

Sorghum occurrence surveys

All regions of a few chosen islands were the subject of field observations and surveys to document the presence of sorghum in real time. The information retrieved from the Herbarium Bogoriense, the Regional Agency for Agriculture and Forestry of the Ministry for Agriculture and Forestry, Indonesia, combined with database developed from literature studies was used to determine the locations for field observations and surveys following Gunawan et al. (2021). The global positioning system (GPS) unit, a Garmin Etrex 30 model, was used to record the geographic locations of *S. bicolor* occurrences (Figure 1) in the field. The data were stored in CSV format and transformed into Microsoft Excel so that habitat suitability modeling could be made. To document the presence of sorghum in real time, field surveys and explorations were carried out from September 2023 to January 2024. From September to October 2023, surveys were conducted in Lombok islands, from October to November 2023 for Sumba and Sumbawa islands, and from November 2023 to January 2024, covering Flores and Timor islands.

Procedures

Environmental predictors and variable selection

Bioclimatic factors (Table 2) from Arshad et al. (2022) and Dong et al. (2023) were used in this investigation for environmental predictors. According to Hijmans et al. (2005), the most frequently used bioclimatic variables that have been extracted from the climate database that is registered in WorldClim (www.worldclim.org, new version 2.0) are Bio 1 through Bio 19 (Figure 2). The pipeline started with performing the multicollinearity test to retrieve the bioclimatic variables with less potential for autocorrelation. The next stage is the habitat suitability modeling using several models. The obtained model was then evaluated. This WorldClim database has been extensively distributed and utilized in several researches on habitat suitability modeling throughout tropical Asia (Rana et al. 2017). Bioclimatic variables were represented at this stage as grids, with a typical spatial resolution of 1 km and a spatial resolution of 30 arc seconds, which in the case of the equator corresponded to around 0.86 km^2 and smaller elsewhere (Fick and Hijmans 2017).

According to Préau et al. (2018), a multicollinearity test together with Pearson's correlation test as parts of variable selection, was used to develop a model with enhanced performance using fewer variables and to prevent collinearity among variables. The model was built on 19 bioclimatic variables, ranging from Bio 1 to Bio 19. In order to build species distribution modeling at a geographical scale, variables exhibiting cross-correlation at high values of r^2 more than 0.8 were removed, whereas variables with r^2 values less than 0.8 were retained for additional study (Figure 3). Multicollinearity in the model indicates that a bioclimatic variable is substantially associated with other variables. Multicollinearity suggests the model has unstable and unreliable estimating capacity, according to As'ary et al. (2023). According to the multicollinearity test, the selected bioclimatic variables to be used were Bio 1, 2, 3, 4, 11, 12, 13, 14, 15, 16, 18, and 19 (Table 2).

Potential distribution analyses

Potential distribution analyses, according to Dolci and Peruzzi (2022), are based on statistical analysis, machine learning, and geoclimate used for crop modelling (Khalil et al. 2021; Ali et al. 2023). Using various species modeling algorithms (Table 3) in the R platform version 3.6.3 package (Table 3) (Mao et al. 2022) will yield estimated suitability maps of *S. bicolor* throughout the Indonesian islands of Lombok, Sumba, Sumbawa, Flores, and Timor. The generated estimated suitability maps were produced using many R packages, including library "sp", library "dismo" (Khan et al. 2022), library "random forest", library "kernlab", library "rgdal" (Bivand 2022), and library "raster" (Lemenkova 2020). Bio 1, 2, 3, 4, 11, 12, 13, 14, 15, 16, 18, and 19 were among the bioclimatic variables that were used as inputs for the model. Since this study only used the data of the presence of sorghum, pseudo-absences, also called background points, are also used and crucial for building accurate species distribution models. The background points are generated from the available environment and used to compare with the observed sorghum presences, helping potential distribution analyses determine the relationship between sorghum presence and environmental variables. Common methods include random sampling from the study area or a biased approach using buffer zones around sorghum presences. The "dismo" R package provides tools for creating background points, including methods for selecting and generating background points.

Table 2. Bioclimatic variables used in this study (Ulak and Paudel 2021)

Variables	Sources	Format	Unit
Annual mean temperature (Bio 1)*	www.worldclim.org	Image data in Raster	°C
Mean diurnal range (Bio 2) * (mean of monthly (max temp-min temp))	www.worldclim.org	Image data in Raster	°C
Isothermality (Bio 3)*	www.worldclim.org	Image data in Raster	%
Temperature seasonality (Bio 4)*	www.worldclim.org	Image data in Raster	°C
Max temperature of warmest month (Bio 5)	www.worldclim.org	Image data in Raster	°C
Min temperature of coldest month (Bio 6)	www.worldclim.org	Image data in Raster	°C
Temperature annual range (Bio 7)	www.worldclim.org	Image data in Raster	°C
Mean temperature of wettest quarter (Bio 8)	www.worldclim.org	Image data in Raster	°C
Mean temperature of driest quarter (Bio 9)	www.worldclim.org	Image data in Raster	°C
Mean temperature of warmest quarter (Bio 10)	www.worldclim.org	Image data in Raster	°C
Mean temperature of coldest quarter (Bio 11) *	www.worldclim.org	Image data in Raster	°C
Annual precipitation (Bio 12) *	www.worldclim.org	Image data in Raster	mm
Precipitation of wettest month (Bio 13) *	www.worldclim.org	Image data in Raster	mm
Precipitation of driest month (Bio 14) *	www.worldclim.org	Image data in Raster	mm
Precipitation seasonality (Bio 15) *	www.worldclim.org	Image data in Raster	coefficient of variation, % variability
Precipitation of wettest quarter (Bio 16) *	www.worldclim.org	Image data in Raster	mm
Precipitation of driest quarter (Bio 17)	www.worldclim.org	Image data in Raster	mm
Precipitation of driest quarter (Bio 18) *	www.worldclim.org	Image data in Raster	mm
Precipitation of coldest quarter (Bio 19) *	www.worldclim.org	Image data in Raster	mm

Note: *: selected variables based on multicollinearity test

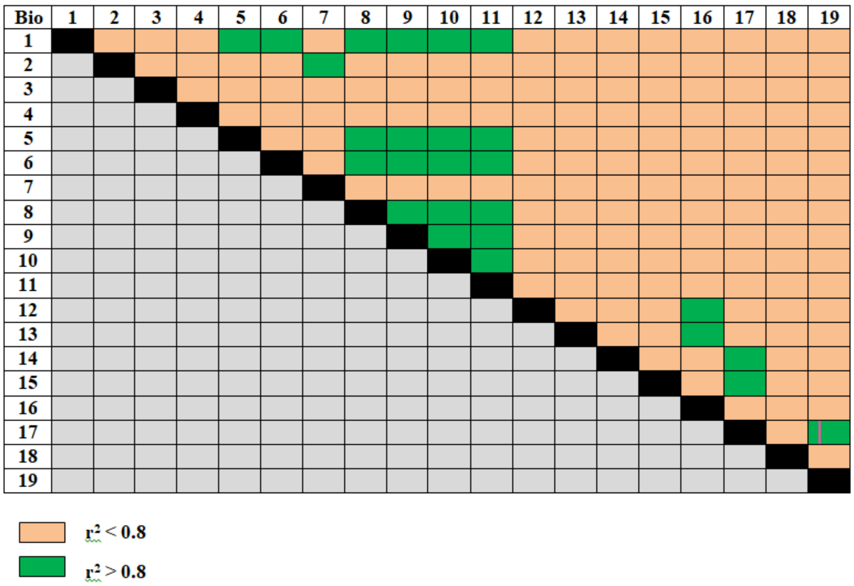

Figure 3. Pearson's correlation analysis matrix of the 19 bioclimatic variables (Bio 1 - Bio 19), and the green squares represent the significant correlation ($r^2 > 0.8$) among variables

Table 3. Evaluated models in this study

Model	Description	Name	Data	R packages
Machine learning	Based on the classification of training data until finally obtaining a better model.	Random Forest	Presence	random forest
		Support Vector Machine	Presence	kernlab
Geoclimate	Based on climate envelope algorithms and calculation of the similarity that exists between candidate pixels with respect to the selected presence records.	Bioclim	Presence	dismo
		Domain	Presence	dismo
Statistical	Based on the median of a response variable and using the Logit Link Function to relate the expected value of the response variable with included predictors.	GAM	Presence	dismo
		GLM	Presence	dismo

The effectiveness of the model was evaluated by looking at the receiving operating curve (AUC) area, and a jackknife test (Promnikorn et al. 2019) was used to analyze the influence and contribution of each bioclimatic variable affecting the appropriateness of *S. bicolor* habitat. AUC values between 0 and 0.5 indicate that the model performs poorly and indicates uninformative data, while values closer to 1.0 indicate that the final model is very informative and regarded as very excellent, according to Zhu et al. (2017). Besides using AUC to measure the model performance, this study also used COR (Calibration of Results) in evaluating models, particularly for classification tasks. COR assesses how well the model's predicted probabilities correspond to the actual probabilities of the event occurring.

Subsequently and according to Hijmans et al. (2012), the machine learning model' output, which estimated the suitability ranges of *S. bicolor*, then imported into GIS for further analysis and mapping display. Consistent with the findings of Wei et al. (2018), the habitat suitability levels on the utilized machine learning model map can be classified into five categories: unsuitable, low, medium, high, and very high suitability, with values ranging from 0.0 to 0.2, 0.2 to 0.4, 0.4 to 0.6, 0.6 to 0.8, and 0.8 to 1.0.

RESULTS AND DISCUSSION

Model evaluation and validation

As indicated by the area under the receiver-operating characteristic (AUC) curve acquired by the accuracy test of the ROC curve analysis method, model assessment and validation ensure the dependability of modeling results. The AUC values fell into multiple value classes and ranged from 0 to 1. The model's execution was inferior to contingency when the AUC value was less than 0.5. The model's performance is deemed moderate when the AUC value is between 0.5 and 0.6; acceptable when it is between 0.6 and 0.7; good when it is between 0.7 and 0.8; very good when it is between 0.8 and 0.9; and excellent when it is between 0.9 and 1. The model is more accurate and descriptive, and has better discrimination when the AUC test value is closer to 1. Based on the result, as can be observed in Figure 4, the AUC of the model is greater than 0.8, among which the Domain model is 0.962, SVM is 0.903, and both GLM and GAM are 0.894.

Response curves of bioclimatic variables

The response curves illustrate the correlations between each bioclimatic variable and the sorghum's degree of occurrence probability and suitability of habitat (Figure 5). The response curves of the areas of sorghum having high suitability were generated for the selected twelve bioclimatic variables. The likelihood of each bioclimatic variable to sorghum illustrate that with the rise in the bioclimatic variable value, the existence probability showed a trend of first increasing rapidly and then decreasing slowly. In this study, the range of climate factors when the probability of suitability is greater than 0.6 was used to represent the bioclimatic characteristics of the sorghum distribution area. The bioclimatic characteristics of the distribution area of sorghum are as follows: Bio1 or the annual mean temperature ranging from 25.0 to 26.0°C, Bio2 or the mean diurnal ranging from 9.0 to 12.0°C, Bio3 or the isothermality ranging from 70 to 80%, Bio4 or the seasonality of temperature ranging from 75.0 to 85.0°C, Bio7 or the annual range of tem-perature ranging from 12.0 to 14.0°C, Bio12 or the annual precipitation ranging from 150 to 250 mm, Bio13 or the precipitation of wettest month ranging from 25 to 35 mm, the precipitation of driest month, or Bio14, is ranging of 1-2 mm, the precipitation seasonality, or Bio15, is ranging of 8-9 mm, the precipitation of wettest quarter, or Bio16, is ranging of 8-10 mm, the precipitation of driest quarter, or Bio18, is ranging of 40-60 mm, and the precipitation of coldest quarter, or Bio19, ranging of is 9-11 mm.

Predictions of suitable habitats for sorghum

The modeling methods differed in predicting distribution areas for all species (Table 4; Figures 6, 7, and 8). For most islands, SVM predicted a larger distribution area. Conversely, Bioclim and Domain predicted less suitable areas of distribution for all islands. All models show consistency since all models confirm that Sumba, Sumbawa, and Flores will have larger suitable areas in comparison to other islands. Under the Bioclim model, Sumba has the smallest suitable area, equal to 485 km^2, and Sumbawa has the largest suitable area, equal to 5,560 km^2. The Domain model has also given similar results, with Lombok having the smallest suitable area at 3,465 km^2 and Sumbawa still has the largest suitable areas equals 15,245 km^2. Other models, including GAM/GLM and SVM, confirm that Timor, followed by Sumbawa and the Flores Islands, have large, suitable areas for sorghum.

Table 4. Distribution area in km^2 predicted by machine learning (SVM), geoclimate (Bioclim, Domain), and statistical (GAM/GLM) methods for the modeling of *Sorghum bicolor* in Lombok, Sumba, Sumbawa, Flores, and Timor Islands, Indonesia

Islands	Area (km^2)	Bioclim		Domain		GAM/GLM		SVM	
		km^2	%	km^2	%	km^2	%	km^2	%
Lombok	4,739	504	10.63	3,465	73.11	2,612	55.11	4,556	96.13
Sumba	11,006	485	4.40	9,556.	86.82	6,495	59.01	10,975	99.71
Sumbawa	15,414	5,560	36.07	15,245	98.90	10,481	67.99	15,331	99.46
Flores	15,531	3,728	24.00	10,333	66.53	5,998	38.61	14,687.	94.56
Timor	30,777	383	1.24	14,482	47.05	17,880	58.09	20,570	66.83

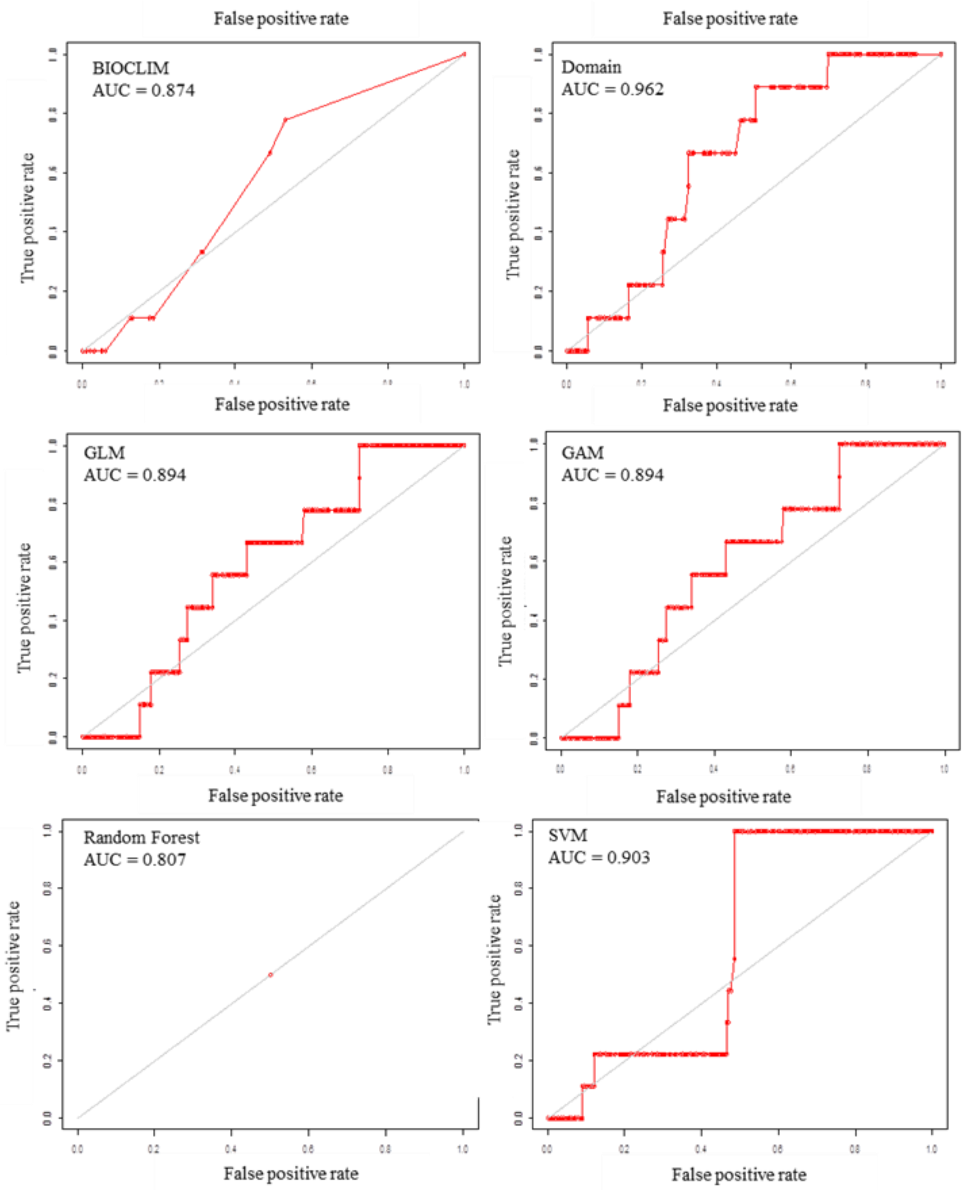

Figure 4. Area under the receiver operating characteristic curves (AUCs) for Bioclim. Domain, GLM, GAM, Random Forest, and SVM

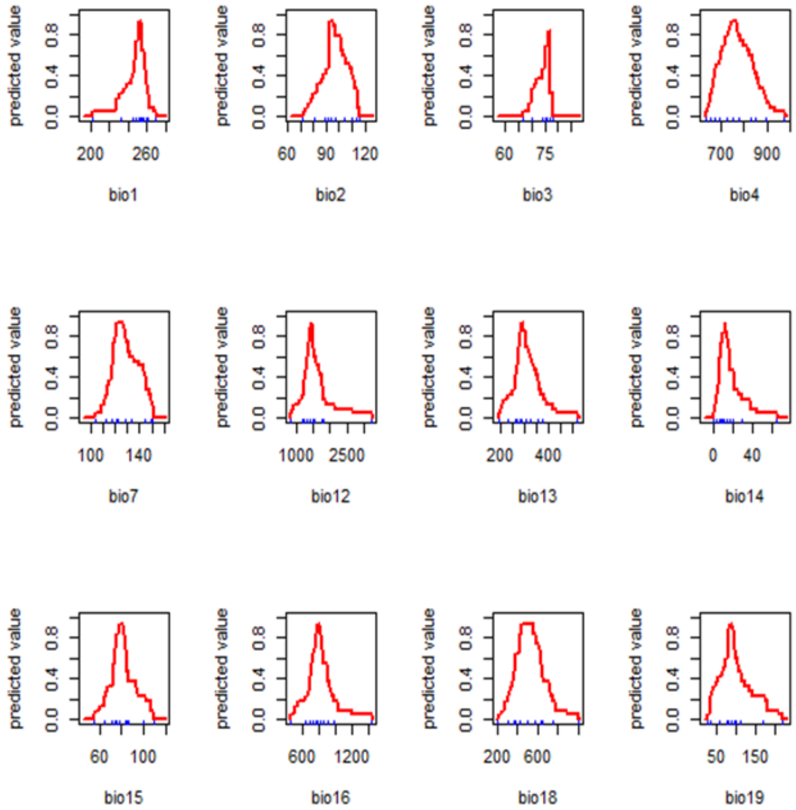

Figure 5. The response curves for Bio 1, 2, 3, 4, 11, 12, 13, 14, 15, 16, 18, and 19 bioclimatic

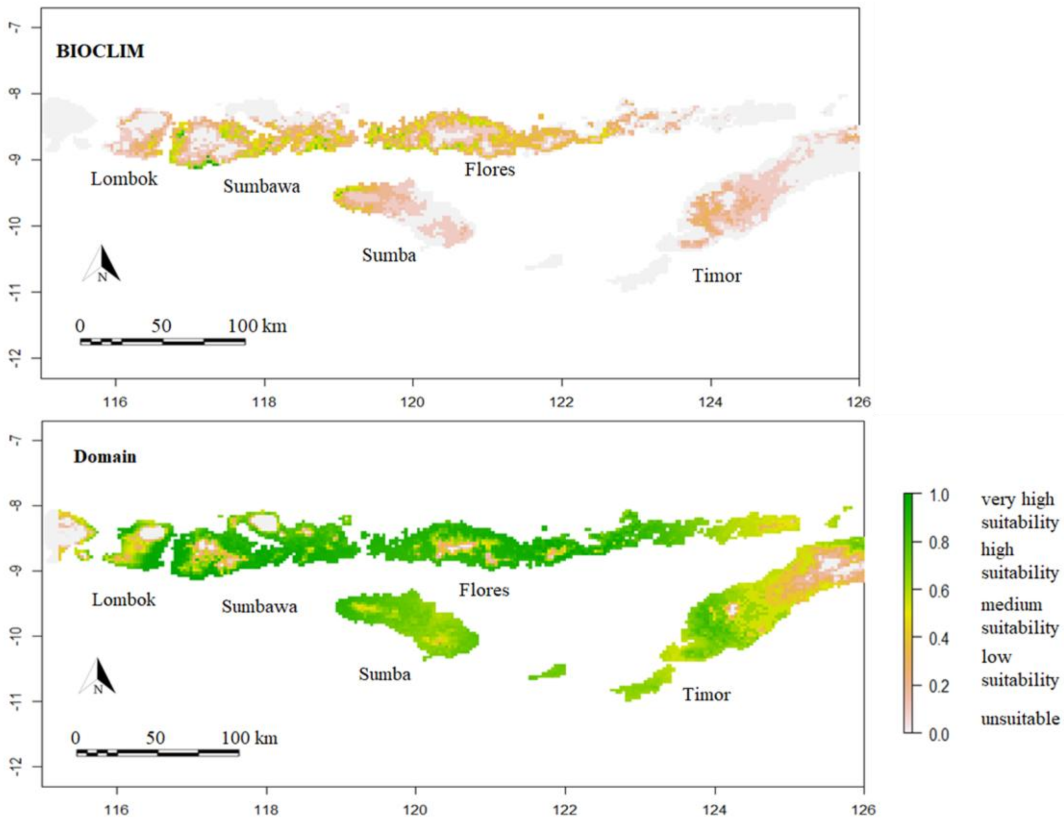

Figure 6. Distribution of suitable area predicted by geoclimate (Bioclim, Domain) for the modeling of *Sorghum bicolor* in Lombok, Sumba, Sumbawa, Flores, and Timor islands, Indonesia. Suitability level included 0.0-0.2: unsuitable, 0.2-0.4: low suitability, 0.4-0.6: medium suitability, 0.6-0.8: high suitability, 0.8-1.0: very high suitability

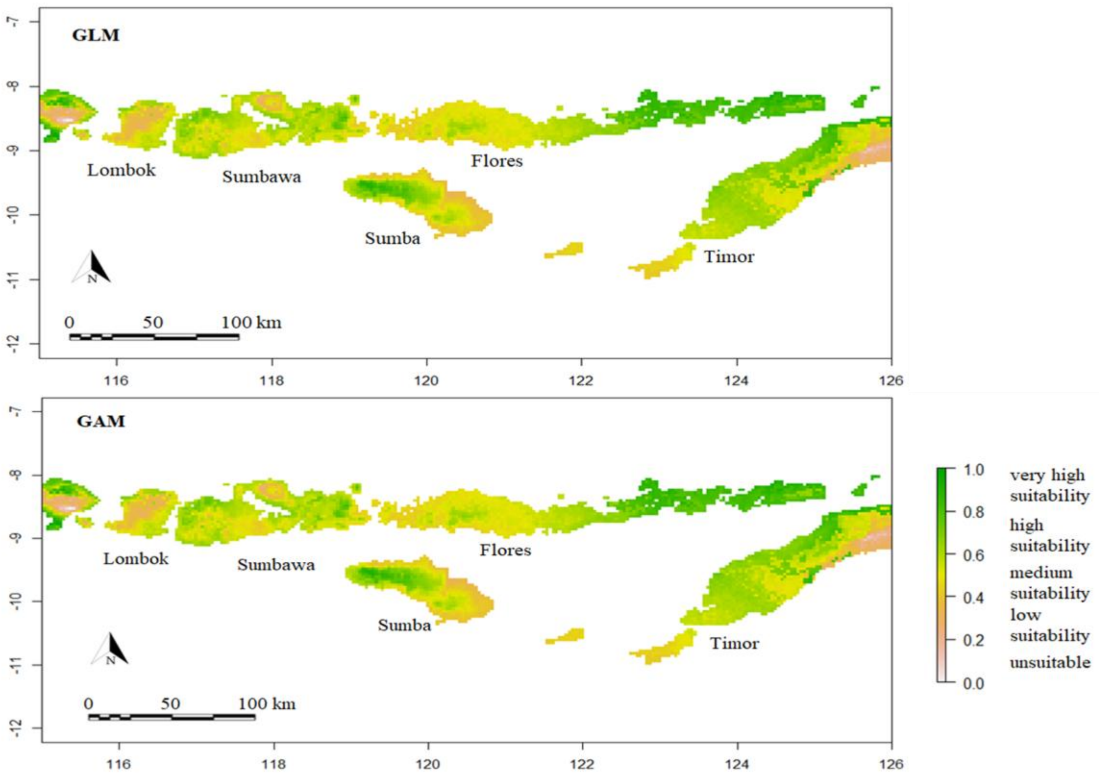

Figure 7. Distribution of suitable area predicted by statistical methods (GLM, GAM) for the modeling of *Sorghum bicolor* in Lombok, Sumba, Sumbawa, Flores, and Timor islands, Indonesia. Suitability level included 0.0-0.2: unsuitable, 0.2-0.4: low suitability, 0.4-0.6: medium suitability, 0.6-0.8: high suitability, 0.8-1.0: very high suitability

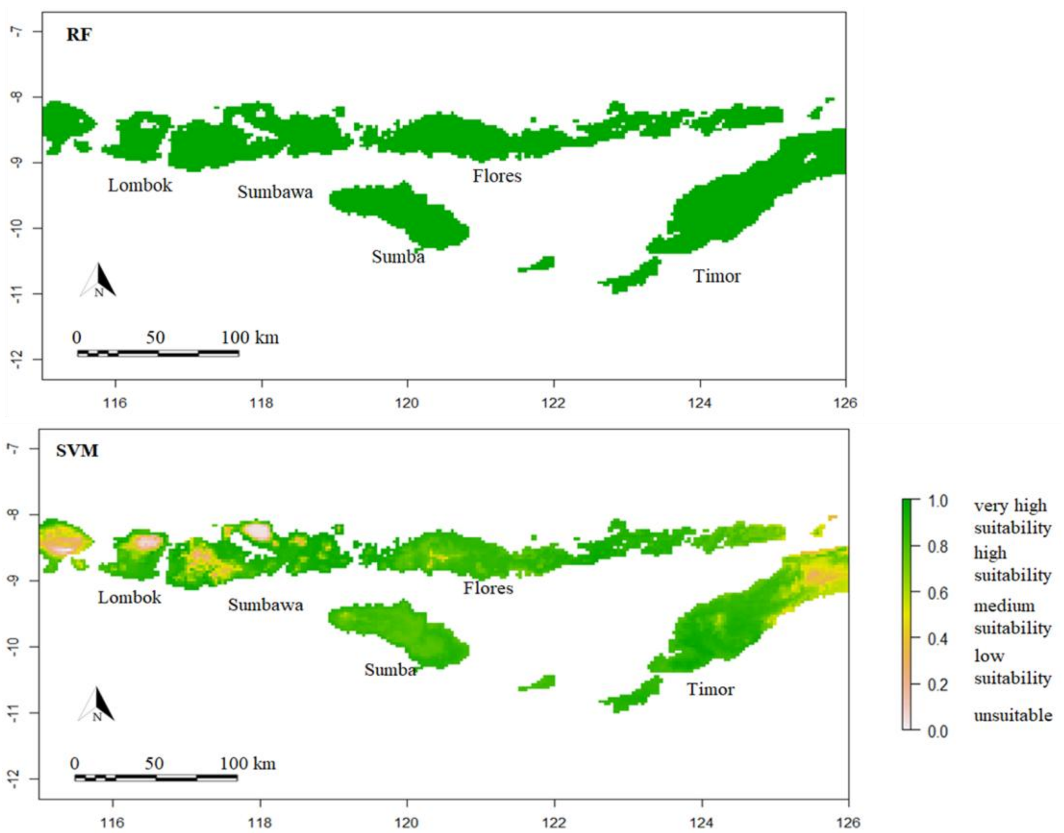

Figure 8. Distribution of suitable area predicted by machine learning (RF, SVM) for the modeling of *Sorghum bicolor* in Lombok, Sumba, Sumbawa, Flores, and Timor islands, Indonesia. Suitability level included 0.0-0.2: unsuitable, 0.2-0.4: low suitability, 0.4-0.6: medium

Table 5. Comparisons of sorghum distribution modeling studies in other locations

Locations	AUC	% high suitable areas	References
KwaZulu-Natal, South Africa	0.93	13.4	Mugiyo et al. (2022)
China	na	na	Niu et al. (2022)
Telangana state, India	na	na	Natarajan et al. (2016)
Kenya, Africa	0.97	-	Kigen et al. (2014)
Lombok, Sumba, Sumbawa, Flores, and Timor Islands, Indonesia	0.807-0.962	1.24 - 99.71	This study

Table 6. AUC: area under the receiver-operated characteristic curve and COR: point biserial correlation coefficient between observed and predicted values of each models

Coeff.	Bioclim	Domain	GLM	GAM	RF	SVM
AUC	0.874	0.962	0.894	0.894	0.807	0.903
COR	0.005	0.112	0.049	0.049	0.024	0.105

Discussion

Certain sorghum species may be comparatively more climate-sensitive in general, and precipitation in particular, since sorghum is a drought-tolerant species. This research forecasted the possible influences of climate variables on the sorghum as a potential crop. This is the first study, especially in the Southeast Asia region, to examine the range extensions of sorghum based on several species distribution models. The species presence data, along with environmental variables, have been wisely chosen and validated to guarantee the accuracy of the model. The AUC was used for sorghum model parameter adjustment and evaluation, and the results showed that the model had a high degree of prediction accuracy. The findings of this study are comparable to those of previous studies (Table 5). Currently, the potential distribution of sorghum has been modeled in China, India, and Africa. At the same time, there is a paucity of this information, mainly in the Southeast Asia region.

The result of this study then contributes significantly to the Indonesian government's policy in promoting sorghum cultivation. The result determines accurately the area suitable for sorghum. The potential areas delineated in this study can assist the small-scale farmer to carefully select the most cultivation areas. The use of modeling to estimate species potential area is in line with previous study (Jeong et al. 2022). Besides that implication, this study also offers a novel method in the form of modeling that can be applied to other species and assist the Indonesian government in shaping cultivation policy, in particular determining potential cultivation zoning for certain species.

Sorghum distributions in arid ecosystems in eastern Indonesia were shown to be impacted by precipitation and to have a negative correlation. At the same time, sorghum can withstand temperature increases. Mugiyo et al. (2022) confirmed that rainfall-related parameters, in this case precipitation, had the greatest influence on potential applicability. Drought is a feature of sorghum, according to Niu et al. (2022). The environmental variables, temperature and precipitation, contributed 86.2% to the model, suggesting that sorghum is heat resistant and avoids places with low temperatures and humidity.

Isothermality and seasonality of temperature factors were observed to have strong contributions adjacent to precipitation variables in this study. This is consistent with the findings of Huang et al. (2021), who found that plant groupings tended to reside in flatter topography areas with more variability of temperature, isothermality, and seasonality of temperature. They also found that the relative influences of isothermality and seasonality of temperature maximized in tropical locations. Sorghum was estimated to be very suitable in flat lowlands with elevations less than 1,000 m on arid islands in eastern Indonesia.

Here we present the comparison of the performance of six modelling methods to estimate the potential distributions of sorghum. Our findings confirm that the preferences of modelling method may affect the determination of suitable habitats for the sorghum (Oppel et al. 2012). Consistent with earlier comparative research, none of the six approaches evaluated produced better estimations in all performance parameters. The Domain and SVM models performed similarly well in our investigation in terms of prediction (Table 6). In spite of the predictions of the six individual models being generally consistent, discrepancies still existed due to the differences in algorithms of each model used, and this is a common phenomenon as observed previously in related studies in Hao et al. (2019) and Liu et al. (2022). The good performances of SVM was in agreement with previous studies (Ghareghan et al. 2020). SVM was recognized as a model with a higher accuracy, and also an inexpensive method for estimating the habitat suitability of a species (Boogar et al. 2019).

In our study, Domain model also shows a good performance. This is contradicted to results by Duan et al. (2014) that stated Domain performance was lower than SVM. The performances of a model were affected by environmental variables and as a result affecting model stability. This study is implemented and limited to small island ecosystems where the data are limited and the environment tends to be homogenous. The domain model is known flexible by Carpenter et al. (1993) and can offer advantages in mapping potential distributions of species, particularly when data is limited and environmental homogeneity is present. Domain can effectively use presence records and biophysical attributes to model potential ranges. Besides that, improved mathematical modeling techniques, machine learning algorithms, and more robust statistical tools will also affect the model performances. The other models that considered have good performances based on AUC values were GAM and GLM. In their study, De et al. (2020) has confirmed higher AUC value of GLM in comparison to RF and SVM. The model's prediction accuracy may be referred to as outstanding based on the ROC results and high AUC values. As a result, this finding can be utilized to determine which models better capture the fitness of sorghum's potential distribution.

Despite this study having succeeded in using and comparing six modeling approaches that are already known to have advantages and have been used widely in the modeling studies, a discrepancy among models is still observed, and this becomes a challenge in this study. In the future, we recommend applying the ensemble approach (Kaky et al. 2020) to gain consensus. Another improvement is regarding the variables used in this study that are limited to bioclimatic variables. Accompanied by the development of modeling approaches, we also recommend including more variables as supplementary data in the model to increase the accuracy of the prediction results and model. Those variables include land use, geological, elevation, and anthropogenic variables. The study is comparing several independent models. Then it is encouraged to compare the individual models with the ensemble approach. This approach has advantages due to its capacity to reduce both bias and variance, particularly in the presence of noise and uncertainty that are common in individual models.

Using machine learning, geoclimate, and statistical methods, the present study estimates comprehensively the spatial distribution of habitat suitability for sorghum in the arid eastern Indonesia ecosystems. The comprehensive result and species distribution model can then generate a knowledge base for future strategies for sorghum crop planners. Modeling methods, such as the one used in this study, can be applied by particular agriculture practitioners and farmers to estimate the areas where the most losses and profits are generated under sorghum cultivation practice, and so maintaining the natural geographic distribution areas of the sorghum under attention needs the greatest consideration and ensure food security, mainly in arid eastern Indonesia ecosystems.

All the models confirm that Timor, followed by Sumbawa and the Flores Islands, have large, suitable areas for sorghum. It is estimated that up to 99.71% of arid island ecosystems in eastern Indonesia were suitable for sorghum. The geoclimate and machine learning model generated the highest values for AUC in comparison to statistical methods. Then geoclimate and machine learning methods can be considered suitable methods to estimate sorghum's potential distribution areas, considering their performances.

The result is considered very useful in contributing to the Indonesian government's zoning policy and climate-resilient agriculture strategies. It provides empirical evidence about suitable areas for sorghum. It is strongly recommended to prioritize Timor, followed by Sumbawa and the Flores Islands, as potential sorghum cultivation zones.

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Agronomic and economic factors influence the productive performance of *Cenchrus ciliaris* under different types of organic fertilizers

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Abstract. *Lugundi HS, Maleko DD, Kizima JB, Nziku ZC, French P, Lugeye S, Selemani IS. 2025. Agronomic and economic factors influence the productive performance of* Cenchrus ciliaris *under different types of organic fertilizers. Intl J Trop Drylands 9: 111-119.* *Cenchrus ciliaris* L. (buffel grass) is among the essential tropical forage grasses, characterized by its high forage yield, nutritive value, grazing, drought, and fire resistance. However, nutrient deficiency in tropical sand soils is known to limit forage and seed yield, as well as the quality of *C. ciliaris.* A study was conducted to evaluate the agronomic and economic factors affecting *C. ciliaris*, focusing on seed yield and quality, forage hay yield, and its composition under different types of organic fertilizers during the rainy season. The results revealed that all fertilizer types significantly influenced seed yield, seed quality, hay biomass, and chemical composition over unfertilized plots; in comparison with other types of fertilizer, green fertilizer was found to increase crude protein content from 6.99 to 7.96% and decrease crude fiber and acid detergent fiber in harvested hay, respectively, from 32.98 to 31.7% and from 40.76 to 38.35%. On the other hand, the composted cow manure yielded the highest seed yield of 70 kg ha^{-1} and had the highest germination percentage (29%). The application of compost cow manure also increased economic return by 0.7 times. Therefore, the application of composted cow manure on *C. ciliaris* under sandy soil in a tropical sub-humid climate is the best management practice for enhancing the performance of grass pasture seeds.

Keywords: Buffel grass, compost cow manure, processed bio-organic fertilizer, seed quality, seed yield

Abbreviations: GDP: Gross Domestic Product, TALIRI: Tanzania Livestock Research Institute, TARI: Tanzania Agriculture Research Institute, SUA: Sokoine University of Agriculture

INTRODUCTION

Agriculture serves as the primary engine of the sub-Saharan African economy (Erdaw 2023). It employs approximately 65 to 70% of the labor force in Africa (Roseboom et al. 2016). Approximately 20-25% of ruminant livestock globally reside in Sub-Saharan Africa, where the variety of products and services provided by livestock can help millions of impoverished individuals in the developing world earn a livelihood (Erdaw 2023). Livestock is crucial to the economy of Sub-Saharan Africa, accounting for nearly 35% of the agricultural GDP (Erdaw 2023).

In Tanzania, the livestock sector accounts for 7.1% of the country's Gross Domestic Product (GDP). The country has a population of 37.9 million cattle, 27.6 million goats, and 9.4 million sheep, of which 90% are dependent on natural pastures from open-access and communal rangelands (Budget Speech MLF 2024/2025). Due to land competition, grazing land is continuously diminishing, resulting in forage scarcity and, consequently, low livestock productivity (Mengistu 2018; Maleko et al. 2019). For these reasons, the demand for establishing high-yielding and quality pastures has increased. The pasture establishment has been promoted as an opportunity to improve the sustainable forage supply for livestock production (Muzzo and Provenza 2018).

There are many types of pasture in Tanzania, but *Cenchrus ciliaris* L. (buffel grass) is considered the best perennial grass for sandy soils in a tropical sub-humid climate. This is because it exhibits high productive performance and nutritional value (Patidar and Mathur 2017; Ruvuga et al. 2022). *C. ciliaris* is resistant to drought, grazing, and fire (Maeresera 2020). It can survive in very high-temperature areas approaching 50°C (Siller-Clavel et al. 2022). *Cenchrus ciliaris* is considered a potential perennial species that may give economic benefits to livestock keepers where widespread pasture production is practiced (Lutatenekwa et al. 2021). *C. ciliaris* is an indigenous species of African semi-arid regions and is highly favored by grazing animals, which diminishes its likelihood of becoming invasive rangeland plants and supplanting other valuable indigenous grass species (Ngenzi et al. 2024)

Despite the unique beneficial characteristics of *C. ciliaris* in tropical regions, the establishment of this species in Tanzania is limited by the poor availability of quality seeds, which forces many farmers to rely on low-quality natural pastures that are insufficient to sustain their cattle throughout the year. Several factors, including soil nutrient deficiency attributed to the lack of fertilizer use, continuous cultivation, and climate change, may impact pasture farming, including pasture seed production, in many developing countries (Tembo et al. 2024). Research has shown that most soils have experienced considerable loss of fertility and require proper management for sustained yield (Stewart et al. 2020). The yield performance of *C. ciliaris* varies in different soil types. Higher yield performance was reported in soils with high moisture retention, adequate soil nutrient availability, and sufficient drainage, such as clay-loam and loam soils (Kisambo et al. 2024). However, soil with poor aeration, such as clay soil, affects root growth and penetration, resulting in a lower pasture yield compared to clay-loam and loam soils (Kisambo et al. 2024). Despite the high influence of root penetration of sandy soil, it gives low yield performance due to low fertility and high lose of moisture in a shorter period (Kisambo et al. 2024)

To mitigate this lack of quality seeds, especially in sandy soil, studies on the proper management of established *C. ciliaris* farms are imperative. Therefore, managing soil fertility was necessary to enhance the quality and productivity of the pasture seeds. Soil fertility can be enhanced through several methods, including the application of organic fertilizers to established pastures, the use of chemical fertilizers, or a combination of both inorganic and organic fertilizers (Bader et al. 2021; Mteta et al. 2022; Tembo et al. 2024).

In Tanzania, *C. ciliaris* was reported to produce high pasture seed yields when treated with urea (Kizima 2015). However, apart from being expensive, using urea as an inorganic fertilizer over a prolonged period can have ecologically negative effects, such as mineral imbalances and environmental degradation (Rashmi et al. 2020). It was anticipated that the use of ecologically friendly organic fertilizer could serve its intended role (Wu 2017). Organic fertilizer improves physiochemical properties of the soil, increase microbial density and activities, total soluble carbon and water-soluble carbon (Wang et al. 2017). Several studies reported the improved seed yield and quality by application of different organic fertilizer in different crops. The application of bio-organic fertilizer on rice enhanced grain yield (Naher et al. 2021). The application of horse manure on *C. ciliaris* led to increased seed yield and quality (Maeresera 2020). The application of cattle manure and bioslurry enhanced seed yield in rhodes grass (Aredo et al. 2020; Getie et al. 2022) in Ethiopia. Charshanbiyev (2023) also reported the increased seed yield and quality on Alfa alfa production by application of organic fertilizer.

This study aimed to address a research gap in the use of various types of organic fertilizers to enhance *C. ciliaris* pasture seed yield and quality, a deficiency currently present in Tanzania. The objective of this study was to enhance seed yields and quality by utilizing cost-effective types of fertilizer effectively during the rainy season. Specifically, the study assessed seed yield, germination, the yield of harvested hay, its chemical composition, and economic efficacy.

MATERIALS AND METHODS

Study area

The study was conducted in 2024 at a station during the rainy season, from February to June, at the Tanzania Livestock Research Institute (TALIRI) - Tanga Centre, situated in the Tanga Region, eastern zone of Tanzania. TALIRI Tanga is 60 meters above sea level and 6 km from Indian Ocean. It is located at 5°05'19.24"S and 39° 03'51.15"E. It experiences a tropical wet and dry season, with temperatures ranging from 26 to 33°C annually, and January and February are the hottest months. It receives between 1,230 and 1,400 mm of rain annually (Habimana et al. 2024). The experimental site is illustrated in Figure 1, and the trends of temperature and rainfall during the experimental period, as recorded by the HOBO data-logging weather station at TALIRI Tanga, are shown in Figure 2.

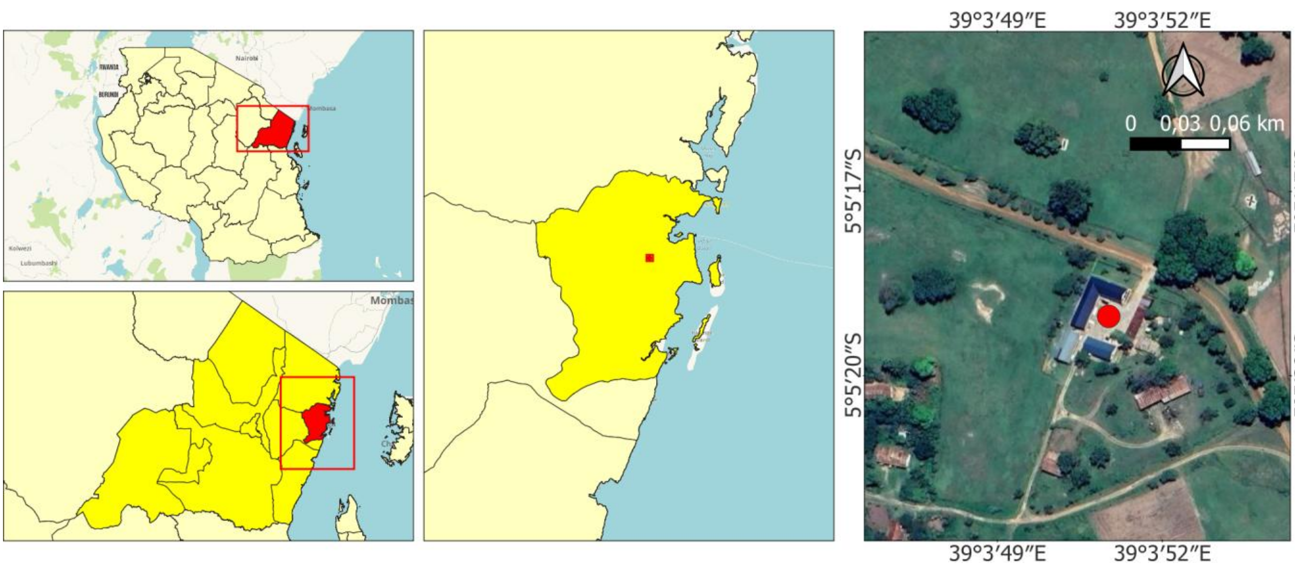

Figure 1. A study area in Tanzania Livestock Research Institute (5°05'19.24"S 39°03'51.15"E), Tanga City, Tanga Region, Tanzania

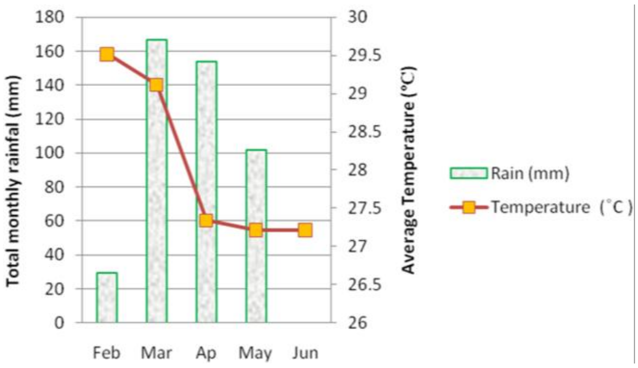

Figure 2. The HOBO data-logging weather station at TALIRI Tanga recorded the trends of mean temperature and rainfall during the experimental period

Procedures

Soil sampling and fertilizer collection

Fertilizers used in this study were processed bio-organic fertilizers (green and liquid fertilizers) and composted cow manure. A green fertilizer with 0.13% total nitrogen was purchased from Afrint Bio Solution Ltd., the company that supplies the product for organic farming in Tanzania. The liquid fertilizer, a plant-based type of bio-organic fertilizer containing 0.112% total nitrogen, was sourced from Lukwangule Organic Product Producers in Morogoro, Tanzania, which produces and supplies organic fertilizers for agricultural use.

Compost cow manure was collected and stored for at least one year prior to application, allowing for decomposition. A portion of the heaped manure was collected and thoroughly mixed to create new heaped composite manure. Subsequently, samples were collected from five different parts of the new heap and thoroughly mixed to obtain a single composite sample for laboratory testing. The total nitrogen content, as determined by laboratory testing, was 1.55%. The source of the compost cow manure was the TALIRI cattle herds, which were crossbreds of Friesian and Boran, grazing on natural pastures near the station campus.

Based on the NRC (2002) soil sampling procedures, a 15 cm V-notch hole was created using a hand hoe to sample the soil. Using a spade, two sides of the notch, approximately 2 cm thick, were sampled, and the soil was collected into a bag. The soil was then thoroughly mixed, spread onto a clean bag, and divided into four equal parts. The two diagonal parts of the soil were collected and combined to form a single sample for laboratory testing. The investigation into soil and compost cow manure samples was conducted at the Tanzania Agricultural Research Institute's (TARI) Mlingano Agricultural Research Centre. The soil type was sandy loam, with a pH of 6.0 (medium acid), a total nitrogen content of 0.1% (very low), an organic carbon content of 1.2% (low), a phosphorus content of 6.62 mg kg^{-1} (low), and a potassium content of 1.41 meq 100 g^{-1} (very high).

Experimental design and layout

The study was done in a 2 × 4 factorial arrangement in a Complete Randomized Design (CRD). There were two schedules of experiments in the rainy season: early-mid rainy and mid-late rainy, with three fertilizer types (compost cow manure (F1), green processed bioorganic fertilizer (F2), and liquid processed bioorganic fertilizer (F3), plus no fertilizer (NF) as a control) in four replicates, making a total of 32 sampling units.

Site preparation and application of fertilizer

In May 2023, a tractor plowed and harrowed the field. The seeds of *C. ciliaris* were manually sown in the field with a spacing of 0.33 meters between rows. All of the important pasture management tasks, except fertilization, were completed. Eight months later, an existing sward of established *C. ciliaris* was demarcated for the experiment. Pegs, manila string, and 100-meter tape were used for the plot's demarcation. The demarcated plots had an area of 15 m^2 (5 × 3 m) and a one-meter path between each experimental plot. The vegetation standardization was achieved by homogeneous cutting of the pasture in all demarcated plots using a grass cutter (shaving machine) at a height of 5 cm above the ground.

The fertilizer application was made to correct a 180 kg N ha^{-1} deficiency in an experimental soil. A rate of 12 t ha^{-1} of compost cow manure (F1) was applied by broadcasting the following day after the uniform cut. This was done once throughout the experimental period. Rates of 7 kg ha^{-1} and 8 L ha^{-1} of green-processed bi-organic fertilizer (F2) and liquid-processed bio-organic fertilizers (F3), respectively, were applied by spraying on the same day. Due to the leaching effect of liquid-form fertilizers in sandy soil (Kang et al. 2011), three application times of the processed bio-organic fertilizers at the same rate were conducted in each schedule of the experiment (early-mid and mid-late rainy) with a seven-day interval skipped to make a total 21 kg ha^{-1} and 24 L ha^{-1} for green and liquid bio-organic fertilizer, respectively. A 7 kg and 8 L ha^{-1} of green processed bio-organic fertilizer and liquid processed bio-organic fertilizers, respectively, were diluted in 1,400 and 4,000 L of water, respectively, prior to application at each time.

Data collection

The regrowth of the plant was visually observed from day one of the homogeneous cut, and the following parameters were recorded: days to first flowering, days to 50% flowering, and days to maturity. After seed maturity, the fertile tillers per tussock were measured by throwing a 0.5 × 0.5 m quadrat randomly into the plot, and all tillers with inflorescences within the quadrat frame of 0.25 m^2 were manually counted and designated as fertile tillers per tussock.

Next, five inflorescences were chosen at random from the randomly thrown 0.25 m^2 quadrat in the plot, and a ruler was used to measure the spike lengths to obtain the average spike length. Furthermore, the digital venier caliper was used to measure the diameter of five randomly selected inflorescences, thereby obtaining the average diameter of the spikelet per quadrat. Once everything was measured, the seeds were picked by hand, cleaned to remove any dirt, and weighed on a digital scale to determine the seed yield per quadrat at harvest. This was then changed to seed yield in kilograms per hectare.

After seed harvest, the grasses within the 0.25 m^2 quadrat in the plot were finally chopped off at a height of 5 cm above the ground. Their leaves and stems were then divided, and their fresh weights were determined by weighing them separately using a weighing balance. In the laboratory, the harvested forages and stems were subjected to an oven at 65°C for 48 hours. Soon after 48 hours, the samples were removed and weighed using a digital weighing balance to obtain the dry matter weights of the leaf and stem, which were then calculated into tons of dry matter per hectare, respectively.

The seeds were air-dried at room temperature for one month and weighed to determine the seed yield after drying, expressed in kilograms per quadrat, which was then converted to kg ha^{-1}. Next, to determine the 1000 seed weight, the 1000 seeds were manually counted and weighed using an analytical weighing balance. For the germination test, 100 seeds were placed on moist blotter paper and placed in a Petri dish at room temperature. Moisture in the seeds was monitored from the start by adding water when it decreased. Germinated seeds were counted and recorded daily from day 3 to day 28, as recommended by ISTA (2009).

Chemical composition of harvested hay

The collected and dried samples were ground, sieved, and packed, ready for proximate analysis. Proximate analysis was done at the laboratory of Sokoine University of Agriculture (SUA). Total dry matter was obtained by drying the ground sample in an oven set at 105°C overnight. Ash and organic matter contents were determined after burning samples using a muffle furnace at 550°C for 3 hours, following the AOAC procedure (1990). Total Nitrogen (N) was determined using the Kjeldahl method and multiplied by 6.25 to obtain Crude Protein (CP). Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF), and Acid Detergent Lignin (ADL) were determined using the procedure of Van Soest et al. (1991) by the Ankom fiber analyzer DELTA at the laboratory of TALIRI Tanga.

Economic efficacy

Next, to evaluate economic efficacy, the Total Variable Cost (TVC), Total Revenue (TR), and returns were calculated. Total variable cost includes the cost of purchasing fertilizer and labor charges for applying the fertilizer. Total Revenue (TR) included total sales of hay, dry matter yield, and seed yield value. ∑ (output x price at harvesting time) whereby the returns were calculated by subtracting the total variable cost of fertilizer application from the total revenue (TR-TVC) and expressed on a per-hectare basis.

Data analysis

Data were analyzed using the General Linear Model procedure of the Statistical Analysis System (SAS 2000), and the following model was used:

$$Y_{ijk} = \mu + A_i + B_j + (AB)_{ij} + \sum_{ijk}$$

Where: Y_{ijk}: Observation (seed yield and quality, yield of harvested hay and quality), μ: Overall mean, A_i: Effect due to i^{th} fertilizer types, B_j: Effect due to schedule of the experiment, (Ab_{ij}): Effect due to interaction effect of fertilizer type and schedule of the experiment, $\sum_{ijk}$: Sampling error.

The Least Significant Difference (LSD) test was used to compare the means that differ at the 0.05 level of significance for all observations.

RESULTS AND DISCUSSION

Growth and dry matter yield of harvested hay

The influence of types of fertilizer on days to first flowering, days to 50% flowering, days to maturity, and dry matter yield is shown in Table 1. All parameters, except days to first flowering, were significantly influenced by the types of fertilizer at $p < 0.05$ compared to the control treatment. The plots that received fertilizers achieved 50% flowering earlier compared to the unfertilized plots. This may be due to the nutrients provided by fertilizers, which promote rapid growth and result in the flowering of many tillers. Sufficient nutrient concentration in the soil provides many plants with strong stems, robust root systems, and healthy foliage, which are essential for the plant's flowering. Plots treated with fertilizer delayed to reach seed maturity, it took 62, 63 and 66 days for plots fertilized green fertilizer, liquid fertilizer and composted cow manure respectively to reach seed maturity from the day of a homogeneous cut. However, unfertilized plots, took only 58 days. Fertilizer-ensured nutrient availability in the soil may be the cause of the delayed seed maturity from forage cuts. This could lead to strong vegetative growth and increased plant vigor, which in turn would delay reproductive activities (Kizima et al. 2015). These results align with those of Kizima (2015), who found that in a tropical, sub-humid climate, it took 66-70 days after a homogeneous cut for *C. ciliaris* treated with different fertilizer levels to reach seed maturity. These results, however, run contrary to those of Kumar et al. (2005), who reported that newly sown *C. ciliaris* seeds in India reached seed maturity in 103-118 days. This discrepancy may result from differences in the stage of the plant under management. Thus, the current findings demonstrate that, in contrast to newly established forage in semi-arid climates, which takes roughly 103-118 days, the management of existing forage can produce mature seeds in a few days, ranging from 58 to 66 days.

Table 1 indicates the yield of leaf, stem, and total forage dry matter. There was no significant influence of processed bi-organic fertilizers (both green and liquid) on forage dry matter yields, as compared to unfertilized plots. Composted cow manure significantly influenced the total forage dry matter yield compared to the control treatment at $p < 0.05$. Plots treated with composted cow manure recorded the highest dry matter yield, while unfertilized plots recorded the lowest. The higher yield from plots fertilized with cow manure compost might be due to the essential nutrients the fertilizer added to the soil, which supported plant growth. Nitrogen can support the formation of chlorophyll and enhance the plant's photosynthesis capacity. Additionally, nitrogen can help plant cells grow and promote the development of vegetative parts, such as stems and leaves, resulting in a higher biomass yield (Leghari et al. 2016). This result falls within the range of 1.9-12.6 t DM ha^{-1} reported by Kizima (2015) for *C. ciliaris*. The influence of fertilizer on biomass yield has also been reported (Nemera et al. 2017; Isa et al. 2019).

In this study, composted cow manure demonstrated the highest performance in biomass yield (12.41 t DM ha^{-1}), surpassing other bio-organic fertilizers type used in this experiment. This might be due to the low organic matter and poor water-holding capacity of sandy soil that could limit the survival and activity of nitrogen-fixing microbes in bio-organic fertilizers (Itelima et al. 2018). Given the potential of solid-form organic fertilizers to retain nutrients in the soil, this may be also the reason why the composted cow manure performed better in terms of biomass yield than processed bio-organic fertilizers. The sandy loam soil supports much leaching of nutrients (Tahir and Marschner 2017). However, nutrient leaching is less with solid organic fertilizer than with liquid organic fertilizer (Kang et al. 2011; Fan et al. 2017; Karimi et al. 2017), which aligns with the current study. Additionally, Tan et al. (2011) found that using organic fertilizer made from solid manure yielded more maize than using liquid cow manure as an organic fertilizer. According to these findings, the most effective way to increase the biomass yield of *C. ciliaris* in sandy loam soil in a sub-humid climate is to use composted cow manure. The current results of composted cow manure fall within the range of the increased forage biomass yield, ranging from 10.1 to 12.6 t DM ha^{-1}, reported by Ngenzi et al. (2023) for *C. ciliaris* when manure levels were applied in a semi-arid climate. However, the effectiveness of composted cow manure can indeed differ significantly depending on local soil health and environmental factors. Therefore, localized studies should be conducted to understand these variations better. By doing so, farmers can be provided with tailored guidance and recommendations on how to effectively utilize organic fertilizers in accordance with their specific soil conditions, ensuring optimal crop production outcomes while maintaining soil health.

On the other hand, the use of organic fertilizer is crucial, as it contributes to reduced land competition by increasing productivity per unit area and reducing the need for pasture hunting. However, it may not address deeper issues of land competition and diminishing grazing areas. Therefore, implementing integrated land management practices and agroecological approaches that balance crop production with sustainable grazing practices is important. Additionally, government policies should prioritize promoting equitable land use and protecting farmers' rights.

Seed yield and quality

Table 2 shows the influence of fertilizer types on fertile tillers, spike length, spike diameter, seed yield, 1000-seed weight, and germination percent of *C. ciliaris*. Fertilizer types had a significant influence on all parameters at $p < 0.05$. Seed yield, fertile tillers (inflorescence density), spike length, and diameters were higher in plots that received fertilizers than in unfertilized plots. These results indicate a high correlation between inflorescence density, spike length, diameter, and seed yield, as supported by Kumar et al. (2005) and Maeresera (2020). The mean value (70 > 59.4 > 53.4 kg ha^{-1}) of seed yield was recorded from plots treated with compost cow manure, liquid fertilizer, and green fertilizer. In contrast, 38.95 kg ha^{-1} was recorded from unfertilized plots. These findings fall within the range of 77.5-35.5 kg ha^{-1} seed yield reported by Kizima (2015), who researched the same species and variety using different fertilizer levels. However, these results are contrary to those of Kumar et al. (2005), who reported a high seed yield of 97 kg ha^{-1} of *C. ciliaris* by nitrogen fertilizer. This difference may be attributed to variations in climate and soil type. Kumar et al. (2005) reported an inflorescence length of 8.4-13 cm following fertilization, which is within the range of the current findings. Isa et al. (2020) also reported a high tiller density resulting from the application of fertilizer, which contributed to a high inflorescence density.

Table 1. Growth and dry matter yield of *Cenchrus ciliaris* as affected by types of fertilizer

Treatment	Variables					
	Days to first flowering	**Days to 50% flowering**	**Days to maturity**	**Leaf DM yield (tDM ha^{-1})**	**Stem DM yield (tDM ha^{-1})**	**Total forage yield (tDM ha^{-1})**
NF	25^{ba}	38^{a}	58^{d}	5.00^{b}	2.48^{b}	7.49^{b}
F1	24^{b}	32^{c}	66^{a}	7.95^{a}	4.46^{a}	12.41^{a}
F2	24^{ba}	35^{b}	62^{c}	6.41^{ba}	3.33^{b}	9.73^{b}
F3	25^{a}	34^{bc}	63^{b}	6.18^{b}	2.98^{b}	9.16^{b}
p-value	0.1509	0.0022	<0.0001	0.0132	0.0016	0.0036
SEM	0.3	0.96	0.34	0.57	0.31	0.82

Note: Days to first flowering: Number of days from homogeneous cut to when the first tiller starts to flower, Days to 50% flowering: Days from homogenous cut to when 50% tillers start to flower, Days to maturity: Days from homogenous cut to when the seed has straw colored. Means with the same superscript within the column are not significantly different at $p > 0.05$, SEM: Standard Error of the Mean, NF: No Fertilizer (control), F1: Compost cow manure, F2: Green processed bio-organic fertilizer, F3: Liquid processed bio-organic fertilizer

Table 2. Effect of types of fertilizer on fertile tiller, spike length, spike diameter and seed yield, and germination percent of *Cenchrus ciliaris*

Treatment	Variables					
	Fertile tillers/tussock	Spike length (cm)	Spike diameter (mm)	Seed yield (Kg ha^{-1})	1000-seed weight (g)	Germination%
NF	11^{c}	7.26^{c}	9.52^{c}	38.95^{d}	0.96^{c}	24^{c}
F1	20^{a}	13.33^{a}	13.22^{a}	70.00^{a}	1.64^{a}	29^{a}
F2	14^{cb}	10.98^{b}	11.13^{b}	53.40^{c}	1.21^{b}	26.5^{b}
F3	16^{b}	11.02^{b}	11.30^{b}	59.40^{b}	1.37^{b}	26^{cb}
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0007
SEM	1.15	0.33	0.29	1.96	0.08	0.71

Note: Means with the same superscript within the column are not significantly different at $p > 0.05$, SEM: Standard Error of the Mean, NF: No Fertilizer (control), F1: Compost cow manure, F2: Green processed bio-organic fertilizer, F3: Liquid processed bio-organic fertilizer

The good results of plots that were fertilized can be attributed to the essential nutrients that the fertilizer provides. These nutrients help the plant produce numerous tillers by promoting vegetative sprouting (Maeresera 2020), which leads to high inflorescence density, spike length, and diameter, ultimately resulting in a higher seed yield. On the other hand, compost cow manure outperformed other types of fertilizer. This can be attributed to its gradual release of nutrients, resulting in a longer-lasting effect. It increases substantial amounts of soil organic matter content, leading to improved nutrient retention capacity. It also helps maintain soil structure, which enhances the soil's ability to retain water and nutrients (Adugna 2016), ultimately leading to increased seed yield. Apart from high yield performance of organic fertilizer especially composted cow manure reported from the current study, using organic fertilizers results to long-term effects on the production of *C. ciliaris* pastures seeds by enhancing soil fertility and improving microbial activities, that ensure sustainable pasture production and reduced long-term environmental impact (Meena et al. 2017; Bedaso et al. 2022).

For seed quality, the 1000-seed weight and germination percentage were significantly influenced by the application of fertilizer ($p < 0.05$), compared to unfertilized plots. The seeds harvested from plots that received types of fertilizer had the highest 1000-seed weight and germination percent compared to unfertilized plots. The added essential nutrients provided by fertilizer, which enhanced effective photosynthesis and produced larger and higher-quality seeds, may be the reason for the good results in fertilized plots. These results are conversely to the finding of Kumar et al. (2005), who reported no significant influence of fertilizer on 1000-seed weight and percentage germination. This difference in findings may be caused by variations in the species diversity used in the two experiments. Yuan et al. (2022), who researched *Kengyilia melanthera*, reported a higher 1000-seed weight by applying fertilizer, which correspondingly supports the present study. Patil et al. (2018) also reported a significant influence of fertilizer on the 1000-seed weight and germination percent in perennial fodder sorghum.

Chemical composition of harvested hay

Crude fiber, protein content

The effect of types of fertilizer on crude fiber and crude protein is indicated in Table 3 below. There was a significant influence of types of fertilizer on crude protein and fiber content of *C. ciliaris* at $p < 0.05$. Unfertilized plots had 32.98% more crude fiber and 6.99% less crude protein compared to those treated with fertilizers. This implies that fertilizer application improves the crude protein content and reduces the crude fiber content in the plant. Brima and Abusuwar (2020) also reported a decrease in fiber content in rhodes grass when the level of nitrogen was increased, which supports the current study. The higher protein content recorded in fertilized plots may be due to the nitrogen (N) applied to the soil, which enhanced protein synthesis in the plant. Green fertilizer, liquid fertilizer, and composted cow manure had the highest crude protein content, at 7.96, 7.95, and 7.78%, respectively. This amount of crude protein ranges from 3.9 to 10.93%, which is the same range reported by Kizima (2015) and Mishra et al. (2010) for *C. ciliaris*. Nonetheless, the protein content value of the current study is slightly higher than the 4-6% CP range reported by Al-Dakheel et al. (2015) for *C. ciliaris* in an arid desert climate, likely due to differences in climate conditions between the two studies.

However, plots fertilized with composted cow manure had lower protein content than plots fertilized with other types of fertilizers. This might be because the stems of plants treated with compost cow manure got thicker, which makes it easier for water and nutrients to move through the plant. This helps maintain the inflorescence, ultimately leading to a high seed yield. In support of this, Kirwa et al. (2015) found a positive correlation between stem thickness and crude fiber content and a negative correlation between crude fiber and crude protein content. According to Van Soest et al. (1991), the crude protein percentage found in this study may only be sufficient to maintain rumen function. Therefore, feeding animals the harvested hay at this stage will necessitate further animal supplementation.

Table 3. Chemical composition of harvested hay of *Cenchrus ciliaris* as influenced by fertilizer types

Treatment	Variables						
	%DM	%ASH	%CF	%CP	%NDF	%ADF	%ADL
NF	93.60[a]	13.03[a]	32.98[a]	6.99[c]	70.04[a]	40.76[a]	4.76[a]
F1	92.10[b]	11.67[b]	31.80[b]	7.78[b]	67.91[ba]	38.45[b]	4.00[b]
F2	92.56[b]	11.46[b]	31.70[c]	7.96[a]	67.38[b]	38.35[b]	4.11[ba]
F3	92.88[ba]	10.53[c]	31.71[b]	7.95[a]	68.31[ba]	39.52[b]	4.21[ba]
p-value	0.0003	0.0002	<0.0001	<0.0001	0.0737	0.0014	0.0927
SEM	0.25	0.19	0.017	0.012	0.7	0.41	0.22

Note: Means with the same superscript within the column are not significantly different at $p > 0.05$, SEM: Standard Error of the Mean, NF: No Fertilizer (control), F1: Compost cow manure, F2: Green processed bio-organic fertilizer, F3: Liquid processed bio-organic fertilizer, DM: Dry Matter, CF: Crude Fiber, CP: Crude Protein, NDF: Neutral Detergent Fiber, ADF: Acid Detergent Fiber, ADL: Acid Detergent Lignin

Table 4. Returns are estimated from sales of seeds and harvested hay

Item	Types of fertilizer			
	NF	F1	F2	F3
Income and expenditure Hay DM yield (t/ha)	7.48	12.96	9.74	9.16
Seed yield (kg/ha)	38.95	70	53.4	59.4
Sales of hay at harvest (USD)	811	1,404	1,055	993
Sales of seed at harvest (USD)	396	711	542	603
Total revenue (USD)	1,206	2,115	1,598	1,596
Cost of fertilizer per hectare (USD)	0	94	253	147
Application labor charge per ha (USD)	0	28	20	20
Total variable cost (USD)	0	123	273	167
Returns (USD)	1,206	1,993	1,325	1,429

Note: NF: No Fertilizer (control), F1: Compost cow manure, F2: Green processed bio-organic fertilizer, F3: Liquid processed bio-organic fertilizer

Fiber contents

Table 3 also displays the influence of fertilizers on Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF), and Acid Detergent Lignin (ADL). There was no significant influence of types of fertilizer on %NDF and %ADL at $p > 0.05$. However, %ADF was significantly influenced by fertilizer type at ($p < 0.05$). Unfertilized plots recorded the highest mean value, 40.76% ADF. Plots fertilized with green fertilizer recorded the lowest value, 38.35% ADF, followed by those fertilized with liquid fertilizer and cow manure compost, respectively. This indicates that the application of fertilizer tends to increase the N level in the soil, which decreases the %ADF of the plant, as reported similarly by Hassan et al. (2015). The results of this study fall within the range of 66.5 to 77.6% NDF and 36.6 to 47.7% ADF for *C. ciliaris* hay harvested after seed harvest, as reported by Al-Dakheel (2015). Plots that received compost cow manure fertilization had a higher ADF percentage than plots that received other fertilizers. This may be a result of the fact that composting cow manure can reduce the loss of nutrients that leach out due to its high organic matter content, which in turn supports robust, well-developed stems that produce high-quality seeds. This causes a low leaves-to-stems ratio at the stage of seed harvest and hence increases the amount of lignin.

Economic efficacy of seed and hay production

The analysis of costs and benefits was conducted to determine the expected return from producing seeds and hay (Table 4). The application labor charge for compost cow manure was slightly higher than for other types of fertilizer. The application of composted cow manure requires more physical effort, more time, and a larger volume, which may explain the high labor cost. The production of seeds and hay for *C. ciliaris*, when applied with any fertilizer used in the current study, yielded a higher return compared to non-applied fertilizers. The application of compost cow manure, green fertilizer, and liquid fertilizers, respectively, increased estimated returns by 0.7, 0.1, and 0.2 times. This study's analysis reveals that farmers can achieve greater profit by producing *C. ciliaris* seeds and hay using composted cow manure than with any other type of fertilizer. This could be due to the less costly and higher-yielding results obtained from the application of composted cow manure. The application of fertilizer further increased the nutritional value of *C. ciliaris* compared to an unfertilized one. This could also cement the economic benefits of using fertilizer if it were economically analyzed.

Organic fertilizers, especially composted cow manure, improve soil structure and microbial activity, thereby enhancing the long-term effects on soil fertility (Adugna 2016). Therefore, it reduces the need for frequent fertilizer applications. By doing so, the cost of fertilizer application is reduced while maintaining stable yields for long-run farming practices. Organic fertilizer, especially composted cow manure, is locally available, reducing purchasing expenses compared to commercial fertilizers that require frequent purchases with price fluctuations, which are economically unfeasible for smallholder farmers in Tanzania. Despite the advantages of organic fertilizer, farmers must be well-equipped with proper knowledge on how to prepare it before utilization, in order to ensure that nutrients are reserved for sustainable, economical pasture production.

On the other hand, different regions may have varying levels of access to organic resources; therefore, the need to train farmers on how to utilize locally available organic fertilizers is necessary for enhancing accessibility and easy implementation of economic and sustainable farming practices.

In conclusion, the results from the current study demonstrated that the yield and quality of seed and harvested hay of *C. ciliaris* can be improved by the application of organic fertilizer. In this manner, all types of fertilizer used in the experiment increased performance over the control. The green, processed bio-organic fertilizer outperformed others in terms of increased protein concentration and decreased fiber content in harvested hay. However, the compost cow manure increased the seed yield, germination percent, and yield of harvested hay more than all other types of fertilizer used in this experiment. The use of compost cow manure was cheaper compared to commercial green and liquid fertilizers, as it increased economic return by 0.7 times more than unfertilized ones. Therefore, to increase the pasture seed quantity and quality of *C. ciliaris* profitably and under environmentally friendly management practices, the application of composted cow manure is recommended for sandy loam soils in sub-humid tropical areas. However, further research is needed on different ecological zones, including arid and semi-arid rangelands.

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Managing transboundary banana blood disease through a resilience-based biosecurity framework in East Nusa Tenggara, Indonesia

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Abstract. *Nampa IW, Mudita IW, Widinugraheni S. 2025. Managing transboundary banana blood disease through a resilience-based biosecurity framework in East Nusa Tenggara, Indonesia. Intl J Trop Drylands 9: 120-134.* Banana Blood Disease (BBD), caused by *Ralstonia syzygii* subsp. *celebesensis* has become a critical threat to banana production in Indonesia's dryland archipelago of East Nusa Tenggara (ENT). The fragile socio-ecological systems in this region exacerbate the impacts of biological invasions, necessitating a paradigm shift in biosecurity. This study, a comprehensive effort that combined field surveys, stakeholder interviews, PCR-based pathogen detection, statistical analysis, and policy assessment, was conducted to identify the drivers of management failure and propose an alternative framework. These findings showed that the nationally mandated Integrated Pest Management (IPM) approach, which is reactive and focused on post-incursion responses, was unable to contain the rapid spread of this transboundary pathogen. The result has been catastrophic yield reductions of up to 65% and estimated annual economic losses exceeding IDR 4.61 trillion, alongside severe impacts on household food security, livestock systems, and rural livelihoods. Critical weaknesses were identified in Indonesia's biosecurity governance, including fragmented policies, weak coordination across sectors, insufficient early surveillance, and the absence of effective controls on the movement of infected planting material. To address these systemic gaps, this study advocated for a paradigm shift toward a resilience-based biosecurity framework that is polycentric, adaptive, and multi-scalar. The proposed framework integrates pre-border, border, and post-border measures, empowers community-led surveillance and response, and strengthens linkages between local practices and national regulatory systems. By embedding socio-ecological resilience into crop protection governance, the framework offers a pathway to safeguard banana biodiversity, protect smallholder livelihoods, and promote sustainable agriculture across ENT's vulnerable drylands.

Keywords: Banana Blood Disease, East Nusa Tenggara, polycentric and adaptive governance, resilience-based biosecurity framework, transboundary plant pathogen

INTRODUCTION

The globalization of agricultural trade and intensified human mobility have accelerated the spread of transboundary plant diseases worldwide, placing increasing stress on fragile agro-ecosystems. Climatic variability, land degradation, and ecosystem disruption further amplify the vulnerability of agricultural systems to biological invasions, making conventional pest management approaches insufficient for current challenges (Findlater and Bogoch 2018; Guo et al. 2022; Prajapati et al. 2024). This insufficiency underscores the need for a paradigm shift from reactive Integrated Pest Management (IPM) toward integrated biosecurity is essential. Biosecurity, defined as "strategic and integrated policy instruments assessing and controlling risks to plant life/health and associated environmental risks" (FAO 2007; Renault et al. 2022), provides a proactive approach that spans pre-border, border, and post-border actions. Unlike compartmentalized crop protection, biosecurity encompasses surveillance, quarantine, certification, and mitigation measures, with proven effectiveness in regions such as Australia and New Zealand (Falk et al. 2011; Arndt et al. 2024).

This global challenge is particularly acute in dryland ecosystems, areas defined by UNEP-WCMC (2007) as having an aridity index (AI) $\leq$0.65. East Nusa Tenggara (ENT), one of Indonesia's most vulnerable provinces, is typified by poor soils, irregular water supply, and dissected topography (Fu and Stafford-Smith 2024). Increasing aridity under climate warming intensifies the ecological susceptibility of ENT's agricultural systems (Lian et al. 2021). Despite these constraints, ENT supports drought-resilient crops such as banana, which plays a central role in household food security, nutrition, and livelihoods (Drenth et al. 2018; Mudita and Benu 2018; Nampa et al. 2022). The province's geographic proximity to Australia and Timor-Leste, coupled with growing inter-island trade and travel, exposes it to heightened risks of biological invasions. Banana Blood Disease (BBD), caused by *Ralstonia syzygii* subsp. *celebesensis* represents a pressing example of a transboundary pathogen that capitalizes on these vulnerabilities (Ray et al. 2021, 2022).

The devastating impacts of BBD highlight both ecological and institutional weaknesses. First reported in Indonesia in the early twentieth century, the disease has re-emerged as a major constraint, severely reducing banana yields and threatening smallholder livelihoods (Safni et al.

2014; Prior et al. 2016). In ENT, BBD was first detected on Sumba around 2010, before spreading to Flores by 2022, causing incidence rates of up to 44% in some districts (Mudita et al. 2018; Nampa et al. 2022; Hahuly et al. 2025). Economic impacts have been severe, with losses exceeding IDR 25 million per hectare annually and regional yield reductions surpassing 65% (Nampa et al. 2025). The collapse of banana production undermines food and feed security, erodes rural incomes, and reduces biodiversity, while the misuse of pesticides has disrupted pollinator and soil microbial communities (Hadiwiyono et al. 2007). This trajectory exemplifies how a transboundary pathogen can destabilize social and ecological systems, especially in regions already facing climate and economic pressure.

A major factor behind this failure is Indonesia's continued reliance on IPM as the dominant crop protection paradigm under Law No. 22 of 2019. IPM is inherently reactive, initiating measures only after outbreaks occur, and it fails to address the epidemiology of BBD. Its shortcomings include neglect of pre-border surveillance and inter-island quarantine, inadequate cross-sector coordination, and the absence of certified pathogen-free planting material (Mudita and Benu 2018; Ray et al. 2022). As a result, control efforts have been fragmented, delayed, and ultimately ineffective, allowing BBD to spread unchecked. This has led to significant economic losses and threatens food security, highlighting the urgent need for a shift from reactive to anticipatory measures. This demonstrates a clear misalignment between the reactive IPM framework and the anticipatory measures needed to combat transboundary bacterial wilt pathogens.

The persistence of this gap underscores the urgency of shifting toward a resilience-based biosecurity system tailored to the socio-ecological realities of ENT's drylands. Such a framework must integrate proactive surveillance, internal quarantine, certification systems, and farmer participation within a multi-level governance structure (FAO 2007; Grafton et al. 2019). It must also account for local contexts, including smallholder livelihood dependence, indigenous knowledge, and the socio-cultural dimensions of dryland agro-ecosystems (Wilbanks and Kates 1999; Noywuli et al. 2024). By strengthening resilience, such a system would enable communities to anticipate, absorb, and adapt to biological shocks, while improving coordination across agricultural, environmental, and trade sectors (Arndt et al. 2024; Henry and Ramirez-Marquez 2012).

The study aimed to develop a comprehensive and systemic biosecurity model tailored to ENT's dryland environment that enhances socio-ecological resilience against BBD. Specifically, the objectives were: (i) to assess the agro-ecological factors and multidimensional impacts of BBD through field surveys, molecular diagnostics, and economic analysis; (ii) to identify institutional gaps in current biosecurity governance by examining policy fragmentation, coordination issues, and technical capacity limitations; and (iii) to design a scalable resilience-based framework that combines pre-border surveillance, border quarantine, and post-border community actions with engagement from stakeholder participations.

MATERIALS AND METHODS

Study site and timing

This study employed a longitudinal, multi-site design to trace the progression and impact of BBD across two major islands in East Nusa Tenggara Province, Indonesia: Sumba and Flores (Figure 1). Surveys were first initiated on Sumba Island in 2019 following the initial reported outbreak of BBD there (Mudita and Benu 2018). This site served as a baseline to understand the disease's established socio-economic and agronomic impacts. Subsequent surveys were then conducted on Flores Island in 2023 in direct response to the disease's recent invasion, which was first officially reported in mid-2022 (Jejak Flores 2022; Pos Kupang 2022).

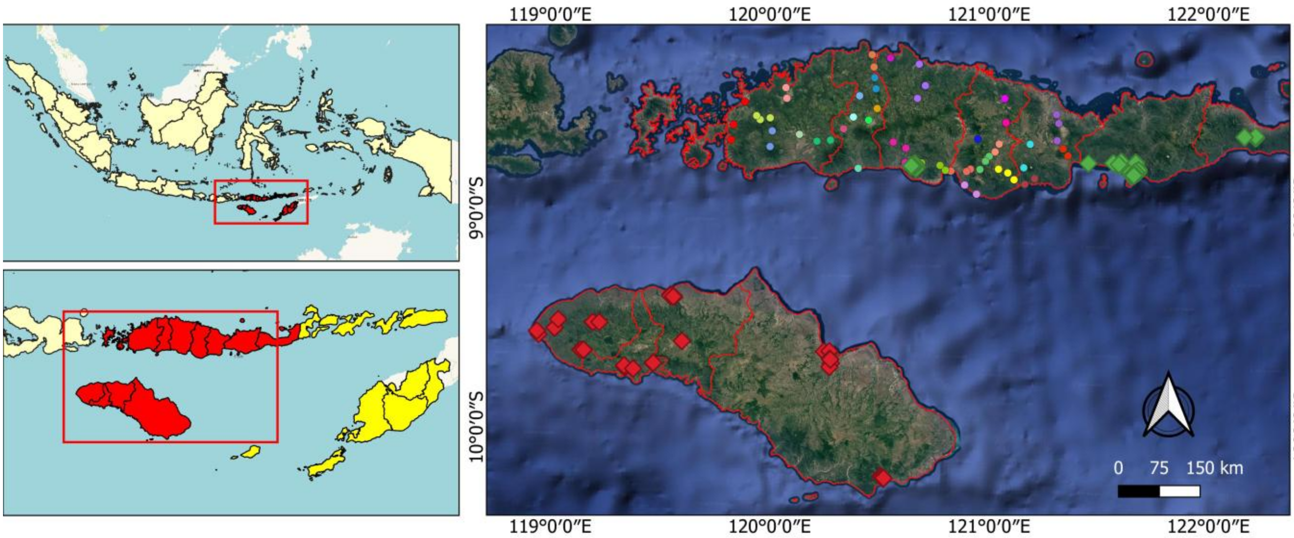

Figure 1. Consolidated sites for data collection, Sumba Island and Flores Island in East Nusa Tenggara Province, Indonesia. Different icon colors indicate different sampled sub-districts in each surveyed district (Note: ●: Aesesa, ●: Aimere, ●: Bajawa, ●: North Bajawa, ●: Boawae, ●: Boleng, ●: Borong, ●: Cibal, ●: Golewa, ●: Inerie, ●: Komodo, ●: Kota Komba, ●: Lamba Leda, ●: Langke Rembong, ●: Lelak, ●: Lembor, ●: Mauponggo, ●: Mbeliling, ●: Nangaroro, ●: North Rahong, ●: Reok, ●: Riung, ●: Ruteng, ●: Sambi Rampas, ●: Sano Nggoang, ●: Satar Mese, ●: Soa, ●: Wae Rii, ●: Welak, ●: Wolomeze, ◆: Non BDB, ◆: BDB) —source: Georeferenced Site Data (2019, 2023)

The survey conducted in 2023 at flores island was focused on measuring the incidence of the disease on ABB 'Pisang Kepok' and 'Pisang Klutuk' cultivars in the central and western parts of the island, as well as identifying the pathogen, its means of transmission, and the governance of the local government responses. Meanwhile, the surveys conducted in 2019 in Sumba Island and 2023 in Flores Island were focused on evaluating the economic values of the banana and the potential loss caused by the disease in the eastern and central parts of the island. The chronological sequence of the surveys—from Sumba to Flores—was a deliberate design feature that mirrors the documented eastward trajectory of BBD in Sumba Island and then northward spread to Flores Island. This approach allowed for a comparative analysis of the disease's immediate incursion phase in Flores against its more entrenched status in Sumba, providing critical insights into the epidemiological progression of the pathogen and the evolving effectiveness of management responses over time and geography, with significant implications for future study and management strategies.

Data collection and research design

Data collection in this study was carried out through a series of longitudinal interviews and field observation surveys. The study started with interviews and field surveys on Sumba Island, aimed at determining the initial incidence rate, pattern of BBD spread, and the eventual socio-economic impacts of the disease on communities after the outbreak. For the detailed economic implications, conducted a subsequent series of interview surveys in eastern and central Flores to specifically assess the economic value of the banana industry and estimate losses caused by the disease. To support this economic emphasis, a simultaneous field survey along with in-depth interviews in central and west Flores focused entirely on etiological, agro-ecological, and policy aspects, including disease occurrence and spread, disease diagnosis and pathogen identification, disease progression, and government policy responses taken by the sub-district levels. Covering this array of different facets in a multi-pronged approach provided a complete picture of the impacts of BBD from the angle of a low-level agro-economic perspective and broader bio-security policy frameworks.

The sampling design for this study was a collaborative effort, employing a multi-stage, purposive approach (Ramanujan et al. 2022). It was initiated through consultations with district agricultural service officials, a crucial step that ensured the study's local knowledge and expertise. These consultations helped to identify villages with confirmed BBD reports and to document policy responses. For the surveys conducted in 2019 in Sumba Island, accessible villages along inter-district roads reporting BBD outbreaks were selected for assessment. Within these villages, sampling was conducted opportunistically by stopping at locations where symptomatic banana clumps were visible. At each site, disease incidence was quantified, a structured interview with the landowner was administered, and geographic coordinates were recorded, with all data captured digitally using the KoboToolbox platform (Nampa et al. 2020). Meanwhile, for the survey focused on evaluating the economic value and the potential loss conducted in Flores Island, samples were taken in purposefully selected sub-districts representing high, medium, and low disease strata, also after consulting the district agricultural service officials. In each selected sub-district, samples were taken opportunistically at different altitudes. In contrast, the survey focusing on measuring the incidence of the deseases utilized a more stratified methodology. Following in-depth interviews with agricultural officials, three sub-districts in each district were purposively selected to represent high, medium, and low disease strata. From each sub-district, three accessible villages were chosen, and within each village, three to five fixed sites along village roads were assessed. Data collection in this survey, including disease incidence measurements, GPS coordinates, and qualitative interview responses, was recorded manually. Across all sites, disease incidence was consistently calculated as the percentage of symptomatic individuals relative to the total number of plants within each sampled clump.

In addition to primary field data collection, a comprehensive literature review formed an integral component of the design of this study. Secondary data were systemically sourced from articles in scientific journals discussing the global origin, transmission, and epidemiology of BBD, in conjunction with Indonesian policy sources on plant protection (e.g., Law No. 22 of 2019) and global guidelines on the implementation of biosecurity (e.g., FAO Biosecurity Toolkit 2007). The overall study utilized a sequential exploratory mixed-methods design (Creswell and Plano Clark 2017), with a marked feature of discrete but repeated iterations in the different phases of study execution. The procedure began with a first literature review in laying the theoretical groundwork that followed the sequential acquisition of qualitative (e.g., in-depth interviews of agricultural officials) and quantitative data (e.g., structured surveys of farmers and disease assessments). A final, synthesizing literature review was then conducted after field data analysis to frame the empirical results in the body of existing scholarship and policy literature. Such a design created the opportunity for the qualitative results to inform the quantitative study, with the entire study procedure framed and refined through the incorporation of the secondary sources.

Data analysis

Data analysis in the current study employed a mixed-methods approach to gain a synoptic understanding of the research problem. Qualitative data from field interviews and literature reviews were coded systematically and subjected to thematic analysis using the NVivo 14 software in line with the six-phase procedure specified by Braun and Clarke (2022). Meanwhile, the quantitative data--for example, disease incidence and economic indicators--were tabulated in Microsoft Excel and statistically examined using the R software environment (Hothorn and Everitt 2014) in order to carry out descriptive and inferential statistics. In order to reveal the geographical evolution of

BBD, all of the georeferenced incidence data were spatially represented and mapped in the Google Earth software in order to reveal the spatial pattern and dynamics of the disease (Visser et al. 2014; Retkute and Gilligan 2025). Finally, a methodological triangulation combined the results from the qualitative thematic analysis, the quantitative statistical analysis, and the inferred themes from the secondary literature (Flick 2018) to strengthen and deepen the trustworthiness of the findings. This integrative approach ensured that the empirical results remained aligned with the broader scholarly and policy discussions on plant disease management and biosecurity.

RESULTS AND DISCUSSION

Agro-ecological aspects and multidimensional impacts of BBD

Bananas are a central feature of the dryland agricultural systems in the islands of Sumba and Flores in Indonesia, where produced in a diverse and complex manner. Almost every household yard (*pekarangan*) on both islands is involved in banana production. This home garden production of bananas is most prominent in Sumba, particularly in areas where open grasslands are used for free-grazing livestock in the landscape. On more consolidated agricultural land on both islands, bananas are also produced in a mixed agroforestry system with a variety of fruit trees and perennial cash crops interspersed with banana clumps. Thematic analysis of in-depth interviewing disclosed that the main historical function of banana production was to contribute to household food and feed security (Table 1). However, a significant shift in function occurred. With rising market demand for bananas triggered by massive production losses from the severe disease Fusarium wilt (*Fusarium oxysporum* f. sp. *cubense*) and, more recently, BBD in the islands of Java and subsequently in Bali, bananas from Sumba and Flores are pulled into commercial trade circuits. This shift has upgraded the status of bananas from a staple underpinning food security to a critical item in the household economy (Damayanti et al. 2021; Vellema et al. 2021).

The incidence, etiology, spread trajectory, and impact of BBD on Sumba Island have been reported by Mudita and Benu (2018), Ray et al. (2021), and Nampa et al. (2022). Ray et al. (2021) verified the identity of the banana disease in Sumba Island as BBD and suggested its first introduction to the island around the year 2010. Previously, a disease diagnosed by disease symptoms and pathogen signs typical of BBD was observed to have wiped out Musa ABB ‘Pisang Kepok’ in the Southwest Sumba District by the year 2016 (Bore 2016; Henci 2016), though it had not yet spread to the island's three other districts (West, Central, and East Sumba) at that time. Nonetheless, in subsequent surveys, Nampa et al. (2020) showed that BBD had extended to East Sumba District, presenting a clear west-to-east pattern of eastward dispersal of the pathogen across the island. Long-distance dispersal of BBD has been described by Ray et al. (2021) to follow an arbitrary, indicative pattern aligned with the movement of infected banana plant material by humans. Conversely, since short-distance and local spread reveals a circular pattern from the source of the first infection, it has been interpreted to involve the activity of transmission agents like insects, birds, and nectar-feeding bats, in addition to other probable transmission through diseased tools, water, or soil (Ray et al. 2021; Molina et al. 2020).

Table 1. Comparative themes on banana cultivation and utilization practices on Sumba and Flores Islands

Second-level theme	First-level theme	
	Sumba Island	**Flores Island**
Sites of Cultivation	Predominantly confined to homegardens due to free-grazing livestock, with outer-yard planting requiring protective fencing.	Cultivation occurs in both homegardens and mixed agroforestry systems intercropped with cash crops.
Common Cultivars	Dominated by the cultivar 'Pisang Kepok' (called Marmi), with rare cultivation of other dessert types.	'Pisang Kepok' is dominant, but is supplemented by a wider diversity of other dessert and cooking cultivars.
Use as a Staple Food	Serves as a critical dietary staple and caloric substitute for rice, especially during periods of shortage.	Primarily consumed as a fresh fruit, utilization as a staple is occasional and geographically specific to lean seasons.
Other Uses (By-products)	Pseudostems are repurposed as livestock feed and an emergency water source for cattle; the inflorescence is consumed as a vegetable.	Pseudostems are processed into livestock feed; the inflorescence is used as a vegetable and for commercial sale.
Use as a Source of Income	The recent transition from subsistence to commercial production, driven by external demand from off-island traders.	Nascent integration into commercial value chains, with traders sourcing for export to major Indonesian markets.

Source: Thematic Analysis of Interview data (2017 for Sumba Island, 2023 for Flores Island)

Initial reports of BBD on Flores Island emerged in 2022, although media coverage exhibited inconsistencies regarding the disease's etiology, initial point of entry, and the primary agents responsible for its dissemination (Table 2). Despite scientific consensus identifying the causative agent as the bacterium *Ralstonia solanacearum* subsp. *celebesensis* (commonly referred to as the Blood Disease Bacterium or BDB), certain media sources erroneously attributed the disease to a viral pathogen (Flores Editorial 2022; Viral NTT 2025). Similarly, discrepancies were noted in reports identifying the first affected location, with some sources citing East Manggarai Regency and others Ende Regency; however, accounts were consistent in describing a westward and eastward trajectory from its first entry point in the island (Pos Kupang 2022; Ekoran NTT 2023). Regarding transmission vectors, widespread reporting indicated that the primary mechanism of spread was the use of contaminated harvesting tools (e.g., machetes or parangs) by traders hiring local farmers during fruit harvesting (Floresa 2024; Mongabay Indonesia 2024). In-depth interviews with agricultural department officials revealed that BBD was first officially reported in Borong, East Manggarai Regency, though the exact cause was initially pending laboratory confirmation. It was hypothesized that the pathogen may have entered the island through the maritime port of Aimere in Ngada Regency (Table 3). Table 3 also shows that farmers and traders largely lacked awareness of the disease's cause and transmission dynamics, mainly due to insufficient official outreach and information.

Based on comprehensive field observations and molecular diagnostics conducted across multiple districts in the central and western parts of Flores Island, BBD presents a complex array of diagnostic symptoms and pathogen signs, particularly evident in susceptible cultivars (Figure 2). While several cultivars, including Pisang Ambon, Pisang Barangan, Pisang Cavendish, Pisang Raja, and Pisang Tembaga, were affected, Musa ABB 'Pisang Kepok' and 'Pisang Klutuk' experienced the most severe destruction, with the highest disease incidence observed in East Manggarai and Ngada districts. The disease initially manifests through foliar symptoms including hanging, broken leaves typically beginning in younger ones (Figure 2.A), progressive yellowing and drying along leaf margins (Figure 2.H), and asymmetric sucker developments (Figure 2.I). Vascular discoloration appears as characteristic reddish-brown streaks and spots in leaf sheaths visible in both longitudinal and transverse sections of the pseudostem (Figures 2.B-2.E). Advanced infection leads to pseudostem necrosis with mature leaf petioles showing brown rotting before breaking (Figure 2.F) and brown decay along the grooves of suckers' petioles (Figure 2.G). The most distinctive disease symptoms appear in reproductive tissues: fruit bunches exhibit reddish-brown streaking on peduncles (Figure 2.K), while pathogen signs manifest as externally healthy fruits that conceal advanced internal decay ranging from light brown to dark brown with reddish-brown mucoid exudate in severely infected fruits (Figure 2.L-2.O). The disease also affects male buds, showing reddish-brown streaks on oblique sections of the flower stalk (Figure 2.P) and decaying brown spots on transverse sections of the rotting bud (Figure 2.Q). The PCR using the BDB-specific primer pair 121F/121R that produces a 317-bp amplicon validated the occurrence of *R. solanacearum* subsp. *celebesensis* in 22 of the sampled sites where symptomatic expression was observed (Figure 2.R). The spatial pattern of disease incidence of the affected sites (Figure 3) indicated that the disease spread along the inter-district road, moving westward initially and later eastward. The appearance of disease symptoms and pathogen signs illustrates the systemic spread of the pathogen and its destructive capacity throughout the entire plant tissue. At the same time, its spatial pattern of incidences explains the epidemiological pattern of transmission of the pathogen across the island.

Table 2. Spatiotemporal spread, etiology, and themes of BBD on Flores Island as documented in online news media (2022-2025)

Year	Site	District	Pathogen	Theme	Source
2022	Borong area	East Manggarai	Bacterium	Human movement of infected material; contaminated tools	Pos Kupang (2022)
2022	Bamo	East Manggarai	Bacterium	Not specified	Suara Buruh (2022)
2022	Not specified	East Manggarai	Incorrectly reported as a virus	Not specified	Flores Editorial (2022)
2023	Various	West Manggarai	Bacterium	Suspected insect vectors and human activity	Victory News (2023)
2023	Various	Ngada	Bacterium	Human-mediated spread (tools, seedlings)	Ekoran NTT (2023)
2024	Nangalimang, Hoba	Sikka	Bacterium	Contaminated tools (parangs); insects	Mongabay Indonesia (2024); Floresa (2024)
2024	Warupele 1	Aimere (Ngada)	Bacterium	Not specified	Suara Flores (2024)
2024	16 sub-districts	Ende	Bacterium	General spread from neighboring regions	Flores Pos (2024)
2024	Various	Nagekeo	Bacterium	Lack of effective containment measures	Ekoran NTT (2024)
2025	Various	Ende	Bacterium	Persistent environmental presence	Flores Pos (2025)
2025	Not specified	Sikka	Incorrectly reported as a virus	Not specified	Viral NTT (2025)

Source: Thematic analysis of online media content (2023)

Table 3. Comparative perceptions regarding BBD introduction and spread across stakeholder groups in the central and western parts of Flores Island

Second-level theme	First level-theme		
	District agriculture officers	**Banana traders**	**Farmers**
Initial Disease Identification and Verification	Official confirmation of the first outbreak was established through field verification following community reports, correcting misattributed initial locations.	Initial awareness of the disease arose from direct encounters with unmarketable, symptomatic fruit, though specific details were not formally recorded.	First-hand observation of disease incidence began at a highly localized level (individual gardens), before the pathogen spread to surrounding areas.
Hypothesized Initial Pathogen Entry Point	Epidemiological tracing points to the introduction of the pathogen through contaminated goods via a major inter-island maritime port.	Anecdotal information suggests the pathogen originated from an external source and was introduced through existing agricultural trade routes.	A significant knowledge gap exists regarding the origin of the pathogen due to a lack of formal communication and extension services.
Perceived Primary Vectors of Pathogen Spread	Human activity, specifically the use of contaminated tools during harvest, is the suspected primary vector, while insect transmission remains a secondary, unconfirmed risk.	Harvesting practices that involve external labor using their own or provided tools are recognized as a potential pathway for pathogen dissemination.	The mechanisms of spread are not understood, with symptoms recognized only by their severe and visible final presentation (e.g., internal rot and oozing).
Perceived Rate of Disease Spread	The pathogen exhibited a rapid rate of spread, with official reports confirming new infections across multiple sub-districts within a week of initial detection.	The disease progression was perceived as exceptionally rapid, with simultaneous emergence of symptoms across multiple villages, suggesting multiple infection points.	The spread was perceived as alarmingly fast, moving from single-garden infections to area-wide infestation within one week.
Understanding of Disease Spread Trajectory	Official monitoring documented a clear spatial trajectory of spread from the initial epicenter to adjacent western regencies, with limited initial data from eastern regions.	Understanding of the geographical spread is limited and focused on the practical challenge of identifying latent infections in apparently healthy fruit.	The geographical direction and pattern of the disease's spread are unknown, with its arrival perceived as sudden and unexplained within the community.

Source: Thematic Analysis of In-depth Interview Data (2023 for Flores Island)

Table 4. Result of paired sample T-Test of farmers' income before and after BDB outbreaks

Condition	Income	StDev	T-calculated	T-table	Significance
Before BBB (IDR/ha/year)	38,585,513.04	29,705,675.25	7.16	1.67	0.00
After BBB (IDR/ha/year)	13,453,214.49	6,087,927.80			
Decrease (IDR/ha/year)	25,132,298.55	29,159,452.01			
Decrease (%)	65.00				

Source: Statistical Analysis of Survey Data (2019, 2023)

The epidemic of BBD in ENT has caused deep and multifaceted consequences, wiping out rural economies, jeopardizing food security, and disrupting socio-ecological systems on a significant scale. At the economic level, the pathogen decreased banana production in Sumba Island, especially in East Sumba District, since 2018 (Figure 4.A). In Flores Island since 2022, except for Sikka District since 2020, for an unknown cause (Figure 4.B). The widespread presence of banana clumps exhibiting BBD symptoms along the inter-district road was noted (Figure 4.C), concurrently with the continued transit of trailers laden with banana bunches (Figure 4.D), indicating a potential disconnect between disease observation and biosecurity risk management. Statistical analysis showed that BBD wrought disastrous losses for smallholder producers; a paired sample t-test resulted in a statistically significant ($p < 0.001$) 65% reduction in annual revenue per hectare, crashing from IDR 38.6 million to IDR 13.5 million upon BBD infestation (Table 4), consistent with results from Sumba Island, where production reduction of 60-90% translated into estimated district-level losses of USD 0.5 to 3.7 million (Mudita et al. 2018). However, the consequences go far beyond loss of livelihoods and income. By being a linchpin of dryland agro-ecosystems, the devastation of Musa ABB 'Pisang Kepok' —an indispensable cultivar for subsistence and cash crops— disproportionately jeopardizes household food security for the 26.6% of producers depending on it as a staple food source, while also engendering severe shortages of banana stem livestock fodder, hence compromising integrated farming systems (Nampa et al. 2022). The local emergency echoes the national losses, where BBD has rendered 27-80% of land in primary production areas such as South Sulawesi and Lampung unproductive, at an estimated loss of USD 1 million in export (Vos et al. 2020). The crisis reveals a strategic vulnerability: the future spread of BBD, exacerbated by the threat of the other destructive Fusarium wilt Tropical Race 4 (TR4), risks initiating a cascade failure in regional food systems. This highlights that BBD is more than a phytopathological phenomenon but a multifaceted socio-ecological disaster deserving of a holistic biosecurity approach to protect livelihoods, nutrition, and ecological integrity, particularly in NTT's vulnerable dryland ecosystems.

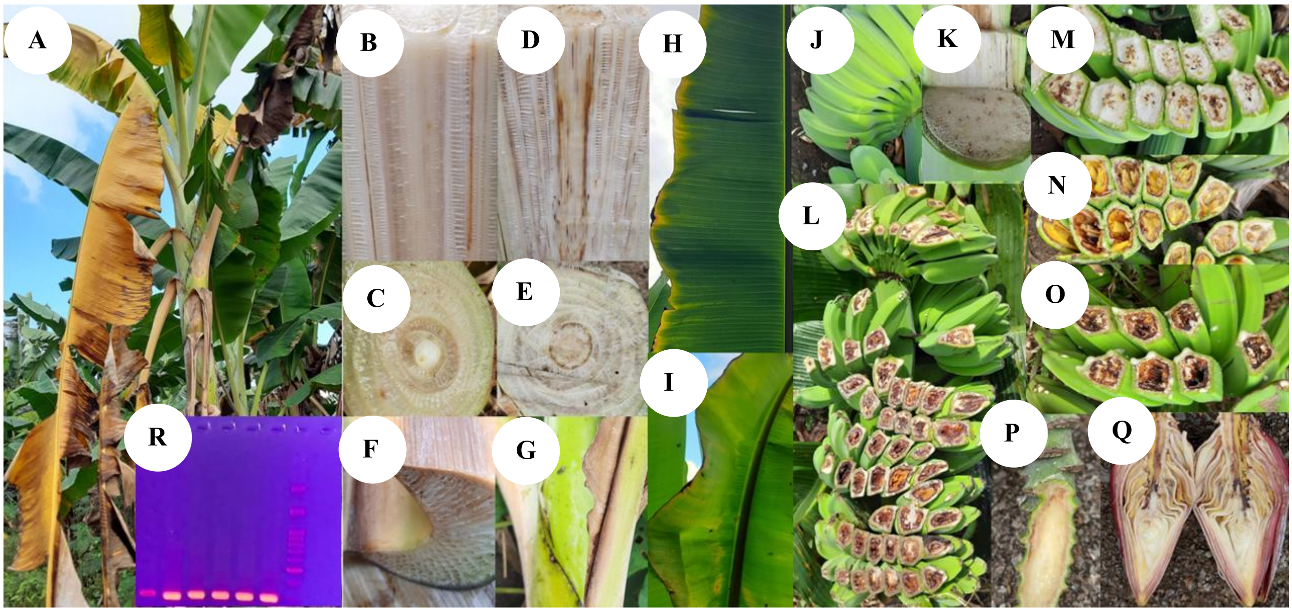

Figure 2. Disease symptoms and pathogen signs of BBD observed in Musa ABB 'Pisang Kepok' across the West Manggarai, Manggarai, East Manggarai, Ngada, and Nagekeo, in Flores Island, the Province of East Nusa Tenggara: A. Broken leaf lamina hanging down, typically initiating from younger leaves; B. Leaf sheath with reddish-brown streaks visible on a longitudinal section of the pseudostem; C. Leaf sheath with reddish-brown spots and blotches visible on a transverse section of the pseudostem; D. Leaf sheath and true stem (constituting the base of the fruit bunch stalk) exhibiting reddish-brown streaks on a longitudinal section of the pseudostem; E. Leaf sheath and true stem (constituting the base of the fruit bunch stalk) exhibiting reddish-brown spots and blotches on a longitudinal section of the pseudostem; F. Browning and rotting petiole of a mature leaf prior to abscission; G. Browning decay along the groove edges of a sucker leaf petiole; H. Leaf lamina exhibiting yellowing and drying along the margins; I. Sucker leaf lamina showing yellowing and drying along the margins, developing asymmetrically; J. Fruit appeared externally fresh; K. Fruit bunch stalk displaying reddish-brown streaking and spotting on longitudinal and transverse sections; L. Internal fruit pulp rot upon cutting a fruit that appears fresh externally; M to O. Progressive stages of rotting and discoloration of the fruit pulp, from tan to reddish-brown to dark brown, accompanied by reddish-brown mucoid exudate in advanced stages of fruit decay; P. Male bud stalk exhibiting reddish-brown spotting and streaking on an oblique section; Q. Decaying brown lesions on a transverse section of the initial rotting male bud, and R. Result of PCR test. Source: Field photos and PCR analysis (2023)

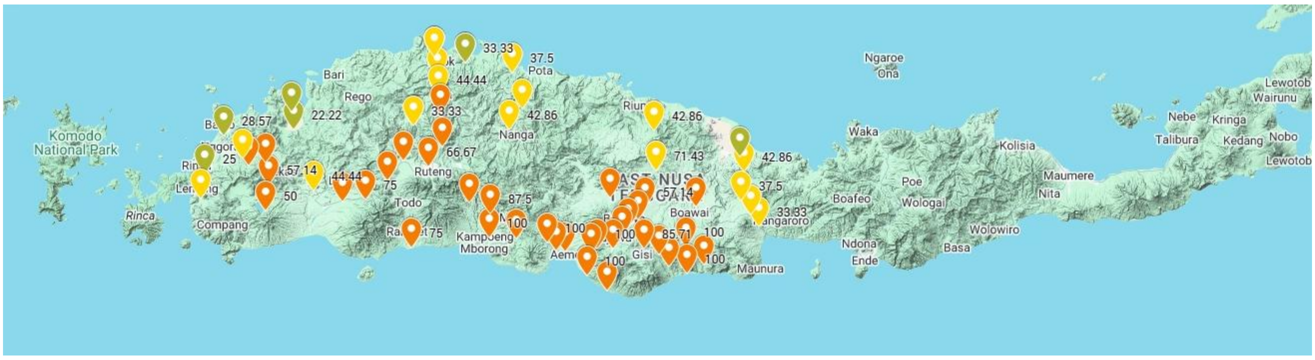

Figure 3. Map showing the spatial distribution of BBD incidences across surveyed areas in the central and western parts of Flores Island. Orange represents high, yellow represents medium, and green represents low incidence, respectively. Source: Georeferenced Incidence Data (2023)

Biosecurity governance and technical capacity constraints

The Indonesian biosecurity governance for agriculture is not regulated by a single Biosecurity Act, but is based on a hierarchy of laws, government regulations, and ministerial decrees. Its main goal is to prevent the entry, establishment, and spread of quarantine pests and diseases and is consistent with international standards established by the International Plant Protection Convention (IPPC). The most important documents in managing threats like BBD include: (i) Law No. 21 Year 2019 concerning Animal, Fish, and Plant Quarantine, which replaces the earlier 1992 Quarantine Law and provide the legal basis for biosecurity activities; (ii) Government Regulation No. 14 Year 2002 concerning Plant Quarantine, which enforce the older law and remains relevant in the present for specific quarantine procedures; (iii) Government Regulation No. 6 Year 1995 concerning Crop Protection, outlining the operational framework for pests control within the country after border defenses are breached; (iv) Minister of Agriculture Regulation No. 25 Year 2020 concerning the Designation of Quarantine Pests, Pathogens, and Weeds, which officially declares certain pathogens, including *Ralstonia syzygii* subsp. *celebesensis*, as quarantine diseases; and (v) The Surveillance Guidelines for Quarantine Plant Pest, Pathogens, and Weeds, issued by the Agricultural Quarantine Agency's to regulate the national system of surveillance important for early detection and rapid response. Thematic analysis of these instruments, summarized in Table 5, shows that Indonesia has a strong regulatory framework on paper that covers the core pillars of biosecurity. However, the effective management of an endemic threat like BBD is severely hampered by systemic gaps in implementation, primarily related to resource shortages, enforcement capacity issues, socio-economic constraints, and stakeholder engagement challenges.

Building upon the thematic analysis of Indonesia's regulatory documents, which identified robust laws hampered by implementation failures in prevention, surveillance, control, and coordination, the findings from in-depth interviews on Flores Island (Table 6) provided stark empirical evidence of these systemic gaps manifesting on the ground. The interview data conclusively showed that the absence of an explicit, overarching biosecurity policy—the core failure identified in the regulatory analysis—directly cascaded into every critical aspect of banana cultivation. For instance, the surveillance and control measures (Agricultural Quarantine Agency 2007; Government of Indonesia 1995) were rendered ineffective because of reliance on reactive, *ad-hoc* responses and a complete lack of early detection systems. Similarly, the strong exclusion principles enshrined in Law No. 21 Year 2019 concerning Animal, Fish, and Plant Quarantine were wholly undermined by the identified gap in the planting material sector, where the absence of pathogen-free certification and controls directly facilitated the anthropogenic spread of the bacterium, a known critical failure in managing bacterial wilt diseases (Molina et al. 2020). This disconnection between the formal regulatory framework and the actual on-the-ground reality, where community-driven initiatives attempt to fill the gap cause by missing technical support and incentives, breaks the integrated, knowledge-based approach to sustainable farming mandated by Law No. 22 Year 2019 concerning Sustainable Agricultural Cultivation Systems. The interview results thus clearly show that without a dedicated national strategy prioritizing biosecurity as a fundamental principle and providing the institutional framework and resources needed for its implementation, policies will likely continue to fail in controlling pandemics like BBD, leaving smallholder farmers at risk and harming national food security (Narvaez et al. 2020).

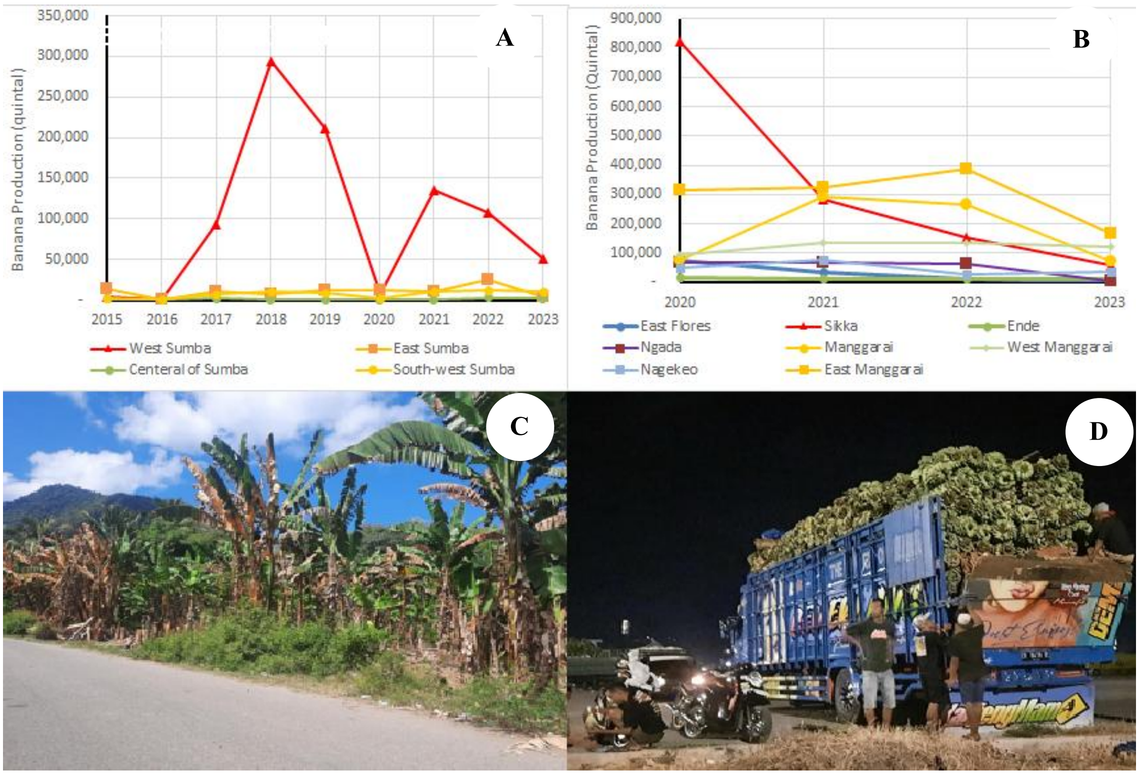

Figure 4. Decrease in Banana Production Associated with BBD: A. In Sumba Island since 2018; B. In Flores Island since 2022; C. Banana Clumps showing BBD Symptoms along the Inter-District Road in Flores Island; and D. Trailers Laden with Bananas amid BBD Outbreaks. Source: BPS (2016, 2018, 2021, 2023, 2024) and Field Photos (2025)

Table 5. Themes, gaps, and implementation challenges emerging from key Indonesian biosecurity laws and regulations

Theme	Core objective	Key regulatory instruments	Relevance and strengths	Gaps and implementation challenges (in context of BBD)
Prevention and Exclusion	To prevent the introduction of quarantine pests into Indonesian territory through stringent import controls.	• Law No. 21 Year 2019 concerning Animal, Fish, and Plant Quarantine (Arts. 8, 9) • Government Regulation No. 29 of 2023 concerning the Implementation Regulation of Law No. 21 Year 2019 • MoA Regulation No. 25 Year 2020 (Designation of Quarantine Pests, Pathogens, and Weeds)	Provides a strong legal basis for inspecting, treating, rejecting, or destroying imported plant material, crucial for preventing the entry of new pathogens or strains	Reactive to External Threats: BBD is already endemic. The framework is less effective against the internal movement of infected planting material between islands, which is a major pathway for BBD spread.
Surveillance and Early Detection	To establish a proactive system for monitoring, quickly detecting, and identifying new pest incursions.	Surveillance Guidelines for Plant Pests, Pathogens, and Weeds or Quarantine Plant Pests, Pathogens, and Weeds (Agricultural Quarantine Agency 2007)	Establishes a formal, top-down system for pest surveillance, mandating roles for local agricultural offices (*Dinas Pertanian*).	Resource and Capacity Limitations: Implementation is often under-resourced. Detection of BBD frequently relies on farmer reports after establishment, not proactive government scouting. Diagnostic delays hinder rapid response.
Management and Containment	To mandate immediate action to contain, suppress, and eradicate a pest upon detection to prevent further spread.	• Government Regulation No. 6 Year 1995 concerning Crop Protection • MoA Decree No. 887/Kpts/OT.210/9/1997 concerning Guidelines for Pest, Pathogen, and Weed Control	Authorizes critical response measures: eradication (destruction of plants), establishment of quarantine zones, and sanitation procedures.	Socio-Economic and Enforcement Challenges: • Compensation: Lack of feasible compensation schemes disincentivizes farmers from reporting outbreaks. • Enforcement: Restricting the movement of host material via informal trade networks is extremely difficult. • Resources: Large-scale eradication is logistically complex and costly.
Stakeholder Coordination and Awareness Raising	To define clear mandates for coordination between agencies and engage stakeholders in biosecurity efforts.	• Law No. 21 Year 2019 concerning Animal, Fish, and Plant Quarantine • Law Number 9 of 2015 concerning the second amendment of the law on regional government	Clearly designates the Quarantine Agency (*Balai Karantina Pertanian*) for border security and the Local Agriculture Services (*Dinas Pertanian*) for internal control	Fragmented Implementation and Lack of Outreach: • Coordination Gaps: Can occur between national and local authorities. • Top-Down Approach: Regulations lack strong mechanisms for mandatory farmer and trader education. Low awareness of BBD pathways and regulations is a critical vulnerability.

Source: Thematic Analysis of Indonesian Biosecurity Laws and Regulations (2025)

The biosecurity response to BBD in ENT is critically undermined by significant technical and knowledge-transfer gaps, as exemplified by two stark inconsistencies. First, despite published research confirming the presence and spread of BBD on Sumba Island since the 2010s (Mudita and Benu 2018; Ray et al. 2021; Nampa et al. 2022), the Provincial Agricultural and Food Security Services inaccurately designate the entire island as a BBD-free zone on its public maps (Department of Agriculture and Food Security of NTT Province 2024). This discrepancy highlights a severe breakdown in surveillance and knowledge translation, where policymakers fail to use scientific findings to inform the public, creating a dangerous blind spot in regional biosecurity awareness. Second, a profound misunderstanding of the pathogen's biology is evident in the widespread recommendation by district agricultural services and agricultural extension officers to apply the antifungal agent *Trichoderma* for controlling the pathogen. This recommendation is fundamentally misaligned with the etiology of BBD, which is caused by the bacterium *Ralstonia syzygii* subsp. *celebesensis* (Safni et al. 2014) and is primarily transmitted through inflorescences via insect, bird, and bat vectors (Sahetapy et al. 2020a; 2020b; Ray et al. 2022). Scientifically validated short-term mechanical control methods, such as the early removal and bagging of the male bud to prevent vector access and long-term cultural control by planting of Musa ABB 'Pisang Kepok' without male inflorescence, a variant known as 'Kepok Tanjung' (Hermanto et al. 2013; Drenth et al. 2018), are neglected in favor of ineffective intervention. These gaps—the failure to integrate expert knowledge into official systems and the dissemination of incorrect control advice—reveal a deep disconnection between research, policy, and extension. This disconnection perpetuates a cycle of ineffective responses, wasting limited resources, eroding farmer trust, and ultimately facilitating the unimpeded spread of the pathogen, as criticized in assessments of plant health systems (Mudita and Benu 2018; Narvaez et al. 2020).

Table 6. Biosecurity gaps and the absence of biosecurity measures resulting from the thematic analysis of in-depth interviews with BBD stakeholder groups in the central and western parts of Flores Island

Identified first-level theme	Second-level policy aspect theme	Identified gaps	Indication of absence of biosecurity measures
• No active cultivation policy has been implemented since the 1990s. • Community-driven initiatives dominate current development efforts. • No technical support or government incentives provided.	Banana Cultivation	The absence of a proactive cultivation strategy that integrates disease prevention mechanisms is a key issue.	Cultivation practices are not integrated with disease-free zoning or crop rotation systems.
• Reactive measures such as public awareness campaigns and the distribution of Trichoderma. • Limited and fragmented coordination across government levels. • Extension activities are non-specific and opportunistic.	Disease Management	• Lack of an established early detection and rapid response system. • No biosecurity protocol based on zoning or quarantine.	No standard operating procedures for sanitation, internal quarantine, planting material movement restrictions, or farmer awareness training.
• The use of certified planting material is only encouraged after disease outbreaks have occurred. • No certified local seed sources available. • Weak regulatory control over seedling distribution.	Seed/Banana Planting Material	Absence of a proactive policy for the supply and distribution of disease-free planting materials.	Seed movement is not subject to pathogen-free certification, inspection, or quarantine controls.
• No dedicated or systematic engagement with technical experts. • Responses rely on *ad hoc* coordination and community reports.	Technical Expertise and Institutional Support	No institutional framework for scientifically-informed biosecurity implementation.	Absence of expert involvement in developing biosecurity protocols or disease surveillance systems.
• No explicit biosecurity policy is currently in place. • Plant quarantine measures are not yet prioritized.	Explicit Biosecurity Policy	Lack of a comprehensive biosecurity system covering upstream (seedlings) to downstream (post-harvest) stages	Biosecurity has not been adopted as a fundamental principle in the design of disease prevention and control strategies.

Source: Thematic Analysis of In-Depth Interview Data (2023)

The government officials in Indonesia are organizationally committed to the Integrated Pest Management (IPM) approach with its guiding philosophy of the Economic Threshold (ET) due to variously related reasons in policy path dependency, adherence to bureaucracy, as well as political economy. Firstly, IPM is constitutionally codified as the country's national crop protection system through Law No. 22 Year 2019 concerning Sustainable Agricultural Cultivation Systems, which superseded Law No. 12/1992 concerning Plant Cultivation Systems. Such legislation creates a formidable institutional path dependency, where officials are obligated to operate within this legally sanctioned framework, regardless of its technical appropriateness for all threats (Thornburn 2014). The ET is a transparent, measurable, and legally justifiable threshold for intervention that facilitates decision-making for inexperienced local extension services that are incapable of working under more sophisticated, proactive monitoring (Thornburn 2014). This is compounded by regional decentralization that has occurred since 1998, whereby agricultural power has shifted to regional governments that have extensive technical limitations as well as short-term perspectives (Resosudarmo 2012). Regional head of governments, looking to obtain tangible outcomes in th foreseen 5-year election period, tend to prefer short term, visible application of pesticide spraying—a response facilitated due to attaining the ET—a solution that contrasts with the more subtle, long-term approach of augmenting ecological resilience through classical IPM that was promoted in the first-phase National IPM Program (McClelland 2002; Winarto 2004). Furthermore, the reactive ET model aligns with the commercial interests of a powerful pesticide industry, which actively promotes chemical solutions. This creates a perverse incentive structure where the response to any pest outbreak, even a bacterial one for which pesticides are ineffective, is often channeled towards chemical control, as this is a well-established and lucrative pathway within the existing system (Thornburn 2015). Consequently, in the case of a systemic, transboundary disease like BBD that needs pre-emptive, area-wide control and stringent quarantine prior to symptom manifestation, the reactive IPM approach is not only ineffective but also adversative. What this does is guarantee that actions are always taken too late after the disease is already widespread and economically destructive, effectively institutionalizing failure as a strategy against invasive species (Mudita and Benu 2018; Deguine et al. 2021).

Designing a scalable, locally feasible, and resilience-based biosecurity framework

The disastrous outbreak and proliferation of BBD throughout the drylands of ENT is a quintessential example of a "global-local" environmental issue, where global biological and economic impulses converge with hyper-local agricultural systems and socio-economic vulnerabilities. A multi-scalar analytical approach is thus adopted from that put forward by Wilbanks and Kates (1999), not merely as an academic exercise but as a critical prerequisite for designing an effective, resilience-based, and locally feasible biosecurity system (Table 7). The BBD pandemic is illustrative of the key principles in their model: the pathogen itself originates from outside ENT. It is dispersed through regionalized trade pathways, while impacts are most severely experienced in the local domain, where smallholder farmers suffer from entire crop destruction and acute food insecurity. A standard top-down, one-size-fits-all approach to biosecurity policy will in this case inevitably fail, as it is likely to become "disembodied from experience" (Wilbanks and Kates 1999), neglecting the extreme local variation in cultivation systems, the powerful though unofficial agency of merchants and farmers, as well as the unique socio-ecological interactions in ENT's drylands agro-ecosystems. A purely local answer, on the other hand, has neither the institutional backstop, scientific capacity, nor regulatory powers to respond to a pathogen that transcends village, district, and provincial borders. Therefore, a framework that explicitly recognizes the importance of scale is needed to span this gap, ensuring that both national and international resources and policies work together to enhance, rather than replace, locally accessible and culturally-compatible actions for containment, monitoring, and sustainable restoration.

Table 7. A Multi-Scalar Framework for Designing a Resilience-Based Biosecurity System against Banana Blood Disease (BBD) in East Nusa Tenggara

Scale dimension	Definition	Global and national scale (Implications for BBD)	Local scale (Implications for BBD in NTT drylands)
Domain	The systemic and cumulative processes by which local problems become global ones and vice versa.	BBD is part of a global pandemic of bacterial wilt affecting bananas. International travel and trade can introduce new pathogen strains. Climate change may alter disease suitability zones.	BBD spread is extreme and devastating at the local level due to shared planting material (suckers), contaminated tools, and a lack of awareness, destroying livelihoods and food security.
Agency	The intentional human actions and the formal and informal institutions that guide them.	Mandates from the International Plant Protection Convention (IPPC) and Indonesian national law (e.g., UU No. 21/2019) provide a structure for quarantine and control but are poorly enforced locally.	Actions are voluntary and community-driven. Farmers and local traders are the primary agents of spread or control. Their practices (e.g., using shared machetes, moving suckers) dictate disease trajectory.
Interaction	The driving forces and consequences of the relationship between global/ national structure and local agency.	National policies must internalize the complexity of local socio-economic realities (e.g., farmer poverty, informal seed systems) to be effective.	Local actions are distinctive but are profoundly influenced by broader forces. E.g., demand from Java/Bali drives traders to enter villages, inadvertently spreading BBD through their operations.
Tractability	How easily a phenomenon can be understood, traced, and grounded in effective actions.	Difficult to ground in direct action. National goals for "BBD control" can become disembodied from the actual experience of farmers, leading to generic, ineffective top-down solutions.	Much more traceable and actionable. Pathogen spread can be directly linked to specific practices (e.g., harvest from infected clumps). Solutions (e.g., community-led sanitation protocols, rogueing) can be grounded in local knowledge and immediate benefits.
Variance	The degree of difference or inconsistency across the system.	Less variance in policy design (a single national strategy), but high variance in implementation success across different islands and provinces.	Extreme variance between and even within villages. Some areas may have a high incidence, while neighboring ones are disease-free, based on specific trade routes and farmer networks.
Perspective	The point of view regarding cause, effect, and responsibility.	Risk of misdiagnosis by viewing BBD only as a biosecurity failure without seeing its roots in rural poverty, lack of alternative planting material, and weak agricultural extension systems.	Risk of misdiagnosis by attributing outbreaks purely to local negligence ("farmer error"), while ignoring the role of broader factors like the lack of affordable, clean seed or effective national quarantine.

Source: Adapted from Wilbanks and Kates (1999)

Table 8. Priority Actions for a Resilience-Based Biosecurity Framework in Managing the Transboundary BBD

Stage of the resilience process	Priority action for BBD biosecurity
Anticipate	• Establish a community-led surveillance network for early detection and reporting of BBD symptoms, supported by mobile technology and rapid diagnostic tools. • Conduct participatory mapping with farmers to identify and prioritize high-risk pathways for pathogen introduction and spread.
Mitigate	• Implement immediate, community-organized rogueing and destruction of infected plants, with agreed-upon compensation mechanisms. • Enforce localized, culturally-sanctioned internal quarantine and movement restrictions on banana planting material. • Promote immediate farm-level biosecurity measures (e.g., tool sanitation protocols) through farmer-to-farmer training.
Adapt	• Evaluate and adapt control measures based on community feedback and local efficacy. • Develop and distribute locally adapted, disease-tolerant banana cultivars through the establishment of community-based seedling gardens. • Promote agro-ecological diversification (e.g., intercropping, livestock integration) to reduce systemic reliance on bananas and build broader livelihood resilience.

Source: Synthesis of Data Analysis Results (2025)

The multi-scalar analysis shows that a resilience-based biosecurity framework for BBD must be intentionally designed to operate across multiple levels, not just one. The global and national levels provide essential support—policy, resources for producing clean seed, and international research collaboration (Molina et al. 2020). However, as Table 7 indicates, these top-down measures are often disconnected from local realities and show wide variation in implementation. On the other hand, the local level is where actions are most manageable, and specific practices influence disease spread. Yet, local actors often lack the resources and knowledge needed to act effectively and may misdiagnose the causes. Therefore, for the framework to work well, feedback between levels is necessary: national policies should consider local differences and perspectives to stay relevant, while local stakeholders need support from national systems to access disease-free planting materials and scientifically-informed protocols (Narvaez et al. 2020). A practical and scalable strategy hinges on using national authority to empower local actions—such as funding local clean seedling gardens and conducting farmer-to-farmer biosecurity training—thus bridging the gap between regional disease transmission systems and the severe local impacts on dryland farmers in ENT.

Designing a resilience-based biosecurity framework for the management of BBD in the dryland agro-ecosystems of ENT requires a significant departure from traditional, top-down control. Instead, a comprehensive strategy that integrates biosecurity into the broader socio-ecological context of resilience is needed. The province's inherent vulnerabilities—degraded lands, low soil fertility, climatic variability, and complex cultural institutions (Seran et al. 2021; Ngongo et al. 2022)—mean that a disturbance like BBD does not simply cause crop loss but risks triggering a cascade of failures across food security and livelihood systems. Therefore, the framework must move beyond reactive measures and integrate the entire resilience process: anticipation, mitigation, and adaptation (Table 8). This approach recognized that a system's recovery depends on its inherent resistance to initial impact and its capacity to reorganize afterwards (Grafton et al. 2019; Walker 2020). As illustrated in Table 8, key elements of the framework should include community-based surveillance for early detection, organized local action for containment, and the long-term adaptation of farming systems through diversified and localized resources. This multi-stage process is essential for building the necessary resistance and reorganization capacity to navigate current and future biological threats, thereby ensuring that the biosecurity system itself is resilience-based and does not exceed critical performance tipping points under pressure from multiple stressors (Pimm et al. 2019; Arndt et al. 2024).

The resilience-based biosecurity framework proposed here requires a radical change in crop protection. It shifts from a centralized, top-down approach to a polycentric and adaptive governance model. This model actively involves stakeholders on various scales (Cook et al. 2010). National and provincial agencies transition from being the sole directors to facilitators and enabling agencies. They decentralize power and funds to district-level entities as well as community collectives to conduct scale-specific anticipatory and mitigation measures (Morrison et al. 2019). Such a structure is essential for managing the complex, cross-scale interactions inherent in biological invasions, as highlighted by Wilbanks and Kates (1999). Effective implementation requires clearly defined yet complementary roles from all the stakeholders. The National and provincial governments provide the broad policy directive, secures financing for compensation schemes, and support large-scale production of clean planting material. Local district government requires technical as well as funding capacity to orchestrate surveillance, enforce localized quarantine, and channel resources. Agricultural extension services require retraining to function as knowledge brokers and facilitators of participatory learning rather than merely disseminating top-down instructions. Above all, farmers and local traders must be recognized as co-implementers, not just beneficiaries; their contributions are vital for ground-truthing surveillance, adhering to community-sanctioned biosecurity protocols, and reorganizing farming systems through diversification (Djalante et al. 2020). Without this genuine devolution of responsibility and the building of trust through transparent communication and shared decision-making, the framework is likely to remain a document exercise, failing to produce the desired collective action to create durable resilience against BBD in ENT's challenging dryland context. Therefore, transparent communication is crucial to keep all stakeholders informed and involved in the process.

This study shows that the current reactive IPM approach mandated under Indonesian law is ineffective in managing Banana Blood Disease (BBD) caused by *Ralstonia syzygii* subsp. *celebesensis* in East Nusa Tenggara. As key stakeholders, your role in implementing the proposed changes is crucial. The current approach has led to a 65% reduction in farmer income, triggered food insecurity, and eroded banana biodiversity. The core challenges, including policy fragmentation, weak cross-sectoral coordination, lack of proactive surveillance, and absence of pathogen-free planting material, are exacerbated by technical capacity gaps and ineffective control advice. A paradigm shift is therefore required toward a resilience-based biosecurity framework that bridges national regulations with local realities and functions across pre-border, border, and post-border levels. Key recommendations include establishing compensation schemes, promoting farm-level biosecurity and agro-ecological diversification, legislating a National Banana Biosecurity Strategy, forming a provincial multi-stakeholder task force, retraining extension officers, strengthening community-based surveillance networks, developing certified seedling gardens, and redefining governance roles from centralized control to enabling locally adapted biosecurity actions.

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GIS-based land suitability and core-plasma partnership for sustainable cattle farming in South Lembor, Indonesia

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Abstract. *Wulakada HH, Nalle AA, Pramatana F, Keon YF. 2025. GIS-based land suitability and core-plasma partnership for sustainable cattle farming in South Lembor, Indonesia. Intl J Trop Drylands 9: 135-147.* Domestic beef production in Indonesia currently only meets about 45% of the total demand. In West Manggarai District, East Nusa Tenggara Province of Indonesia, South Lembor Sub-district is designated to produce beef to anticipate the growing demand from tourism in the nearby Labuan Bajo. This study aims to explore the potential of cattle livestock development through land suitability analysis and partnership model design for beef cattle farming in the South Lembor. This research integrated GIS-based method (a systematic approach to analyze spatial data using Geographic Information Systems (GIS) to solve problems and gain insights from geographic patterns) and focus group discussion to capture stakeholders' perspective. The findings propose a core-plasma partnership entity as a model for design development, with Benteng Dewa Village in South Lembor Sub-district, identified as a focal point for advancing the livestock sector. The spatial analysis delineates the core zone 943.94 ha for grazing pasture, 459.59 ha for forage plantation, and the plasma zone of 276.29 ha, and optimizes the buffer zone in other villages within South Lembor Sub-district (1,528.66 ha) to support activities in the core zone. This study suggests in the introduction of a core–plasma partnership model in East Nusa Tenggara which connects core companies with local farmers to ensure technology transfer, financial access, and sustainable market integration.

Keywords: Core-plasma partnership, design development, East Nusa Tenggara, GIS-based, livestock model

INTRODUCTION

Indonesia's beef consumption per capita remains among the lowest in Asia, averaging only around 2-2.7 kg annually, far below the FAO's recommendation of 33 kg per capita (Chafid 2022; Astiti et al. 2023; Islami et al. 2025). Demand continues to rise with a growing population and increased income, with estimates of national consumption to reach more than 764,000 tons by 2025. Retail prices are relatively high, ranging from IDR 120,000-160,000 per kilogram, creating disparities between consumer access and domestic supply (Mubarok et al. 2024). Current production is estimated at about 570,000 tons, fulfilling only 45% of national demand (Firdayati et al. 2024; Sunyigono et al. 2024). This persistent deficit underscores the failure of self-sufficiency programs and forces reliance on imports (Smith et al. 2018; Danasari et al. 2023). Contributing factors of such gaps include high slaughter rates of productive females, weak integration with other agricultural commodities, and unsustainable production systems (Kandachar and Halme 2017; Agus and Widi 2018).

Demand for beef is further stimulated by the tourism sector, particularly in East Nusa Tenggara (ENT), where Labuan Bajo serves as a Super Priority Tourism Destination (Kapa 2015; Rahmayani et al. 2022). South Lembor Sub-district, West Manggarai District, has been designated for cattle development to meet the rising demand, considering that the majority of the population in South Lembor are cattle breeders, with a population of 4,261 cattle in 2023 and a grassland area of 14,743.04 Hectares (Nur et al. 2023). The success of livestock enterprises depends heavily on access to sustainable feed resources, which account for up to 70% of production costs (Indonesian Ministry of Agriculture 2014; Gwiriri et al. 2019). Forage availability, therefore, represents a key limiting factor for scaling up beef production in ENT. Despite its designation as a development zone, no previous study has combined GIS-based land suitability analysis with participatory approaches to design livestock development strategies in South Lembor.

The ENT region is ecologically vulnerable, characterized by dryland ecosystems with low rainfall, frequent droughts and variable soil fertility (Kuswanto et al. 2019a, b; Mukkun et al. 2021). Climate change intensifies these challenges, reducing pasture quality, limiting water availability, and heightening the risks of land degradation (Stavi et al. 2022; Slayi et al. 2024). Local communities have responded with adaptive measures such as mixed crop–livestock systems, rotational grazing, and diversification of livestock species (Niranjan and Bose 2020; Riptanti et al. 2022). Sustainable strategies for rangeland management, including integrating trees and legumes, are increasingly recognized as critical for maintaining productivity in drylands (Assani et al. 2024). Given these challenges, Geographic Information Systems (GIS) emerge as a vital tool to map biophysical characteristics of a region such as slope, vegetation, and soil conditions, supporting the allocation of land for pastures, forage plantations, and integrated crop–livestock systems (Parracciani et al. 2024; Praptiwi and Lesik 2025). GIS-based approaches also facilitate climate risk mapping and adaptive planning, enhancing resilience at both community and regional levels (Ngongo et al. 2023; Parlato et al. 2024).

Besides land suitability assessment, innovative institutional models are needed to strengthen smallholder farmers’ capacity. The core–plasma partnership offers a viable solution for resource-scarce regions like ENT. In this system, core companies provide improved breeding stock, finance, technology, and access to markets, while smallholder farmers (plasma) contribute land and labor (Widiati et al. 2019). This partnership improves efficiency, reduces transaction costs, and enhances bargaining power (Qin et al. 2021). It also promotes climate adaptation by facilitating access to resilient breeds, water conservation, and sustainable practices (Lu et al. 2024). Unlike contract farming, which often disadvantages smallholders (Bellemare 2018; Mao et al. 2021), the core–plasma model emphasizes profit-sharing, knowledge transfer, and more equitable risk distribution (Alary and Gautier 2023). Successful applications in Sulawesi and other regions show that such models can raise income, stabilize supply, and integrate smallholders into formal value chains (Dedu et al. 2023; Harifuddin et al. 2023).

This research aims to analyze land suitability and design a core–plasma partnership model for sustainable beef cattle farming in South Lembor. By integrating GIS-based spatial analysis with participatory stakeholder engagement, the study seeks to identify optimal zones for grazing, forage plantations, and community-based plasma areas, thereby providing a replicable framework to enhance livestock productivity, farmer livelihoods, and regional food security.

MATERIALS AND METHODS

Study area

The research was conducted in the South Lembor Sub-district (119^{0}52’57.8” E - 120^{0}18’48.5” E; 8^{0}41’23.3” S - 8^{0}52’2.6” S) of West Manggarai District, East Nusa Tenggara Province, Indonesia (Figure 1). South Lembor Sub-district has an annual mean temperature ranging from 18 to 27°C and an annual precipitation range of 1373-3182 mm (Fick and Hijman 2017). These climatic factors provide favorable conditions for beef cattle farming, influencing animal health, productivity, and economic viability. Temperatures exceeding 30°C can lead to significant challenges, including heat stress, which adversely affects cattle performance by reducing feed efficiency and increasing susceptibility to diseases (Lees et al. 2019; Wankar et al. 2024). Effective management strategies, such as environmental modifications and nutritional adjustments, are crucial for mitigating heat stress, thereby emphasizing the importance of maintaining temperatures within the optimal range (Lees et al. 2019). Sufficient rainfall fosters the growth of high-quality forage that is critical for the feeding of beef cattle. Optimal moisture conditions lead to improved pasture productivity, thereby enhancing the profitability of cattle farming operations (Addis et al. 2021). This is particularly important, as quality forage directly correlates with the health and growth rates of beef cattle, thereby reducing the need for supplementary feeding costs that can otherwise erode farm profitability. West Manggarai District, which is closely associated with Labuan Bajo, has a considerable market potential due to its tourism activities, which in turn increase the demand for meat.

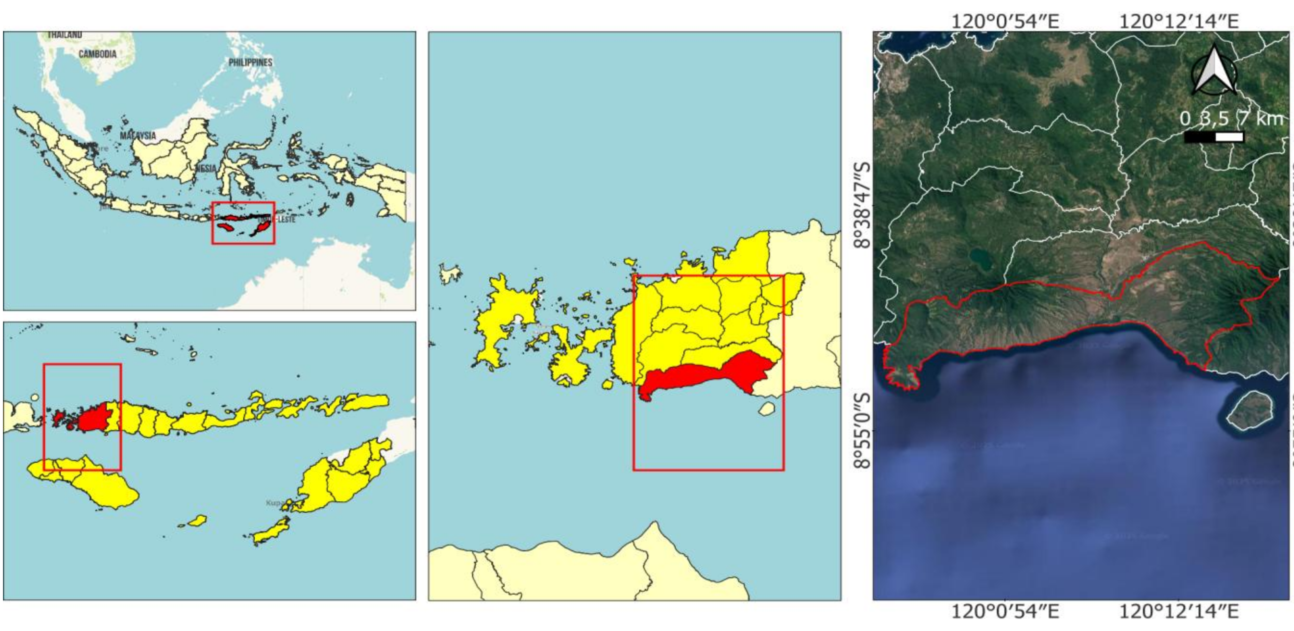

Figure 1. Map of study area in South Lembor Sub-district, West Manggarai District, East Nusa Tenggara Province, Indonesia

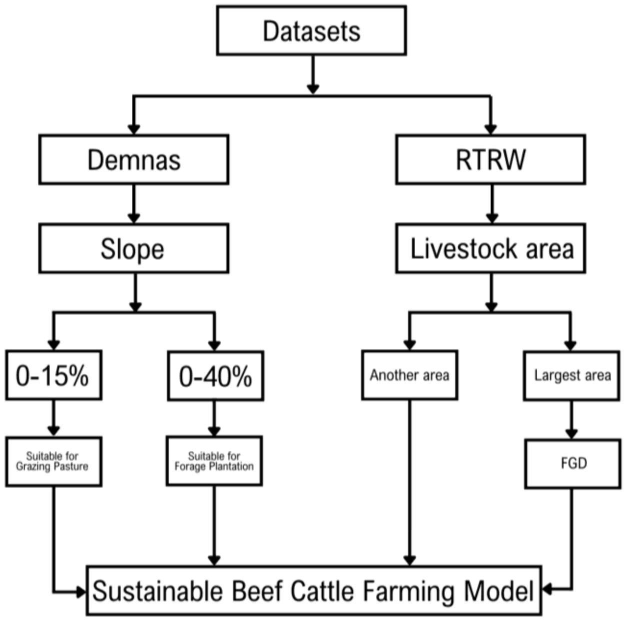

Figure 2. Analytical framework of the study to spatially allocate and design a sustainable beef cattle farming model in South Lembor Sub-district, West Manggarai District, East Nusa Tenggara Province, Indonesia

Analytical framework

This study utilized a socio-economic analysis by combining spatial analysis and Focus Group Discussion (FGD) (Figure 2).

Spatial analysis

In general, to assess the potential of livestock sector in South Lembor using GIS tools (ArcMap 10.8.2), several basic data are required including land spatial allocation based on the Regional Spatial Plan (*Rencana Tata Ruang Wilayah*/RTRW) of West Manggarai District (Santoso and Prasetiyono 2018), and slope gradient generated from the Digital Elevation Model National (DEMNAS), with a resolution of 8.25 m (Figure 2). One of the primary advantages is that DEMNAS can be used to assess topographical features crucial for livestock management, such as slope and elevation, which significantly influence water drainage and forage availability, thereby impacting accessibility for grazing animals (Aristin and Purnomo 2021). For instance, a detailed elevation model can help identify suitable grazing lands that are not prone to erosion or waterlogging, thereby improving the sustainability of livestock farming systems (González-Quintero et al. 2019). This aligns with findings by Li et al. (2024) regarding the importance of understanding local geographical factors in dryland farming. Furthermore, integrating DEMNAS into livestock models can facilitate effective land-use planning by allowing farmers to optimize the placement of infrastructure, such as water sources, feeding stations, and housing for livestock. By understanding how landscape features impact livestock behavior and health, interventions can be tailored to improve animal welfare and productivity (Firmansyah et al. 2022). For example, strategically placing water sources in alignment with the natural topography can minimize travel distance for livestock, promoting better hydration and reducing stress (Ahmed et al. 2022).

Slope values were classified using the Reclassify Spatial Analyst Toolbox in ArcMap to delineate the suitable area according to the criteria. Understanding the slope values associated with livestock models has significant implications for optimizing livestock management and ensuring environmental sustainability in various terrains, particularly in regions such as Indonesia's drylands. Research indicates that sloped terrains present unique challenges and opportunities for livestock farming. For instance, studies have demonstrated that grazing on slopes can influence soil compaction and health, particularly in relation to livestock densities (Blanco-Sepúlveda et al. 2024). Increased compaction can adversely affect vegetation cover and soil fertility, which are crucial for providing adequate forage for grazing livestock. The ecological dynamics on slopes also play a critical role in livestock planning. Locations on steeper slopes may be less hospitable for livestock due to an increased risk of erosion and runoff, which can wash away essential nutrients (Pittarello et al. 2021). Research by Pittarello et al. (2021) highlights how slope and proximity to buildings can effectively separate areas based on livestock site-use intensity, guiding farmers to make informed decisions about pasture use. Thus, maintaining optimal slope angles can foster better livestock productivity while minimizing landscape degradation. Vegetation management strategies that incorporate slope data can help foster beneficial plant-animal interactions, promoting healthier pastures and ensuring the long-term productivity of the farming systems (Sunardi et al. 2025).

GIS tools effectively assess land suitability for livestock farming and are widely used by various researchers (Qiu et al. 2017; Balew et al. 2022; Rana and Moniruzzaman 2023a, b). This allows for potential assessment and development based on land suitability, current regional conditions, and the socio-cultural context of the population in South Lembor District, West Manggarai District (Santoso and Prasetiyono 2018; Agustine et al. 2023). Furthermore, environmental variables were integrated according to the criteria and technical standards established by the Indonesian Ministry of Agriculture (2014) for the potential development of livestock areas, specifically areas with an optimal slope for forage plantations of 40%. For grazing pastures, the recommended slope is 15%. This criterion is also supported by Mano et al. (2024), who indicate that areas with a slope less than 15% significantly increase the capacity for healthy forage growth, which is essential for livestock nutrition. Higher slopes are often associated with increased soil erosion and reduced water retention, leading to less favorable grazing conditions. Slopes exceeding 15% can lead to substantial soil degradation, resulting in a decrease in both the quality and quantity of forage available for grazing livestock (Severoğlu and Gullap 2020; Hartono et al. 2024). The management of slope gradient is vital for the welfare of cattle, as well as for reducing soil erosion and improving pasture quality. Research has shown that grazing pressures are higher in areas with gentler slopes, as these conditions support more robust forage growth, thus providing better nutrition for the cattle (Zhang et al. 2018).

Maintaining lower slope gradients helps enhance soil health and water retention capabilities, which are critical for sustainable beef production systems (Dahal et al. 2018).

Focus group discussion

The socio-economic and livestock potential areas obtained were then developed into models that could encompass the entire sub-district area under a sustainable development system. Several livestock sector models were developed through Focus Group Discussions (FGDs) with the community centered on Benteng Dewa Village, which has the most significant potential in the livestock sector, as guided by the local government. The FGD participants included community figures (seven individuals), village government representatives (two individuals), and livestock breeders (33 individuals). The rationale of the selection of respondents was based on community figures who influence village policies, village government as decision-makers, and livestock farmers, as all households in Benteng Dewa Village have livestock. The FGD implementation followed the Standard Operating Procedure for Focus Group Discussions from the Indonesian Government (49/SOP/2500/01/2022). Careful participant selection is crucial. Foraker et al. (2022) emphasized the importance of appropriate participant demographics, arguing that ensuring diverse representation can enhance the robustness and richness of the data collected. FGDs allow participants to discuss and debate various topics, thereby generating a range of insights that statistical methods might overlook. As noted by Krampe et al. (2021), FGDs enable researchers to explore participant perceptions about complex topics, making it possible to uncover themes that emerge from group discussions rather than predetermined questions. The interactive nature of FGDs encourages participants to build on one another's responses. This interaction often leads to the emergence of new ideas, challenges, and collective sentiments. Okafor et al. (2022) highlighted that discussions among cattle producers revealed not only their individual opinions but also a range of emotive themes that could contribute to a better understanding of responsible practices within the industry. The back-and-forth dialogue actively engages participants and promotes a richer data set than solitary interviews. The livestock model agreed upon by stakeholders in the FGD was proposed to the Investment and Integrated One-Stop Services Agency (*Dinas Penanaman Modal dan Pelayanan Terpadu Satu Pintu*/DPMPTSP) as a form of investment transparency for investors who wish to collaborate with the community.

RESULTS AND DISCUSSION

Livestock potential areas in South Lembor Sub-district

The beef cattle population in South Lembor Sub-district totalled 4,261 individuals, with Nanga Lili Village was the largest with 2,041 individuals, while Modo Village having the smallest with 31 individuals, and no cattle present in Surunumbeng and Benteng Tado Villages (BPS-Statistics of Manggarai Barat District 2023). According to the technical recommendations for developing livestock areas (Indonesian Ministry of Agriculture 2014), various technical requirements and criteria exist for forage gardens and grazing pastures. The establishment of technical criteria and standards is anticipated to enhance the quality of forage plantations for livestock and grazing pastures, supply superior forage for livestock, and convert temporarily uncultivated or neglected land into productive forage for livestock (Rao et al. 2017; Moyo and Ravhuhali 2022). Figure 3 provides additional details regarding the suitable locations for livestock development.

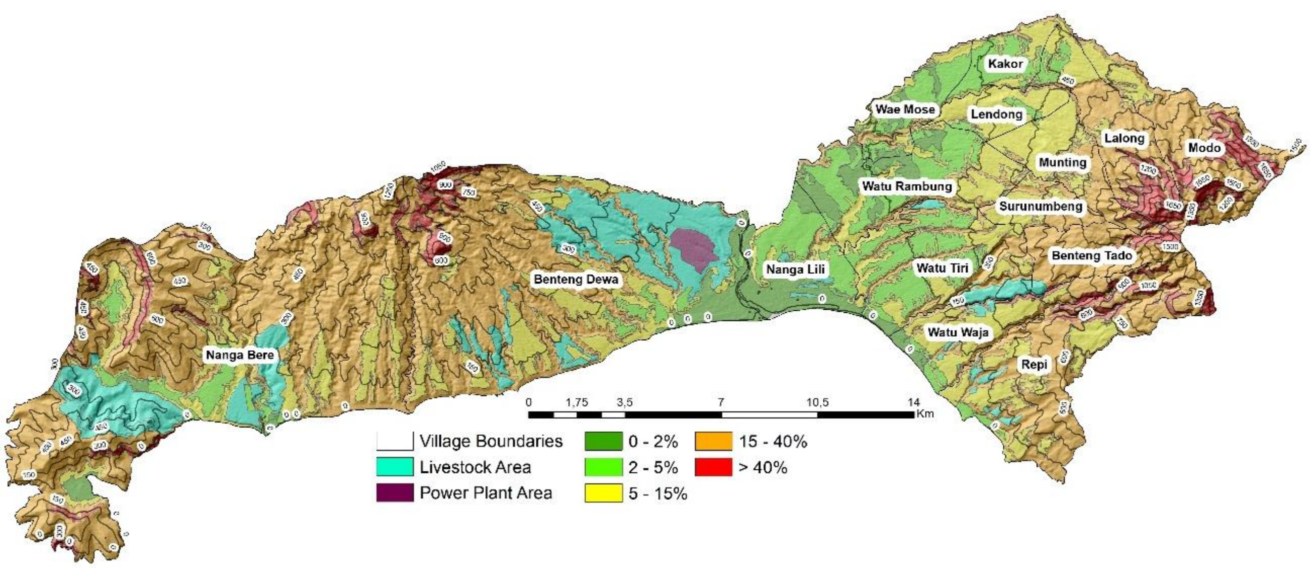

Figure 3. Potential areas for livestock development in South Lembor Sub-district, West Manggarai District, East Nusa Tenggara Province, Indonesia, based on slope. Slopes of 0-15% can be developed into grazing pastures, and slopes of 15-40% can be developed into forage plantations

Table 1. Potential of forage productivity in South Lembor Sub-district, West Manggarai District, East Nusa Tenggara Province, Indonesia

Village	VA (Ha)	LA (Ha)	LVA (%)	PLA (%)	PFP (Ha)	PGP (Ha)	POFP (Ha)
Benteng Dewa	8,049.80	1,679,84	20.87	52.07	1,679.84	1,010.66	669.18
Benteng Tado	898.92	26.40	2.94	0.82	22.53	-	22.53
Nanga Bere	10,801.25	1,172.11	10.85	36.33	1,172.11	342.07	830.04
Nanga Lili	1,365.52	55.26	4.05	1.71	55.26	55.26	0
Repi	2,968.63	72.75	2.45	2.26	72.75	21.57	51.18
Watu Tiri	2,197.92	172.15	7.83	5.34	161.83	85.23	76.60
Watu Waja	1,140.12	47.34	4.15	1.47	44.18	33.56	10.62
Total	36,389.91	3,225.95	53.14	100.00	3,208.50	1,548.34	1,660.16

Note: VA: Village Area, LA: Livestock Area based on RTRW, LVA: Percentage of livestock area per village Area (LA/VA), PLA: Percentage of potential livestock area (LA/ Total LA), PFP: Potential Forage Plantation (Slope value 0-40%), PGP: Potential Grazing Pasture (Slope value 0-15%), POFP: Potential only to be used as a forage plantation (PFP-PGP with Slope value > 15-40%)

Based solely on slope, South Lembor Sub-district has potential land for developing grazing pastures (slope 0-15%) at 14,778.76 hectares and forage plantations (0-40%) at 34,381.55 hectares. Based on this result, the land suitable for livestock production as specified in the West Manggarai RTRW needs modifications for developing extensive livestock operations or permanent zones (Metternicht 2018; Zhang et al. 2019). If a site with an allotment configuration beyond the livestock zone has been neglected and uncultivated for a prolonged period, local farmers may utilize natural resources, such as grass, to meet the forage requirements for livestock (Nelson et al. 2017; Prasetyani et al. 2023). If the area is utilized and administered according to its spatial allocation, local breeders are prohibited from reusing it. Consequently, it is essential to consider spatial allocation patterns in extensive and permanent growth to optimize and sustain cattle advancement (Widiatmaka et al. 2016). Table 1 presents information concerning the prospective regions for animal fodder production in the South Lembor Sub-district.

There are seven villages with livestock sector in South Lembor Sub-district: Benteng Dewa, Benteng Tado, Nanga Bere, Nanga Lili, Repi, Watu Tiri, and Watu Waja. The largest livestock area is located in Benteng Dewa, encompassing 1,679.84 hectares, which accounts for 52.07% of the total. In contrast, the smallest area is found in Benteng Tado, measuring 26.40 hectares, which accounts for 0.82% of the total. When analyzing data from the livestock sector about the village administration area, Benteng Dewa exhibits the highest percentage at 20.87% of the village area, while Repi shows the lowest rate at 2.45%. Benteng Dewa possesses significant potential for enhancing forage productivity for livestock, with a development area suitable for a forage plantation spanning 1,679.84 hectares. This includes areas well-suited for conversion into grazing land, encompassing an area of 1,010.66 hectares. Referring to the Table 1, the slope gradient criteria suitable for use in forage plantations areas, based on the allocation of space for the livestock sector, are in Nanga Bere Village, with an area of 830.04 Ha, and then followed by Benteng Dewa Village with 669.18 Ha. Smith et al. (2018) noted that natural resources, including land area and its utilization, rainfall, access to animal feed, and economic resilience, are key determinants of the sustainability of beef production. The development of this potential is essential due to the significant demand for beef in Indonesia. Additionally, the supply and production aspects present substantial opportunities to be structured to satisfy market needs (Agus and Widi 2018; Astiti et al. 2023). Chafid (2022) indicates that the anticipated production and consumption of beef and buffalo from 2022 to 2026 will consistently face a deficit, indicating an inability to satisfy market demand. According to his projections, Indonesia is expected to face a deficit of 307,321 tons of beef and buffalo by 2026. The burgeoning population and economic advancement within society significantly contribute to the heightened demand for meat, driven by an escalating inclination towards consuming high-quality protein sources (Milford et al. 2019).

The substantial potential coupled with elevated market demand is essential for expanding livestock production in the South Lembor sub-district (Sodiq et al. 2019). Smith et al. (2018) noted that natural resources, including land area and its utilization, rainfall, access to animal feed, and economic resilience, are key determinants of the sustainability of beef production. With a potential area of 1,548.34 hectares for grazing pasture and 1,660.16 hectares for forage plantations in South Lembor, it could help address the deficit if appropriately managed. Utilizing grazing pastures and forage plantations offers an alternative approach to addressing the challenges of climate change in the livestock sector of dryland areas (Assani et al. 2024). Implementing well-managed grazing systems can significantly enhance soil health, leading to increased biomass production and improved carbon sequestration (Zhou et al. 2017). Sustainable grazing practices can enhance soil carbon storage, a crucial step in mitigating the effects of climate change while also improving pasture productivity (Zhou et al. 2017). Such practices also help maintain forage quality and availability, which are crucial for livestock health, especially under the stresses associated with climate variability. The integration of grazing animals within forage plantations promotes biodiversity. Livestock can help control wildlife risks by reducing flammability through the consumption of dry and dead vegetation (Li and Jiang 2021). This function is particularly beneficial in the context of increasing wildfires driven by climate change. Additionally, maintaining diverse forage species can yield multiple ecosystem services, enhancing both resilience and productivity in grazing systems (Putri et al. 2022). The importance of adapting grazing management to the dynamic conditions driven by climate change. Shifts in plant community composition influenced by hydrological changes necessitate adaptive grazing strategies that account for variations in precipitation and forage availability (Oles et al. 2017). This adaptability is critical as climate patterns become increasingly unpredictable, impacting the timing and quality of forage for livestock.

Effective management practices are essential for maximizing forage productivity, which directly influences livestock feeding costs. Jobirov et al. (2022) state that the availability of well-managed pastures can significantly decrease feed costs in beef cattle farming, particularly when the price of supplementary feed is taken into account. By utilizing free or low-cost forage resources, farmers can increase their profitability in beef production (Jobirov et al. 2022). Additionally, Insúa et al. (2019) highlight that GIS technology for monitoring pasture growth enables precision in managing forage availability, allowing for optimal grazing and enhanced herd performance (Insúa et al. 2019). The synergistic relationship highlights the importance of integrating high-nutritional forage varieties into pasture management strategies to maximize livestock production (Gultekin et al. 2021). Expanding forage areas and integrating perennial forage crops result in enhanced environmental benefits and economic viability (Kulshreshtha et al. 2016). Shifting from annual crops to perennial forages not only enhances carbon sequestration but also improves soil health, which can yield long-term economic benefits for cattle farmers. This shift enables them to rely less on external feed sources, ultimately resulting in lower production costs (Kulshreshtha et al. 2016).

Design of the development of cattle farming in South Lembor

Benteng Dewa Village has the highest proportion of designated livestock land among other villages in South Lembor Sub-district. Therefore, this village possesses the potential to evolve into a hub for livestock sector activity within South Lembor Sub-district. Based on further assessment of livestock sector in Benteng Dewa Village, the potential areas are distributed across a minimum of three locations (Figure 4). The first area encompasses a substantial grassland area of 1,403.53 hectares (Area I in Figure 4), which includes a designated power station site covering 168.39 hectares (Area I in Figure 4). If energy-producing activities are well managed, they are expected to serve as a supplier for the electrification of facilities and infrastructure in the livestock sector.

The livestock areas II and III of Benteng Dewa Village are smaller and fragmented with total extent of 276.29 Ha. The area I is suggested as the central focus for developing the livestock sector center. The area I is situated in one of the hamlets closest to the transportation network connecting to Nanga Lili Village (Lokesha and Mahesha 2017). Additionally, following the Indonesian Ministry of Agriculture (2014) criteria, regions II and III are characterized by slope values conducive to forage plantations. The first area features a more extensive distribution of suitable grazing pasture, encompassing 943.94 hectares (with a slope value of 0-15% in Area I, Figure 4), which represents approximately 67% of the total area. Land unsuitable for grazing area development can be utilized to cultivate legume forage, thereby contributing to the provision of livestock feed sources (Hassen et al. 2017). The provision of legume forage is crucial in addressing the forage requirements of livestock (Phelan et al. 2015; Kebede et al. 2016). Approximately 459.60 hectares are available for development as legume forage. For the development of livestock sector areas, various models can be implemented based on the stakeholders' capabilities, while also adapting to the region's physical and ecological conditions. These include intensive livestock farming (Eijrond et al. 2019), semi-intensive models (Amiri et al. 2022), extensive livestock farming (Cameroni and Fort 2017; Fort et al. 2017), and integrated livestock-crop models (Osak and Hartono 2016; Septiadi et al. 2022). In the development of the livestock sector, engaging multiple stakeholders in business or investment can involve various models. These include vertical integration (Crespi and Saitone 2018), circular farming (Herrera et al. 2023), cluster farming (Kuivanen et al. 2016), contract farming (Bellemare 2018; Ruml et al. 2022), cooperative farming (Nosov et al. 2020), agrosilvopastura (Adnani et al. 2018), pasture-based farming (Macdonald et al. 2017), core plasma partnership (Widiati et al. 2019; Anggraini et al. 2023), feedlot operations (Flores et al. 2017), organic farming (Wolde and Tamir 2016), community-based farming (Mueller et al. 2015), precision livestock farming (Bianchi et al. 2022; Kleen and Guatteo 2023), and rotational grazing (Jordon et al. 2023).

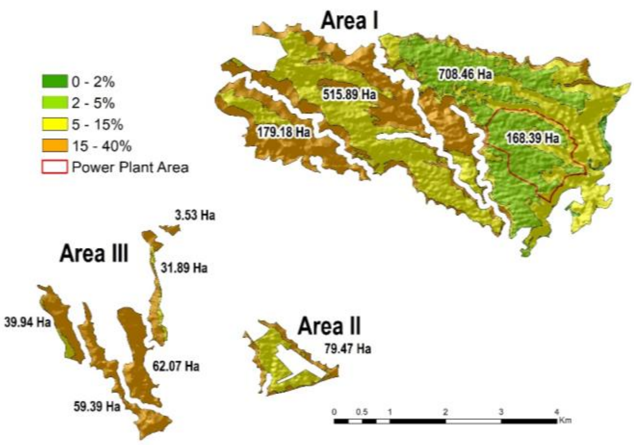

Figure 4. Potential area for cattle farming development in Benteng Dewa Village, South Lembor Sub-district, West Manggarai District, East Nusa Tenggara Province, Indonesia

The results of FGDs revealed that core-plasma model is the most scalable and sustainable cattle farming model in South Lembor Sub-district. It was proposed that Benteng Dewa Village can be developed through a core-plasma partnership, and at the same time makes this village a core-plasma zone by designating area I as the core zone while the remaining areas are classified as the plasma zone. The allocation of livestock areas in alternative villages may serve as a protective buffer zone (Figure 5). The development model is suitable given the community's receptiveness to the company as a catalyst for economic growth in Benteng Dewa Village. The community anticipates advancing the beef cattle enterprise, as each household possesses a minimum of four beef cattle. Engagement with the community is essential for the company's acceptance, contingent upon reaching a consensus through thoughtful discussion with the entire village populace. These results are also based on the socio-economic conditions of the Benteng Dewa community, which comprises small-scale livestock farmers who require intervention from a company that can bridge the gap.

The core-plasma partnership represents a dynamic relationship between breeders and livestock companies, or entities across various sectors, wherein livestock companies serve as the core and breeders function as the plasma (Widiati et al. 2019). The collaboration between the core and plasma regions facilitates technology transfer from the core to the plasma zone (Suarda et al. 2020). The limitations of the community that require intervention from core companies as investors make the core-plasma partnership model a novelty in the ENT region, which is dominated by dryland areas. Core companies typically have better access to resources and advanced technologies that small-scale farmers may lack, including improved breeding stock, veterinary care, and efficient feeding regimes. Collaborations enable plasma farmers to adopt these technologies, thereby enhancing livestock productivity, profitability, and improving meat quality (Ilham 2020). The core-plasma model also enhances market access for smallholder farmers by directly linking them with larger markets, thereby helping to ensure fair prices for their livestock. This relationship can help stabilize incomes for small-scale farmers by reducing the risks typically associated with traditional market transactions (Zimmermann et al. 2024). Policies promoting fair trading practices between core companies and small-scale farmers are essential for the sustainability of these partnerships (Ilham 2020). In addition, small-scale farmers have a chance to benefit from training programs organized by core companies that focus on animal husbandry, disease management, and effective marketing strategies. These training initiatives create an environment of continuous improvement and education, enabling plasma farmers to manage their operations more independently (Habimana 2024). Collaborations implemented through the core-plasma model can also foster environmentally friendly practices. Core companies often promote sustainable farming techniques that align with local ecology while supporting the economic viability of small-scale operations (Semin and Kislitsky 2023). Techniques such as rotational grazing can enhance pasture quality and reduce land degradation. Core-plasma partnerships can strengthen advocacy efforts for small-scale farmers at both the regional and national levels. Core companies can leverage their influence to advocate for supportive policies that create a favorable business environment and ensure fair regulations that assist small-scale livestock operations (Morris et al. 2023).

Management of the core plasma zone is advised to be undertaken by large or medium-scale livestock enterprises or companies from other sectors to bolster the livestock industry (Wulandari et al. 2023). This area will provide resources and infrastructure for livestock production, encompassing beef cattle breeding and the processing of livestock products (Hasanah et al. 2024). The plasma core zone purchases production outputs from the plasma and buffer zones at predetermined prices (Ismiyah 2023). The plasma core zone offers livestock sector enterprises guidance, development, and support, ensuring efficient production in both the plasma and buffer zones (Suarda et al. 2020). The plasma and buffer zone comprises breeders, groups of breeders, combinations of breeder groups, or livestock cooperatives that convert the available inputs into products required by the core company (Suhendar and Sukardi 2022). This zone functions as both a seller and supplier of production products at predetermined prices (Wulandari et al. 2018). The buffer zone functions similarly to the plasma zone, mitigating the most severe risks associated with livestock sector activities within the core plasma zone (Bernabucci 2019). The most concerning scenario is that climatic factors and extreme climate changes may influence the availability of food and water in the core plasma zone, potentially affecting industrial activities in that region (Gaughan and Cawdell-Smith 2015; Sejian et al. 2015). The buffer zone is a proposed solution to facilitate industrial activities within the plasma core, ensuring its continued operation (Rojas-Downing et al. 2017). The buffer area may include feed providers, nurseries, fatteners, or product processing industries, all of which have agreements integrated into the core plasma zone.

The core-plasma collaboration aims to influence several factors through investment activity by offering mutual advantages of the core, plasma, and buffer; enhancing plasma's role in technology, finance, institutions, and beyond; expanding the economic scale of plasma to achieve efficiency; and elevating the quality and competitiveness of plasma products. The allocation of profits and risks in the core-plasma partnership is established based on service contributions and working capital proportions, as mutually agreed upon by both parties in the agreement (Wulandari et al. 2018; Widiati et al. 2019; Suarda et al. 2020; Anggraini et al. 2023). The contributions of each party, the costs of production inputs (such as feed, seeds, medicines, vaccinations, and vitamins), and the prices of the produced goods are collectively established and documented in the agreement (Suarda et al. 2020). The product's pricing is determined by the production cost and the quality specified in the contract (Anggraini et al. 2023).

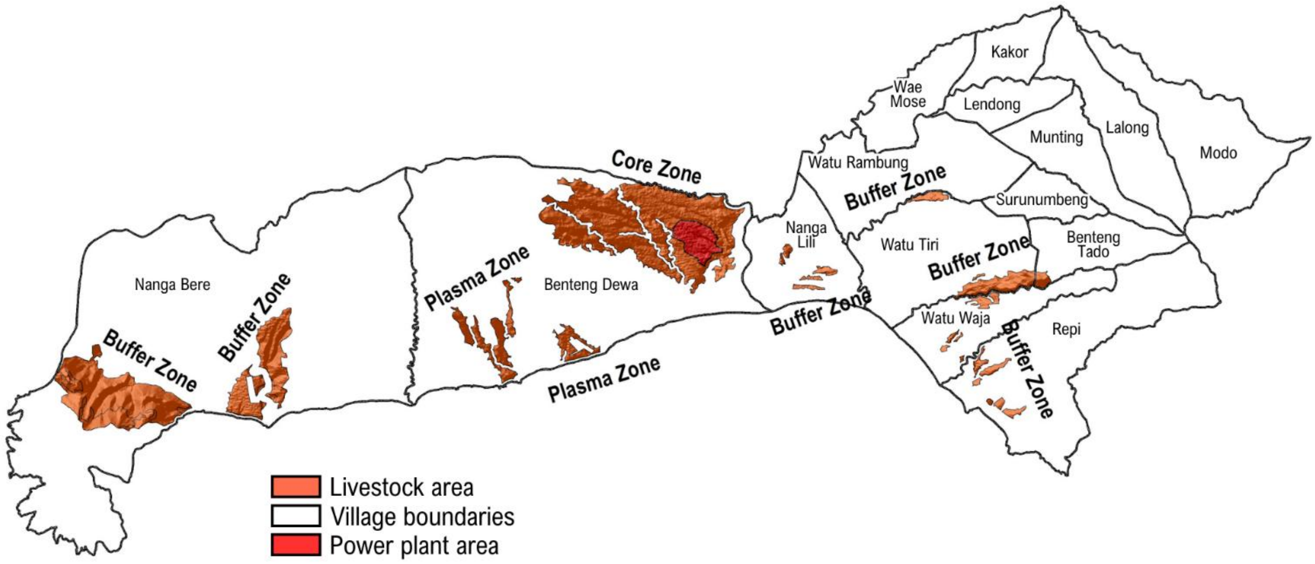

Figure 5. Core-plasma partnership design model of cattle farming in South Lembor Sub-district, East Nusa Tenggara Province, Indonesia

In executing the fundamental plasma partnership across each zone, the integration of livestock and crops can be employed to ensure that no resources are wasted, fostering a mutually beneficial system that promotes sustainable, circular agriculture. According to Nur et al. (2023) in the West Manggarai Agricultural Master Plan for 2023-2043, the agricultural-livestock integration strategies that can be pursued in West Manggarai District include combining cattle with rice, corn, and vegetable crops, as well as integrating livestock with fruit crops. The integration of crop and livestock systems represents the optimal utilisation of local resources, thereby promoting the sustainability of agricultural practices (Martin et al. 2016). The crop and livestock systems integration utilises byproducts from agricultural production as inputs or advantages for other agrarian endeavours (Yang et al. 2022). Agricultural waste serves a dual purpose, functioning as forage for livestock, while the residual feed and manure generated from livestock operations can be repurposed as fertiliser for agrarian endeavours (Baiyeri et al. 2019; Yue et al. 2022). The application of livestock manure has the potential to enhance soil quality while simultaneously decreasing the reliance on sodium and phosphorus fertilisers (Yagüe et al. 2016; Almeida et al. 2019; Rayne and Aula 2020; Vanotti et al. 2020). Integrating crop and livestock systems yields greater profitability than traditional methods (Mendonça et al. 2020; Vinholis et al. 2021). Thus, the development of the core-plasma partnership model is expected to address the challenges faced by the livestock sector in dryland areas, amid the increasing demand for meat consumption at local, regional, and national scales, which is anticipated to result in a deficit.

The core-plasma partnership model, centered on Benteng Dewa Village, optimizes the core zone 943.94 ha (67%) for grazing pasture, 459.59 Ha (33%) for forage plantation, optimizes the plasma zone 276.29 ha, and optimizes the buffer zone in other villages within the South Lembor Sub-district (1,528.66 Ha) to support activities in the core zone. Core-plasma partnerships serve as an alternative bridge for communities to access a viable market for livestock products through an agreement between the buffer zone and the plasma zone, with the core zone being bound by a mutual need for economic sustainability. Core companies are crucial for ensuring economic growth among small and medium-sized farmers. Schemes involving other core companies, such as contract farming, may be an option, but the various significant drawbacks that can occur are highly detrimental to farmers. Ruml and Qaim (2021) found that smallholder farmers frequently express dissatisfaction with their contracts, despite potential economic benefits, due to ongoing issues related to mistrust and the opaque nature of the agreements. When farmers lack clear information about pricing mechanisms, quality expectations, and payment terms, their ability to navigate these contracts effectively is hampered, creating a precarious situation regarding their income stability. While initial studies indicate that contract farming can lead to increased incomes, the long-term prospects may not be as positive due to potential exploitation by larger firms (Wu et al. 2020). The pricing mechanisms often favor contract companies, leaving farmers vulnerable to fluctuations in market prices and input costs, which can jeopardize their financial stability over time. In contrast, core-plasma models often provide a more equitable distribution of benefits, fostering better long-term relationships between farmers and their cooperatives or plasma partners. In addition, Bellemare (2018) argues that the initial costs associated with meeting contractual obligations (such as purchasing specific inputs or adhering to quality standards) can be substantial. Additionally, if market conditions change, farmers may find themselves locked into unfavorable contracts, leading to reduced profitability compared to non-contract farming scenarios. Bellemare and Novak (2017) also highlight that, particularly in dynamic market conditions, farmers may find themselves earning less than expected, which can impact their overall welfare. Contract farming can sometimes create a false sense of security about stable prices, ultimately leading to greater financial distress during downturns. Contract farming can exacerbate existing inequalities within rural communities, particularly when wealthier farmers or agribusinesses dominate the market. This tends to push smallholder farmers to the periphery, leaving them with fewer opportunities for advancement in the agricultural sector. Ncube (2020) emphasizes the need for policies that empower smaller-scale producers to negotiate equitable contracts, thereby mitigating these effects and ensuring fair access to resources. Thus, the potential land suitable for livestock farming in South Lembor could help reduce the supply-demand deficit for beef, both regionally and nationally, if it is managed appropriately. The proposed core-plasma partnership model can help bridge the gap between small- and medium-scale farmers, ensuring economic growth. Land management can also help reduce production costs, particularly the cost of providing forage. Proper feed management can also be a comprehensive step in addressing climate change. Participation in contract farming can lead farmers to become reliant on contract partners for critical decisions, effectively reducing their autonomy in making choices related to production practices (Dubbert et al. 2021). This decreased autonomy can undermine traditional agricultural practices, as farmers may feel pressured to conform to the specifications set by contracting companies, potentially leading to a homogenization of farming methods at the expense of local practices and knowledge. Additionally, the complexity and potential lack of clarity in contract terms present challenges for farmers engaged in contract farming. Mao et al. (2021) discuss how incomplete contracts can lead to "hold-up" situations, where contracts do not adequately cover all contingencies, leaving farmers exposed to various risks, such as market volatility and changing production conditions (Mao et al. 2021). This contrasts with the core-plasma model, which typically emphasizes more transparent and comprehensive agreements to mitigate risks.

One notable study is the implementation of core-plasma partnerships in Sulawesi. In this partnership, the core company provides essential resources and supports intensive farming operations, while the plasma farmers manage the actual farming processes and contribute labor and land (Dedu et al. 2023). The core company supplies input materials, including feed, veterinary services, and training on best management practices. This support is crucial for smallholder farmers who often lack the financial leverage and technical skills necessary to invest in modern farming techniques (Dedu et al. 2023). Further explanation in the research, core companies facilitate a direct line to markets, enabling plasma farmers to sell their produce without being subject to generalized market volatilities. This steadiness helps prevent income loss and provides farmers with more predictable cash flows, which are necessary for sustainable operations (Dedu et al. 2023). The collaboration has shown improved income levels for plasma farmers compared to independent farmers outside the partnership. Dedu et al. (2023) noted that the average revenue per farmer participating in the core-plasma system was significantly higher due to better production practices and guaranteed market access. The analysis indicated a favorable R/C (Revenue to Cost) ratio, often exceeding the threshold showing profitability, thereby confirming the economic viability of such partnerships (Dedu et al. 2023). Another example of the application of the core-plasma partnership model in Indonesia's beef cattle sector, particularly in its dryland areas, can be found in the collaboration between the Maiwa Breeding Center (MBC) and local farmers in Sulawesi (Harifuddin et al. 2023). This partnership effectively demonstrates how integrating different farming operations can enhance productivity and sustainability in livestock farming within challenging environments. The core company, MBC, supplies high-quality breeding cattle to local farmers. This supply enables farmers to enhance the genetic quality of their herds, which has a positive impact on overall productivity in terms of meat yield and growth rates (Harifuddin et al. 2023). Farmers receive training in cattle management practices, nutrition, and veterinary care from MBC. This educational support enhances farmers' skills, allowing them to effectively manage their investments and improve herd productivity. Research indicates that educated farmers are more likely to adopt better farming practices and manage risks associated with livestock operations (Harifuddin et al. 2023). A profit-sharing in a core-plasma partnership model based on the production outcomes achieved. This arrangement incentivizes farmers to optimize their cattle management practices, thereby improving profitability while ensuring that the core company has a vested interest in the success of participating farmers (Achmad 2024). Harifuddin et al. (2023) note that the core companies facilitate access to markets for beef products produced by farmers in the partnership. By linking farmers to local markets and buyers, the core company ensures that farmers receive fair prices for their livestock, thus stabilizing their income and enhancing their ability to invest in their farms (Rohani et al. 2020). The core-plasma partnership structure enables shared risks, where the core company helps absorb variations in feed costs or provides backup support during times of drought or disease outbreaks. This safety net is crucial for smallholder farmers who often lack sufficient financial reserves (Tameno et al. 2021).

Overall, this study has several limitations, including the omission of other variables that may not have been fully considered, such as the potential impact of climate change and the reliance on stakeholder willingness. One of the most immediate effects of climate change is the alteration of environmental conditions that affect the health of livestock (Auma and Badr 2022). Auma and Badr (2022) highlight that extreme temperatures directly impact the immune systems of livestock, making them more susceptible to diseases, which can lead to increased mortality rates. Similarly, the negative consequences of climate change on the quality of feed crops and the availability of water resources are crucial for maintaining livestock health and production levels (Pham-Thanh et al. 2020). These challenges are exacerbated by the anticipated increase in the frequency and severity of livestock disease outbreaks, particularly in low-income countries that are most vulnerable to such shifts. Furthermore, the global food supply chain is susceptible to the impacts of climate change. Godde et al. (2021) indicate that adaptation measures will be required across various levels, from farm management to institutional frameworks, to safeguard livestock production. This reflects the systemic nature of the challenges posed by climate change, where direct impacts on animal health and feed availability are interlinked with broader socio-economic conditions. Climate change is also shown to produce fluctuations in precipitation and an increase in extreme weather events, leading to degraded pastures and reduced forage availability. Climate-induced aridification leads to degradation of grasslands, posing significant challenges to livestock health, growth, and survival. Khurshid et al. (2023) further note that climate change can disrupt the delicate balance necessary for livestock growth and reproduction, severely impacting farmers' livelihoods. The community is generally very receptive to corporate involvement and wants this model to be implemented, as it significantly contributes to economic growth, with the note that there is a joint agreement from all of society, including in facing the challenges of climate change.

Conclusion, the core-plasma partnership livestock model, centered on Benteng Dewa Village, optimizes the core zone (943.94 ha) for grazing pasture and 459.59 Ha for forage plantation. It optimizes the plasma zone (276.29 ha) and the buffer zone in other villages within the South Lembor Sub-district (1,528.66 Ha) to support activities in the core zone. This model was proposed to the DPMPTSP of West Manggarai District to attract investors who want to become core companies and, together with the community, develop the livestock sector, leveraging the main market opportunity of tourism activities in the Labuan Bajo DPSP area. This study has several limitations, including the omission of other variables that may not have been fully considered, such as the potential impact of climate change and the reliance on stakeholder willingness. Further studies could be conducted to validate the model if a core company is willing to invest in this area. Another possible study would be to examine the impact of climate change on this model, including its strengths, weaknesses, and challenges.

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Impact of integrated crop management on rice farming efficiency in semi-arid West Timor, Indonesia

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Abstract. *Joka U, Nubatonis A, Nino J, Tabenu O, Ludji DG. 2025. Impact of integrated crop management on rice farming efficiency in semi-arid West Timor, Indonesia. Intl J Trop Drylands 9: 148-158.* This study assesses the impact of Integrated Crop Management (ICM) on the technical efficiency of rice farmers in the semi-arid border regions of West Timor, Indonesia, specifically North Central Timor and Kupang District. These regions face significant agricultural challenges, including low soil fertility, erratic rainfall, and limited access to modern farming technologies. Despite national promotion of ICM, there is a lack of empirical evidence on how ICM adoption influences technical efficiency in semi-arid border environments, representing a critical research gap that this study aims to address. Using data from a structured survey of 150 rice farmers, the research applies a Stochastic Frontier Analysis (SFA) with a Cobb-Douglas production function to estimate technical efficiency. The study revealed that seed input and labor significantly influence rice output, while education and full-time farming engagement are associated with reduced inefficiency. The mean technical efficiency score is 0.705, indicating that farmers operate at approximately 70.5% of their potential output. The gamma value of 0.821 suggests that 82.1% of output variation is due to inefficiency rather than random shocks. Comparative analysis revealed that high ICM adopters achieved higher efficiency (0.717) and yields (6,502 kg/ha) than low adopters (0.697 and 5,664 kg/ha, respectively). These findings demonstrate that ICM adoption improves resource-use efficiency and productivity, but its benefits depend on enabling conditions such as education, farm specialization, and extension access. Strengthening context-specific ICM adaptation, farmer training, and supportive policies is essential for enhancing resilience and reducing productivity gaps in semi-arid rice ecosystems.

Keywords: ICM, productivity, rice, technology, Timor

INTRODUCTION

Indonesia ranks among the world's top rice producers, with over 10.20 million hectares of paddy fields, yielding approximately 53.63 million tons of dry, unhusked rice, equivalent to around 30.90 million tons of rice (BPS 2025). Such substantial production underscores rice's importance as a staple food and key agricultural commodity in Indonesia. However, productivity remains uneven across regions, particularly in climate-vulnerable and economically marginal areas such as the border regions of West Timor.

Border agriculture presents unique challenges and opportunities. These regions often suffer from underinvestment, weak institutional support, and limited access to modern technologies. However, they are critical for regional food systems and cross-border trade, especially in areas adjacent to Timor-Leste. The average rice yield in these border zones is approximately 4.2 tons/ha, significantly below the national average of 5.2 tons/ha (BPS East Nusa Tenggara Province 2025). Addressing this gap is essential for local development and national resilience in the face of climate change and geopolitical pressures. The border regions are crucial to West Timor's rice output, as lowland rice is a primary food source. In 2023, rice production in these areas was approximately 443.69 thousand tons, a modest increase of 0.85 thousand tons, or 0.19% from the previous year (BPS East Nusa Tenggara Province 2025). Despite this growth, farmers continue to face multiple constraints: semi-arid climates, low soil fertility, rugged terrain, and limited rainfall, all of which hinder consistent, high-yield rice cultivation. Economic hardship and technological adoption barriers further exacerbate these challenges.

Integrated Crop Management (ICM) has emerged as a promising strategy to enhance productivity and sustainability in smallholder systems (Lankamo et al. 2025). ICM combines best practices, such as improved seed varieties, intermittent irrigation, balanced fertilization, pest control, and conservation agriculture, tailored to local agroecological conditions (Billah et al. 2025; Ewulo et al. 2025). Evidence from the Mekong Delta, Ghana, and Bangladesh shows that ICM can improve technical efficiency by 10-24% and boost productivity by up to 76% compared to non-adopters (Villano et al. 2015; Abdulai et al. 2018).

However, the success of ICM is highly context-dependent. In marginal ecologies, drylands, uplands, and border regions, adoption is often hindered by financial constraints, limited extension services, and low education levels (Wossen et al. 2017; Acevedo et al. 2020; Girma 2022). In Indonesia, while national programs have promoted ICM in irrigated lowlands, its implementation in border regions remains partial and inconsistent (Novitaningrum et al. 2020; Sumaryanto et al. 2023). Despite the limitations, ICM components remain applicable for adoption in dryland areas, where rainfed is the primary water source, offering clear solutions that include targeted training and full support or protection for inputs.

The Indonesian Ministry of Agriculture (Departemen Pertanian 2003) classifies ICM components into location-specific and efficiency-based groups. Five components are considered essential: selecting locally adapted varieties, proper land preparation and levelling, efficient water management, balanced fertilizer application, and regular farm monitoring. Further research is needed to assess how economic and policy strategies enhance technical efficiency and to understand the impact of these factors on efficiency.

Globally, modern agricultural technologies, such as precision agriculture, digital tools, and ICM, have shown strong potential to boost farm productivity. However, a significant research gap persists regarding how environmental, geographic, and socio-economic factors jointly hinder technology adoption in climate-vulnerable border areas (Balyan et al. 2024; Fragomeli et al. 2024; Geng et al. 2024). In Indonesia, this gap is especially evident, with limited empirical evidence on how policies and economic strategies can address these obstacles. Although ICM approaches in semi-arid regions, such as West Timor, show clear agronomic benefits, including drought-tolerant crops, livestock integration, and water-smart practices, their success depends heavily on adaptable design, strong local participation, and responsiveness to physical and socio-economic conditions (Tjoe et al. 2019; Benu et al. 2024). Failures in similar contexts are often due to rigid, top-down planning that overlooks key issues, such as water scarcity, labor availability, and insecure land tenure (Borrell et al. 1997).

This research aims to fill these gaps by examining the technical efficiency of ICM adoption in West Timor's border regions, where these challenges are most severe. The border region of West Timor is a distinct and under-studied agroecological zone characterized by harsh climate, poor soil, and proximity to Timor-Leste, which influences cross-border socio-economic interactions (Tjoe 2017). Unlike Indonesia's fully irrigated rice belts, this area faces seasonal water shortages, fragmented landholdings, and elevated poverty levels- about 18.1% in 2024 (BPS East Nusa Tenggara Province 2025). Districts such as North Central Timor and Kupang exhibit persistent poverty, primarily due to low agricultural innovation and productivity. Previous studies by Dewi and Yustikaningrum (2018) and Taena et al. (2023) have highlighted the lack of tailored agricultural policies and the underutilization of technology in these marginal areas. This research aims to investigate how ICM can be adapted to address these constraints, providing insights into the adoption of technology in frontier farming systems. Building on these contextual challenges and knowledge gaps, this study seeks to clarify whether the extent of ICM adoption translates into measurable efficiency gains under the unique biophysical and socio-economic conditions of West Timor's semi-arid border regions. We hypothesize that higher ICM adoption is associated with higher technical efficiency among rice farmers in the semi-arid region of West Timor.

MATERIALS AND METHODS

Research sites

The study was conducted in the border regions between the Republic of Indonesia and Timor-Leste, specifically in North Central Timor and Kupang District, as shown in Figure 1. These regions are characterized by semi-arid conditions, low soil fertility, and limited rainfall, creating substantial obstacles for rice farming. The selected sites are significant due to their key role in regional rice production and high poverty levels, underscoring the need for targeted agricultural interventions.

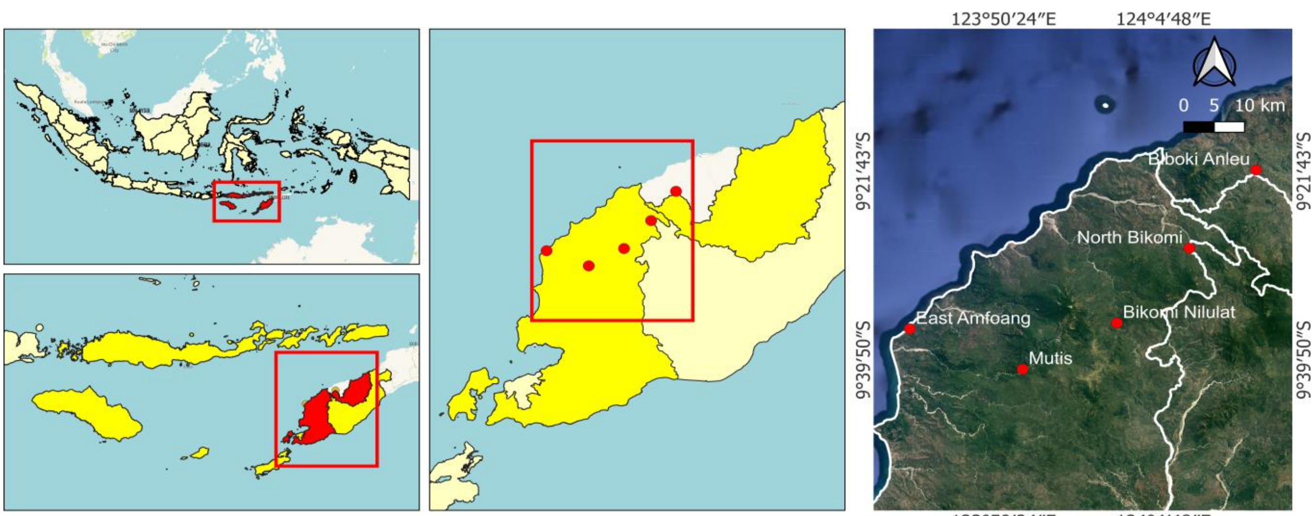

Figure 1. Map of the study area in Kupang and North Central Timor District, East Nusa Tenggara, Indonesia

Data collection

The study used purposive sampling to select 150 rice farmers from five sub-districts in North Central Timor and Kupang District: East Amfoang, Mutis, Bikomi Nilulat, North Bikomi, and Biboki Anleu. These regions were chosen due to their importance in lowland rice farming and their location in semi-arid, climate-vulnerable border areas. The farmers included in the study had adopted at least one component of the Integrated Crop Management (ICM) package. This approach ensured the sample represented a variety of ICM adoption levels and farming conditions relevant to the research aims. The survey gathered information on farmers' socio-economic backgrounds, farming methods, the extent of ICM use, and their opinions on how ICM affected productivity and livelihoods (FAO 2019). Field observations were also conducted to evaluate ICM implementation and assess the condition of rice fields, providing qualitative insights into the challenges and opportunities farmers face. Secondary data on rice production, yields, and input use were collected from local agricultural offices and national statistical agencies (BPS 2025). Additionally, relevant literature and reports regarding technical efficiency, ICM adoption, and agricultural practices in similar settings were reviewed to provide a thorough background for the research (Wang et al. 2017).

Data analysis

The production function parameters will be estimated using Maximum Likelihood Estimation (MLE), which separates random statistical noise (such as weather variations) from farm-specific inefficiency effects. This method produces Technical Efficiency (TE) scores for individual farms, indicating their ability to maximize output with available resources. At the same time, the half-normal assumption is tested empirically for goodness of fit and retained if it performs comparably to alternatives for interpretability and comparability. The analysis will then examine how ICM adoption affects these efficiency scores and assess the impact of socio-economic variables (such as education, farm size, and access to credit) on efficiency outcomes (Battese and Coelli 1995; Bravo-Ureta et al. 2007).

The framework (Figure 2) illustrates that the interplay of socio-economic factors and agricultural practices has a significant impact on farming outcomes, with education, credit access, and farm size directly influencing both the adoption of Integrated Crop Management (ICM) practices and overall farm efficiency. ICM adoption, quantified by the implementation of its various components, serves as a crucial mediating variable, directly affecting the productivity of inputs. Ultimately, these dynamics culminate in technical efficiency and rice yield, estimated through a stochastic frontier Cobb-Douglas production function, representing the primary outcomes. Improvements in efficiency and yield, in turn, contribute to enhanced farmer welfare and bolster local food security.

Functional form of the stochastic production function

The Technical Efficiency (TE) of rice farms using the ICM technology package is evaluated using a Stochastic Frontier Production Function, where Stochastic Frontier Analysis (SFA) helps quantify how efficiently farmers convert inputs into outputs and how much of the yield gap is due to inefficiency versus environmental limitations. This is particularly important in semi-arid zones, such as West Timor, where low yields may reflect structural constraints rather than poor management. By identifying the sources of inefficiency, SFA can inform targeted interventions that improve productivity without requiring uniform solutions.

This study employs the Cobb-Douglas production function because it offers simplicity, interpretability, and suitability for small to moderate sample sizes. It directly estimates the elasticity of each input, making it easier to understand the relationships between inputs (labor, capital, land, and technology adoption) and outputs (rice yield). Compared to the more flexible Translog model, the Cobb-Douglas model is more straightforward, reducing the likelihood of overfitting, which is especially important when working with limited data or when there is multicollinearity among inputs (Mahaboob et al. 2019).

Unlike deterministic models, such as Data Envelopment Analysis (DEA), which attribute all deviations from optimal output to inefficiency, SFA distinguishes between inefficiency and statistical noise, a critical distinction in dryland systems, where yield fluctuations often result from factors like rainfall variability, soil degradation, and pest outbreaks. This feature makes SFA particularly suitable for semi-arid and climate-vulnerable regions, where production outcomes are not solely determined by farmer effort or input use (Kumbhakar et al. 2020).

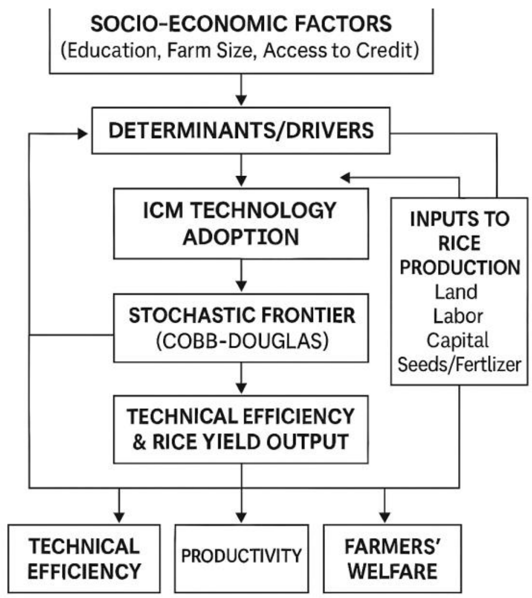

Figure 2. Conceptual framework. Source: Author's own conceptualization based on SFA literature (Aigner et al. 1977; Meeusen and van Den Broeck 1977) and technology adoption studies

The stochastic frontier model is represented as:

$$Y_i = X_i;\beta + \varepsilon_i \quad [1]$$

The Cobb-Douglas type's stochastic production frontier function model is the empirical model to estimate technical efficiency. Which is given below:

$$\ln Y_i = \beta_0 + \beta_1 \ln X_{1i} + \beta_2 \ln X_{2i} + \beta_3 \ln X_{3i} + \beta_4 \ln X_{4i} + \beta_5 \ln X_{5i} + \beta_6 \ln X_{6i} + \varepsilon_i \quad [2]$$

Specify a production function (Cobb-Douglas) that relates output to inputs:

$$y_i = f(x_i;\beta) + v_i - u_i \quad [3]$$

In dryland contexts, such as West Timor, where farming is shaped by environmental variability and resource constraints, SFA provides a robust method for assessing how efficiently farmers (i^{th}) convert inputs (x_i) into outputs (y_i). It distinguishes between inefficiency (u_i) and random shocks (v_i), such as drought or poor soil, making it especially relevant where low yields may reflect structural limitations rather than poor management. Assume v_i follows a normal distribution N (0, σ^2), and u_i follows a non-negative distribution such as half-normal. The study also incorporates the model from Battese and Coelli (1995), which expresses the technical inefficiency effect as follows:

$$u_i = Z_i\,\delta + w_i \quad [4]$$

Z_i is a (1 × m) vector of explanatory variables linked to the TI (Technical Inefficiency) effects; δ is a (m × 1) vector of unknown parameters to be estimated; and w_i represents an unobservable random variable. These parameters reflect the influence of variables in Z on TE, where a negative value indicates a positive effect on TE, and vice versa. The inefficiency model has been adopted, as shown below.

$$u_i = \delta_0 + \delta_1 Z_1 + \delta_2 Z_2 + \delta_3 Z_3 + \delta_4 Z_4 + \delta_5 Z_5 + \delta_6 Z_6 + \delta_7 Z_7 + w_i \quad [5]$$

The model's parameters are estimated using the Maximum Likelihood Estimation (MLE) method. Technical Efficiency scores for each farmer can then be calculated based on:

$$TE = \frac{f(X_i;\beta)\exp(v_i - u_i)}{f(X_i;\beta)\exp v_i} = \exp(-u_i) \quad [6]$$

The theoretical basis (Table 1) for variable selection is grounded in production economics and empirical studies on technical efficiency (Battese and Coelli 1995; Bravo-Ureta et al. 2007).

Software used

The analysis used Frontier 4.1, a specialized software for estimating stochastic frontier models through Maximum Likelihood Estimation (MLE). Frontier 4.1 provides flexible options for specifying inefficiency effects and supports various distributions, including the half-normal distribution, for the inefficiency term.

RESULTS AND DISCUSSION

Socio-economic characteristics of the respondent

Table 2 shows the socio-economic profile of farmers in the research site (Kupang and North Central Timor District). It reveals a predominantly mature farming population, with most individuals falling within the 40–59 age bracket.

This age distribution suggests a workforce with considerable life and field experience, consistent with findings from Southeast Asia, where older farmers dominate rural agricultural communities (Mekonnen et al. 2021; Woh et al. 2025). Educational attainment among these farmers is generally low to moderate, with the majority having completed only primary or secondary education, and relatively few reaching tertiary levels. This pattern aligns with broader trends in developing countries, where limited access to higher education constrains human capital development in rural areas (FAO 2020). Farming experience is notably high, with many farmers having over a decade of experience, indicating a deep-rooted knowledge and skill in agriculture. Such experience is a critical factor influencing the adoption of sustainable agricultural practices (Abdulai and Huffman 2014; Xayavong et al. 2016; Zhou and Li 2022).

Table 1. Variable, unit, type, and theoretical basis

Variable	Unit	Type	Theoretical basis
Rice output (Y)	Kilograms	Dependent	Farm productivity (Gautam 2024)
Farm size (X_1)	Hectares	Input	Scale of operation (Gautam 2024)
Seed input (X_2)	Kilograms	Input	Genetic potential (Senapati and Semenov 2020; Aziz et al. 2022)
Urea fertilizer (X_3)	Kilograms	Input	Nitrogen supply (Motasim et al. 2024)
NPK fertilizer (X_4)	Kilograms	Input	Balanced nutrients (Nabayi et al. 2021)
Pesticide (X_5)	Liters	Input	Pest control (Fahad and Wang 2018)
Labor (X_6)	Man-days	Input	Human capital (Abidin et al. 2022)
Extension access (Z_1)	Frequency	Inefficiency	Knowledge transfer (Danjumah et al. 2024)
Education (Z_2)	Years	Inefficiency	Decision-making ability (Paltasingh and Goyari 2018; Taramuel-Taramuel et al. 2023)
Age (Z_3)	Years	Inefficiency	Experience vs inertia (Woh et al. 2025)
Farming experience (Z_4)	Years	Inefficiency	Skill accumulation (Xayavong et al. 2016; Zhou and Li 2022)
ICM adoption (Z_5)	Dummy (1/0)	Inefficiency	Technology use (Wang et al. 2017; Ambong 2022)
Land ownership (Z_6)	Dummy (1/0)	Inefficiency	Investment incentive (Ardiansyah and Hartono 2014; Akber et al. 2024)
Occupation (Z_7)	Dummy (1/0)	Inefficiency	Time commitment (Hoang-Khac et al. 2022)

Table 2. Socio-economic attributes of farmers

Variable	Frequency
Age in years	
20-39	35
40-59	88
60+	27
Educational level (years)	
Non-formal education (0)	2
Primary education (1-6)	96
Secondary education (7-12)	41
Tertiary education (>12)	11
Farming experience (years)	
1-5	13
6-10	22
11+	115
Farm Size (hectare)	
0.1-0.9	129
1.0-2.0	19
2.1-3.0	2
Land Ownership	
Tenant	4
Landlord	146
Occupation	
Farmers	101
Civil Servant	44
Traders	5

Regarding landholding, most farmers operate on small to medium-sized plots, reflecting the region's typical structure of smallholder agriculture. Land ownership is widespread, supporting long-term investment and stewardship of agricultural resources (Deininger and Jin 2006; Ardiansyah and Hartono 2014; Akber et al. 2024). Finally, farming remains the primary occupation for most individuals, although a minority are engaged in civil service or trade, highlighting the mixed livelihood strategies often employed in rural economies (Hoang-Khac et al. 2022; Race et al. 2022).

The socio-economic characteristics of farmers in North Central Timor and Kupang District provide valuable insights into the structure and potential of rural agricultural communities. The average education level is 7.66 years, mostly completing primary or early secondary school, typical for rural areas and influential in technology adoption and decision-making (Paltasingh and Goyari 2018; Ruzzante et al. 2021; Taramuel-Taramuel et al. 2023). The average age of farmers is 47.1 years, indicating a mature farming population, with older farmers often relying on traditional methods (Han et al. 2022). With 20.19 years of farming experience, most possess deep agricultural knowledge and resilience (Bhatnagar et al. 2024; Chao 2024). Farm sizes average 1.24 hectares, highlighting the prevalence of smallholder farming and resource constraints (FAO 2020). Access to extension services is limited, averaging just 0.36 contacts, indicating a lack of institutional support, despite its importance for improving productivity (Yanfika et al. 2024).

OLS and Maximum Likelihood Estimates (MLE) of the Stochastic Frontier Cobb-Douglas production function

The Stochastic Frontier Analysis (SFA) is commonly used to measure technical efficiency by modeling the production function, often in the Cobb-Douglas form, with a composite error term that separates statistical noise from inefficiency (Aigner and Schmidt 1977). This method is ideal for agriculture, like rice farming, due to environmental variability and input differences. SFA provides more accurate efficiency estimates than traditional regression models. The Cobb-Douglas function helps analyze input-output relationships and resource allocation efficiency (Başeğmez 2021; Gautam 2024).

In SFA, the Maximum Likelihood Estimation (MLE) method is usually used to estimate the production function parameters and separate the error term into its noise and inefficiency components (e.g., half-normal, exponential, gamma, Nakagami), which allows for the calculation of firm-specific efficiency scores (Greene 1990; Papadopoulos 2024).

Table 3 presents the Stochastic Frontier Analysis (SFA) results for rice farmers in the Indonesia-Timor Leste border area. The estimates show that seed input has a strong, positive, and statistically significant effect on output in both OLS and Maximum Likelihood models, highlighting its key role in productivity. Labor also shows a positive coefficient and nears statistical significance, indicating its importance. However, land size, fertilizer (urea, NPK), and pesticide use have limited impact in the sample. Seed use and labor are the main factors affecting rice output, while land size, urea, and NPK fertilizers are not significant. The ICM coefficient's insignificance suggests partial or inconsistent implementation among farmers, rather than a lack of agronomic benefits, primarily in terms of dose and timing, which contradicts the extension agent's suggestion.

The sigma squared (σ^2) value indicates the total variance in the combined error term of the stochastic production frontier, capturing both random noise (v_i), such as weather conditions beyond farmers' control, and technical inefficiency (farmer-specific management capacity). The sigma square value from MLE (1.22) surpasses that from OLS (0.42), indicating greater variability captured by the stochastic frontier model. This suggests that the variation in rice farmers' output is due to both inefficiency (u_i) and random effects (v_i), or total error variance (Adinya et al. 2012; Ho et al. 2022; Okoh et al. 2022). The gamma (γ) value of 0.82, meaning 82% of output variation is due to technical efficiency, while 18% results from random shocks (Samat et al. 2023; Baruah and Saha 2024; Akinsulu 2025). This aligns with findings from Nigeria and Bangladesh by Chikezie et al. (2020) and Regmi (2016), who indicated that inefficiency is the leading cause of output loss among rice farmers. The log-likelihood for MLE (-135.93) is better than for OLS (-145.4), and the Likelihood Ratio (LR) test value 19.03 confirms that the stochastic frontier model is statistically superior to the OLS model (Greene 2001; Simar et al. 2017; Wang et al. 2025).

Table 3. Descriptive statistics of the socio-economic characteristics

Socio-economic variables	Measurement unit	Observation	Mean	Standard deviation	Minimum	Maximum
Education level	Year	150	7.66	3.26	0	17
Age	Year	150	47.1	11.6	25	79
Farming experience	Year	150	20.19	10.62	2	54
Farm size	Ha	150	1.24	6.85	0.02	8
Extension service	Frequency	150	0.36	0.73	0	4

Table 4. The results of the estimated average production function using the MLE Method

Variables	OLS estimates				Maximum Likelihood Estimates		
	Parameters	Coefficients (SE)	t-ratios	p-value	Coefficients (SE)	t-ratios	p-value
Production function							
Intercept	β_0	5.84 (0.52)	11.15		6.30 (0.54)	11.54	
Land Size	β_1	-0.10 (0.063)	-1.7	0.08	-0.045 (0.06)	-0.75	0.33
Seeds	β_2	0.34 (0.07)	4.45	0.00*	0.32 (0.06)	4.72	0.00*
Urea	β_3	0.062 (0.064)	0.96	0.33	0.04 (0.05)	0.78	0.45
NPK	β_4	0.018 (0.05)	0.33	0.73	0.014 (0.05)	0.27	0.76
Pesticide	β_5	0.04 (0.042)	1	0.31	0.05(0.03)	1.30	0.15*
Labor	β_6	0.13 (0.081)	1.65	0.09	0.15 (0.09)	1.67	0.05**
Technical inefficiency							
Intercept	δ_0				-3.02 (3.86)	-0.78	
Extension	δ_1				-1.47 (1.08)	-1.35	0.07
Education	δ_2				-0.19 (0.12)	-1.61	0.03**
Age	δ_3				0.018 (0.02)	0.89	0.14
Experience	δ_4				-0.02 (0.02)	-1.02	0.05**
ICM	δ_5				-1.30 (1.18)	-1.09	0.30
Dummy land ownership	δ_6				3.99 (3.83)	1.03	0.11
Dummy occupations	δ_7				-0.66 (0.55)	-1.88	0.19
Sigma square	σ^2	0.42			1.22 (0.53)	2.30	
Gamma	γ				0.821 (0.079)	10.28	
Log likelihood		-145.4			-135.93		
LR test					19.03		

Note: Numbers of observation: 150, significance *: 1% level, **: 5% level. Source: Field work survey (2024)

The production function model reveals that in semi-arid dryland rice systems, particularly in Indonesia's eastern border regions, seed and labor are significant drivers of productivity (Senapati and Semenov 2020; Abidin et al. 2022; Aziz et al. 2022), while education and full-time farming reduce inefficiency. Education (δ2) and full-time farming (δ7) reduce inefficiency, as educated farmers utilize resources effectively and adopt innovations more quickly. In contrast, full-time farmers enhance yields through greater labor and technology adoption (Njeru 2010; Paltasingh and Goyari 2018; Kumbhakar et al. 2020; Andrianarison et al. 2021). Access to extension services (δ1) and Integrated Crop Management (ICM) adoption (δ5) show potential to improve efficiency further, supporting resilience and productivity in these border agricultural economies (Acevedo et al. 2020; Jabbar et al. 2022).

Table 3 shows that rice farmers in Kupang and North Central Timor District, on average, achieve a technical efficiency of 0.708, indicating they produce approximately 70.8%, which is consistent with Indonesia's national average for smallholder rice farms, typically between 65% and 75% (Oelviani et al. 2024; Rachmina et al. 2025), implying a significant efficiency gap, where farmers could increase output by nearly 29%, without needing additional inputs (Acharya et al. 2020).

This degree of efficiency is commonly observed in traditional or non-mechanized rice systems across Asia and Africa, as highlighted by Chandel et al. (2022) and Ho et al. (2022), who found average technical efficiency levels ranging from 62% to 76%. For instance, a study of traditional rice farms in Nepal found a mean technical efficiency of 70.11% (Acharya et al. 2020). In comparison, fully mechanized or highly sustainable rice farms can reach 80-90% efficiency, indicating significant room for improvement through technology adoption, input optimization, or enhanced training and extension services (Min et al. 2021; Hien et al. 2023).

As the result in Table 5 did not include any farmers with an ICM score of zero, a binary classification distinguishing between "adopters" and "non-adopters" was not feasible. Instead, Table 6 presents a comparative analysis between low-level adopters (ICM score ≤ 0.625) and high-level adopters (ICM score ≥ 0.625), enabling a nuanced examination of adoption intensity and its associated outcomes.

Table 5. Farm level technical efficiency index in the study area

Frequency distribution (technical efficiency)	Number of farms	Percent
0.00-0.10	0	0.00
0.10-0.20	1	0.67
0.20-0.30	2	1.33
0.30-0.40	6	4.00
0.40-0.50	3	2.00
0.50-0.60	9	6.00
0.60-0.70	23	15.33
0.70-0.80	51	34.00
0.80-0.90	54	36.00
0.90-1.00	1	0.67
Total	150	100
Descriptive statistics		
Number of observations: 150		
Mean: 0.70		
Minimum: 0.09		
Maximum: 0.89		
Standard deviation:0.14		

Table 6. Efficiency across ICM adopters

Category	Number of farmers	Average ICM score	Average efficiency score	Average yield (kg/ha)
High adopters	79	0.707	0.717	6,502
Low adopters	71	0.386	0.697	5,664

Note: Source: Compilations based on data processing

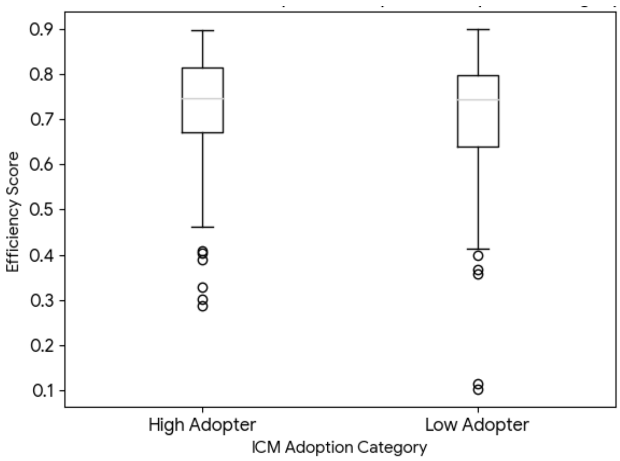

Figure 3. Distribution of efficiency scores by ICM adoption category

A growing body of evidence indicates a positive relationship between the level of ICM adoption and both technical efficiency and crop yields within agricultural systems. Concerning technical efficiency, a comparative analysis reveals that high ICM adopters demonstrate an average efficiency score of 0.717 compared to 0.697 for low adopters. This suggests that farmers integrating a broader spectrum of ICM practices are more effective in converting inputs into outputs. This is consistent with other studies showing that adopting environmentally friendly and control-intensive agricultural technologies is associated with improved technical efficiency scores among crop producers (Lampach et al. 2021; Esuh-Nnoko et al. 2022; Biswakarma et al. 2025).

The effect on crop yield is even more pronounced. High ICM adopters achieve an average yield of 6,502kg/ha, approximately 14.8% higher than the 5,664kg/ha recorded among low adopters, despite pervasive constraints like water scarcity, insecure land tenure, and labor migration. This substantial difference underscores how enhanced ICM practices, including water-efficient techniques, Alternate Wetting and Drying (AWD), and drought-tolerant varieties, directly bolster productivity and resilience by mitigating water scarcity in West Timor's rainfed lowlands, where droughts intensify during the dry season (May-October) and disrupt planting cycles in non-irrigated areas (Singh et al. 2021). Land tenure issues, such as rapid conversion of agricultural land to urban uses and insecure ownership, further hinder long-term investments in adaptive practices, reducing farmers' ability to sustain yields amid soil degradation and limited access to irrigation infrastructure (Lulan et al. 2017). Labor migration, driven by the aging of rural workforces and urban opportunities, exacerbates labor scarcity, thereby lowering technical efficiency in rice production (Ngadi et al. 2023). However, remittances provide partial economic buffers. In contrast, ICM adoption counters this by optimizing labor through mechanization and site-specific management, thereby enhancing household resilience to economic shocks.

Numerous Indonesian and global studies align with these findings, providing further context for the observed efficiency and yield gaps. In the Indonesian context, recent studies report an average technical efficiency of rice farms of 0.82 from 2018 to 2021. Nonetheless, considerable regional disparities remain, with Java demonstrating higher efficiency levels than provinces outside Java, suggesting institutional and resource-based disparities. Research conducted in East Java further identifies technical efficiency as a key constraint to productivity, with significant contributions from extension services, access to irrigation, and practical government assistance. Interestingly, membership in farmer organizations, which typically enhances technology transfer and collective action, was not always linked to improved efficiency in that region (Hakim et al. 2021; Sinuraya et al. 2024). On the global stage, ICM has consistently yielded gains of 10–19% in rice across diverse environments, including China, India, and Bangladesh, reflecting the universal benefits of comprehensive, resource-optimized practices. Adopting digital and precision agriculture tools, as seen in Vietnam, also leads to significant annual yield increases, further reinforcing the notion that multifaceted, informed management is crucial for productivity growth (Wang et al. 2017; Yamini et al. 2025).

The box plot in Figure 3 below illustrates the distribution of technical efficiency scores among rice farmers, stratified by their level of adoption of Integrated Crop Management (ICM). Partitioning the dataset at the median ICM score of 0.625 resulted in two distinct groups: "low adopters" (ICM score < 0.625) and "high adopters" (ICM score ≥ 0.625).

As illustrated in Figure 3, the median efficiency score (shown by the line within each box) for high adopters is notably greater than that for low adopters, indicating a positive association between the intensity of ICM adoption and efficiency. Moreover, the interquartile range is narrower for high adopters, indicating reduced variability and a more concentrated distribution of efficiency among this group. This finding aligns with the literature, which demonstrates that the consistent and comprehensive implementation of ICM practices, often facilitated by field school programs or strategic management, contributes to higher and more consistent technical efficiency outcomes in rice production. Such programs have been shown to promote the adoption of best practices, enabling farmers to optimize input use and production processes, thereby reducing the risk of low-efficiency results (Rasyid et al. 2016; Deng et al. 2022).

Conversely, the broader spread of efficiency scores among low adopters reflects greater heterogeneity, with a significant portion of farmers operating at lower efficiency levels. This disparity may be attributed to the partial or inconsistent application of key ICM components, resulting in unpredictable efficiency outcomes. Prior research has noted that variability in management practices, such as fertilizer strategies, water management, and knowledge transfer, directly influences technical efficiency heterogeneity among rice producers. These outcomes collectively suggest that a comprehensive and sustained approach to ICM adoption is essential for increasing and stabilizing technical efficiency within rice-based agricultural systems (Deng et al. 2022).

Practical implication

Policies to improve technical efficiency in rice farming should prioritize expanding educational and training opportunities via formal schooling and informal agricultural education. Extension services and training programs should specifically target older farmers, who may be less inclined or physically less able to adopt new technologies, while encouraging knowledge transfer from experienced to less experienced farmers through farmer field schools, mentoring, or demonstration plots (Ndubueze-Ogaraku and Ogbonna 2016; Acharya et al. 2020). Facilitating greater access to ICM training and resources, and promoting comprehensive ICM adoption, can further enhance efficiency and productivity, consistent with existing evidence from multiple rice-producing regions (Novitaningrum et al. 2020; Biswas et al. 2021). Additionally, land tenure reforms, effective land management education, and incentive structures for landowners have been shown to influence technical efficiency by addressing inefficiencies linked to land ownership (Koirala et al. 2016; Ganiyu et al. 2024). Finally, supporting rice farmers in engaging in full-time, professional farming through improved market access, training, and social protections can substantially raise technical efficiency, in line with studies highlighting the benefits of dedicated labor and occupation focus (Darmawan et al. 2024; Raghua et al. 2025).

Conclusion, this study identifies a significant efficiency gap among rice farmers in West Timor's dryland border regions, with average output reaching only 70% of potential. It highlights the role of Integrated Crop Management (ICM) in improving productivity, though its effectiveness depends on enabling conditions. Key factors such as education, labor, and full-time farming are shown to reduce inefficiency, underscoring the importance of human capital and institutional support. The findings contribute to dryland agricultural research by demonstrating that context-specific ICM adaptation, combined with strengthened extension services and policy support, can enhance resilience and resource-use efficiency. This research is limited by its cross-sectional design, reliance on self-reported data, and focus solely on technical efficiency. Future studies should use multi-season or panel data, incorporate allocative and economic efficiency, and assess the long-term impacts of ICM under variable climate and market conditions. Evaluating targeted interventions, such as water-saving technologies, improved land tenure security, and farmer field schools, would further guide scalable strategies for sustainable intensification in semi-arid rice ecosystems.

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Evaluating trichocompost for disease control and yield improvement in potatoes under tropical dryland conditions in South Central Timor, Indonesia

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Abstract. *Simamora AV, Serangmo DYL, Londingkene JA, Nahas AE, Nenotek PS, Hahuly MV, Kasim M, Mahayasa INW, Gandut YRY, Widinugraheni S, Hosang EY. 2025. Evaluating trichocompost for disease control and yield improvement in potatoes under tropical dryland conditions in South Central Timor, Indonesia. Intl J Trop Drylands 9: 159-168.* Potato (*Solanum tuberosum*) is a key horticultural crop in Indonesia. In tropical dryland areas such as South-Central Timor, Indonesia, potato cultivation faces challenges including limited rainfall, poor soil fertility, and high disease pressure. Late blight caused by *Phytophthora infestans* remains one of the most destructive diseases. This study evaluated the biocontrol efficacy of *Trichoderma harzianum* formulated as trichocompost for disease suppression and yield improvement under dryland conditions. Unlike many previous studies that focused on in vitro or greenhouse testing, this research prioritized native *Trichoderma* isolates adapted to potato rhizosphere soil and validated their performance under harsh Entisol-based dryland field conditions. Five isolates were obtained from the rhizosphere of healthy potato plants and characterized morphologically. Their antagonistic activity against *P. infestans* was assessed using the dual culture method. All isolates inhibited *P. infestans* by more than 70%, with *Trichoderma* 04 showing the highest inhibition. Molecular identification confirmed this isolate as *T. harzianum*, which was selected for field evaluation in four treatments: control, trichocompost applied two weeks before planting (T1), at planting (T2), and two weeks after planting (T3). Data from the dual culture assay and field experiment were analyzed using ANOVA and followed by DMRT at $p<0.05$. Field trials showed that T1 extended the incubation period, substantially reduced disease severity, and increased both tuber number and tuber weight. These results demonstrate the dual function of *T. harzianum* trichocompost as a biocontrol agent and organic soil amendment, supporting sustainable potato production in tropical drylands.

Keywords: Biological control, late blight disease, *Phytophthora infestans*, potato production, *Trichoderma harzianum*

INTRODUCTION

Potato (*Solanum tuberosum*) is a globally important horticultural crop valued for nutritional and economic contributions. In Indonesia, it plays supports food diversification programs, strengthens farmer livelihoods, contributes to non-oil export earnings, and supplies raw material for the processed food industry, underscoring its importance for food security and economic development (Devaux et al. 2020).

East Nusa Tenggara (ENT), particularly South Central Timor (SCT) District, is a notable potato-producing area. However, productivity remains low due to tropical dryland conditions characterized by erratic rainfall, prolonged dry periods, and infertile Entisol soils with poor water retention and nutrient availability. These stresses reduce soil organic matter, limit microbial activity, and exacerbate land degradation. Most farmers depend on low-input production systems with minimal fertilizer or fungicide use due to costs and access constraints. These conditions highlight the need for sustainable, site-specific approaches to soil fertility and disease management (Moata and Takalapeta 2021; Riptanti et al. 2022).

Regional production data further illustrate these challenges. Potato yields in SCT declined from 87.3 quintals per hectare in 2021 to 53.3 in 2022, with only a modest recovery to 59.9 in 2023. By contrast, national yields increased steadily to 196.3 quintals per hectare over the same period (Central Statistics Agency 2024). This disparity indicates SCT's vulnerability and the importance of addressing local production constraints.

Late blight, caused by *P. infestans*, is one of the most destructive constraints in potato systems and cause total crop loss under favorable conditions (Abewoy 2018). Globally, the disease is responsible for annual economic losses of approximately USD 6.7 billion through reduced yield and quality (Liu et al. 2020). Although partial resistance exists, no potato variety is complete immune, leaving the pathogen a persistent threat (Islam et al. 2022). Its adaptability makes control difficult. The pathogen's heterothallic reproductive system and significant genetic variability facilitate swift circumvention of host resistance

(Pazderu and Hamouz 2017). It thrives in highland regions with cool temperatures and high humidity, such as SCT, and can persist in infected tubers, stems, soil, plant debris, and volunteer plants, serving as a source of inoculum for subsequent seasons (Hashemi et al. 2022; Lamichhane et al. 2024). This persistence further complicates its control (Islam et al. 2022; Lamichhane et al. 2024).

Biological control has gained attention as a sustainable alternative. *Trichoderma* species, particularly *T. harzianum*, are effective antagonists that suppress pathogens through mycoparasitism, nutrient competition, enzyme secretion, antibiosis, and induced systemic resistance (Kai et al. 2018; Guo et al. 2022; Tyśkiewicz et al. 2022). These mechanisms support their effectiveness across diverse agroecological conditions, including drylands stress.

Trichoderma can be also formulated into trichocompost, an enriched compost that improves soil microbial activity, organic matter levels, nutrient cycling, and the availability of nitrogen, phosphorus, and potassium. These nutrients are often limited in Entisol soils in SCT (Asghar and Kataoka 2021; Wei et al. 2024). Compost application also increases soil porosity and moisture retention improving crop resilience in low-moisture environments (Hao and Ashley 2021). *Trichoderma*-fortified composts provide the combined benefits of reducing disease incidence and enhancing nutrient mobilization and soil health (Rahman et al. 2024).

Despite these the application of *Trichoderma*-enriched compost in potato systems under naturally infested dryland soils remains underexplored. Existing studies are often limited to in vitro antagonism or greenhouse trials, with few conducted under real field conditions. Addressing this gap is essential for developing sustainable and locally adaptable management strategies in SCT. Therefore, this study aimed to isolate and evaluate native *Trichoderma* species from potato rhizosphere soils for antagonism against *P. infestans* in vitro, and to assess the field efficacy of the most promising isolate (*T. harzianum*) formulated as trichocompost for managing late blight and improving potato productivity under tropical dryland conditions.

We hypothesized that native *Trichoderma* isolates from tropical dryland potato rhizosphere would show strong antagonisms against *P. infestans* and remain effective under challenging field conditions. This study is novel because it uses locally adapted strains and evaluates trichocompost directly in smallholder dryland potato fields with naturally infested soils, limited water availability, and no synthetic inputs, conditions rarely explored in previous *Trichoderma*-potato studies.

MATERIALS AND METHODS

Isolation and identification of *Trichoderma* spp.

Sampling was conducted at a local potato cultivation site in Ayofanu Village, Kie Sub-district, South Central Timor (TTS) District, East Nusa Tenggara, Indonesia. Rhizosphere soil was collected from apparently healthy potato plants situated within a field historically affected by recurring outbreaks of late blight caused by *P. infestans*. The consistent presence of symptom-free plants adjacent to severely infected individuals suggested the potential involvement of protective microbial communities in the root zone. Based on this hypothesis, rhizosphere soils were targeted as potential sources of antagonistic microorganisms, particularly *Trichoderma* spp.

To isolate *Trichoderma* spp. soil samples were processed using the direct planting method. Emerging fungal colonies were cultured on Potato Dextrose Agar (PDA) medium supplemented with 50 ppm chloramphenicol and incubated at room temperature for 7 to 14 days. Following incubation, isolates were characterized based on macroscopic and microscopic features, and taxonomic identification was carried out using morphological criteria described by Watanabe (2010).

All laboratory procedures were performed at the Plant Disease Laboratory, Faculty of Agriculture, Universitas Nusa Cendana. A total of five *Trichoderma* isolates were recovered and evaluated for antagonistic activity against *P. infestans* using in vitro dual culture assays. For the field trial, only one isolate, *Trichoderma* 04 identified as *T. harzianum*, was used because it showed the strongest inhibitory effect.

Pathogen source and maintenance in this study

Phytophthora infestans used in this study was obtained from the culture collection of the Plant Disease Laboratory, Faculty of Agriculture, Universitas Nusa Cendana. This isolate had been previously collected from potato leaves exhibiting typical late blight symptoms in the field and isolated using standard procedures. Briefly, infected leaf segments were placed on Triton Ethanol Agar (TEA) supplemented with 50 ppm chloramphenicol and incubated at room temperature for three days. Colonies displaying typical *P. infestans* morphology were then sub-cultured onto PDA for purification. The identity of the isolate was confirmed using morphological criteria described by Erwin and Ribeiro (1996), and it has since been maintained as part of the laboratory's reference culture collection.

In vitro antagonism assay

A total of five *Trichoderma* isolates obtained from potato rhizosphere soil were tested for antagonistic activity against *P. infestans*. Each isolate was cultured on Potato Dextrose Agar (PDA) medium and incubated at 25 ± 2°C for four days. Mycelial plugs (0.5 cm diameter), taken from the actively growing margins using a sterile cork borer, were placed on one edge of a Petri dish. A similarly sized plug of *P. infestans* was positioned on the opposite edge. The plates were then incubated at 25±2°C for seven days on a laboratory bench to assess antagonistic activity. Each *Trichoderma* isolate was tested in four replicates, and the colony diameter of *P. infestans* was measured daily. The percentage inhibition of pathogen growth was calculated using the formula:

$$\text{Percentage inhibition (\%)} = ((R1 - R2) / R1) \times 100$$

Where, R1 represents the radius of the *P. infestans* colony growing away from the *Trichoderma* isolate, and

R2 represents the radius of the colony growing toward the *Trichoderma* isolate.

Selection of *Trichoderma* isolate for field application

Based on in vitro antagonism tests, the isolate showing the highest inhibition against *P. infestans*, *Trichoderma* 04, was selected for field evaluation. Morphological and molecular analyses confirmed its identity as *T. harzianum*. This isolate, having demonstrated the strongest antagonistic effect, was subsequently incorporated into trichocompost to assess its efficacy under field conditions.

Preparation of trichocompost

Trichocompost was prepared with reference to the protocol outlined by Susanto et al. (2018) with several adjustments to field conditions. *Trichoderma harzianum* was mass-cultured on a corn-based medium. Briefly, 100 g broken corn kernels were sterilized at 121°C and 1 atm for 15 minutes and used as the substrate. After cooling, the corn was placed into heat-resistant plastic bags and re-sterilized under the same conditions. Each cooled bas was then inoculated with five 0.5 cm^2 mycelial plugs from a 7-day-old PDA culture and incubated at room temperature for 7 days. The resulting actively growing cultures were used as inoculants for the composting process.

The compost mixture comprised 10 kg of chopped straw, 10 kg of cow manure, 50 g of dolomite, and 150 g of *T. harzianum* inoculum grown on broken corn kernels. The process began by moistening half of the chopped straw to a water content of approximately 60-70%. This moistened straw was layered with dolomite and the *T. harzianum* corn-based inoculum, followed by a layer of cow manure. The remaining materials were then added in alternating layers to ensure uniform microbial distribution and efficient decomposition.

All composting activities were carried out on a plastic tarpaulin laid directly on the ground. This setup helped prevent nutrient leaching and minimize contamination from soil-borne organisms. Once assembled, the compost pile was covered with an additional plastic tarpaulin to maintain adequate moisture and temperature. Throughout the composting period, internal temperature and humidity were regularly monitored using a digital thermohygrometer. Water was added as needed to maintain the target moisture range of 60-70%. Compost temperature reached ~70ºC during active fermentation, indicating vigorous microbial activity. To improve aeration and promote uniform breakdown of organic material, the compost was manually turned every 10 days, for a total of three times. After approximately 30-35 days, the compost was fully decomposed, dark brown in color, with a crumbly texture and no unpleasant odor, and was ready for application in the field. Trichocompost viability was confirmed prior to field application by plating representative samples on PDA, where active *T. harzianum* colony growth verified the presence of viable propagules.

Field experiment design and treatments

Field evaluation of *T. harzianum* trichocompost for controlling potato late blight was carried out in a potato farmer's field in Ayofanu Village, Kie Sub-district, SCT District (Latitude: -9.880387; Longitude: 124.600679; elevation: 1,034 meters above sea level), from June to October 2023. The site is classified as an Entisol, characterized by a soil pH of 7.1, organic matter of 3.10%, C-organic of 1.74%, total N of 0.35%, available P of 31 ppm, and exchangeable K of 0.75 me per 100 g soil. Farmers in this area do not use chemical fertilizers or irrigation systems. Water availability is extremely limited due to elevation and the absence of irrigation infrastructure; however, daily dew accumulation provides an important moisture source during the dry season and helps sustain crop growth under rainfed conditions.

Rainfall data from the nearest weather station indicated 6 rainy days totaling in 119 mm in June, 10 rainy days totaling 61 mm in July, 5 rainy days totaling 26 mm in August, and no rainfall in September. During the growing season, minimum air temperatures ranged from 17-23°C and daytime temperatures reached 26-33°C. Relative humidity averaged 60-70% with strong daily fluctuations. Theses cool and dry highland conditions are characteristic of the dry season in Timor Island and support early morning dew formation as a results of significant nighttime cooling. This dew provides a small but meaningful source of moisture for potato plants grown without irrigation.

The experimental field had a documented history of late blight, with confirmed *P. infestans* outbreaks in the previous cropping season, ensuring the natural presence of the pathogen. Although no laboratory soil assay was conducted prior to planting, recurrence of typical late blight symptoms during crop development confirmed active *P. infestans* presence in the field. No artificial inoculation was performed in order to maintain real farmer-field conditions and represent the production context of smallholder systems in the region. Disease pressure was allowed to develop naturally, consistent with established and widely accepted approaches in field epidemiological trials for potato late blight and other foliar pathogens as is commonly practiced in late blight field studies (Mollah and Hassan 2023; Shahni et al. 2023).

The field was plowed to achieve a fine tilth, creating optimal conditions for planting. Healthy, visually uniform seed tubers of a locally grown highland potato cultivar were selected from a farmer's stock. Tubers were screened for health and uniformity, measuring 35-40 mm in diameter and having at least three viable eyes. Trichocompost was applied according to the experimental treatments at a rate of 30 tons ha^{-1}, equivalent to 8.25 kg per plot. The crop was managed following standard local farmers practices to ensure consistency with traditional agricultural productions systems. In accordance with local dryland farming practices specific to this highland area, no irrigation was applied during the cropping period, as potato cultivation here depends on daily dew formation during the cool dry season. No synthetic fertilizers were used, and trichocompost served as the sole soil amendments.

The field experiment followed a RCBD with four treatments and three replicates. Each plot measured 2.5×1.1 m^2 with 30×40 cm plant spacing. The treatments applied were: T0: No trichocompost (control), T1, trichocompost applied two weeks before planting; T2, trichocompost applied at planting; T3, trichocompost applied two weeks after planting.

Disease assessment and yield measurement

The study evaluated several parameters to determine the efficacy of trichocompost treatment, including incubation time, disease severity, the Area Under the Disease Progress Curve (AUDPC), number of tubers per plant, and fresh tuber weight. The incubation time was recorded as the period between the last trichocompost application (T3, applied two weeks after planting) and the first appearance of visible late blight symptoms. Disease severity was assessed by examining leaf tissues and estimating the percentage of infected leaf area, with observations conducted weekly over seven intervals starting on day 35 after planting.

Disease severity was determined using the formula proposed by Directorate General of Agricultural Infrastructure and Facilities (2013):

$$DS= (\sum(n\times v)/(N\times Z))\times 100\%$$

Where, DS: Disease severity (%), n: Number of plant leaves in each attack category, v: Scale value for each attack category, N: Total number of leaves observed, and Z: Highest scale value for disease severity

The attack scale values were assigned as follows: 0=no leaf damage, 1=0–10% leaf damage, 2=10–20% leaf damage, 3=20-30% leaf damage, 4=30-50% leaf damage, 5=50-75% leaf damage, 6=>75% leaf damage.

Disease progress was quantified using the Area Under Disease Progress Curve (AUDPC). The AUDPC values were computed in Microsoft Excel using the trapezoidal method applied to weekly disease severity data and were subsequently subjected to ANOVA and DMRT at α=0.05. For clarity, AUDPC results are reported as "disease severity (AUDPC)" in tables and figures.

At 120 days after planting, all plants were harvested, and both the number of tubers and their fresh weight were recorded to assess yield performance. Yield data were collected from all plants except the border plants within each plot. Each plot contained 15 plants, and three replicated plots were used per treatment, resulting in 45 plants per treatment being evaluated. The harvested tubers were then weighed using digital scales to ensure accurate measurement.

Data analysis

The data on percentage inhibition, incubation period, disease severity, number of tubers, and tuber weight were statistically analyzed using Analysis of Variance (ANOVA) based on a Randomized Complete Block Design (RCBD) model. Post hoc comparisons were conducted using Duncan's Multiple Range Test (DMRT) at a 5% significance level. All analyses were performed using SAS software version 9.4 (SAS Institute Inc 2021).

RESULTS AND DISCUSSION

Isolation and identification of *Trichoderma* spp.

Five isolates of *Trichoderma* were obtained from the rhizosphere of healthy potato plants. Their macroscopic and microscopic characteristics are detailed below:

Trichoderma *01*

The colony of *Trichoderma* 01 was circular with a ring-like appearance. Initially, the mycelium was white and gradually turned light green, completely covering the 9 cm Petri dish within five days of cultivation. Microscopically, *Trichoderma* 01 exhibited round conidia, hyaline, branched conidiophores, and short phialides, as displayed in Figure 1.A.

Trichoderma *02*

Characterized by a well-defined circular colony, *Trichoderma* 02 had mycelium that changed from white to green during incubation, reaching the edges of the dish by the fifth day. Under the microscope, this isolate demonstrated grape-like clusters of round conidia with branched conidiophores and thick, short phialides (Figure 1.B).

Trichoderma *03*

The colony of *Trichoderma* 03 exhibited a lateral expansion with a cottony yet slightly rough texture. It filled the Petri dish completely after five days. Microscopically, it was identified by upright, branched conidiophores, short, thick phialides, and oval conidia, as depicted in Figure 1.C.

Trichoderma *04*

Trichoderma 04 formed a circular colony with a ring-like pattern. Initially white, the mycelium turned green as it matured, covering the dish by day five. Microscopically, it displayed hyaline, spherical conidia attached to elongated conidiophores via short phialides (Figure 1.D).

Trichoderma 05

The colony of *Trichoderma* 05 was circular and ring-like, with the mycelium initially appearing white before turning green, dominated by white mycelial strands. It completely covered the Petri dish within five days. Microscopically, *Trichoderma* 05 exhibited upright, branched conidiophores, short and thick phialides, and oval-shaped conidia, as presented in Figure 1.E.

Molecular identification showed that *Trichoderma* 04 formed a well-supported clade with reference sequences of *T. harzianum*, confirming its classification as *T. harzianum* (Figure 2). BLASTn comparison of its ITS revealed 100% identity and full query coverage with *T. harzianum* strain NECC30402 (MH153633.1) and other *T. harzianum* accessions. To further verify its placement, a phylogenetic analysis was performed using the NPGPhylogeni.fr platform (Lemoine et al. 2019), which integrates MAFFT alignment and Maximum Likelihood inference with bootstrap support. This analysis consistently grouped *Trichoderma* 04 within a well-supported *T. harzianum* clade.

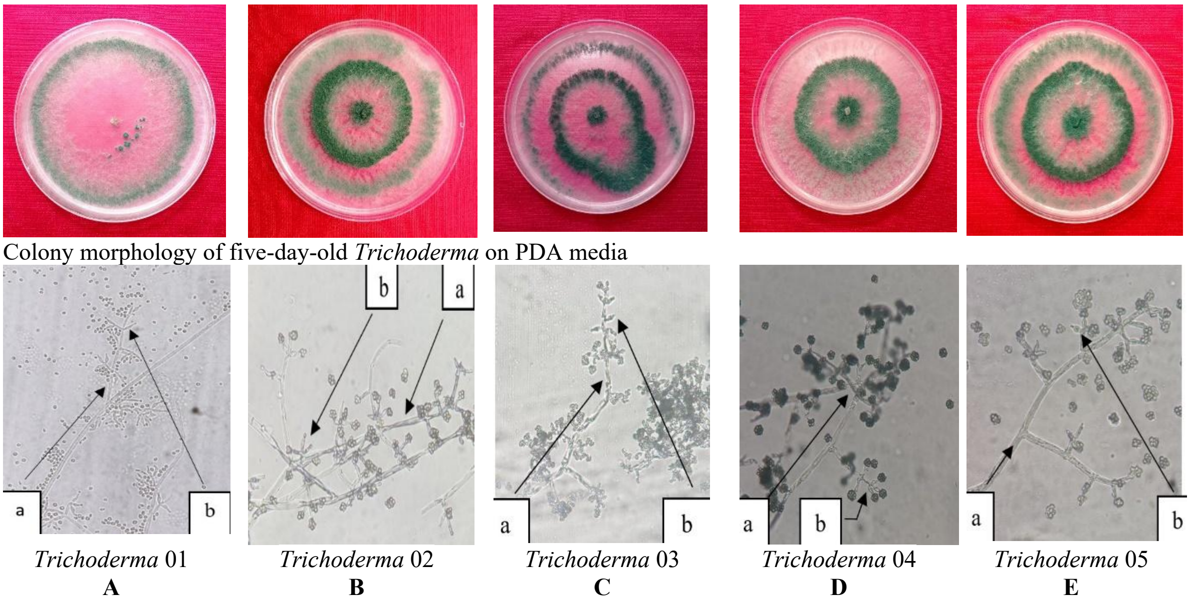

Figure 1. Colony morphology, conidiophore, and phialides of five isolates of *Trichoderma*. a. Conidiophore, b. Phialide

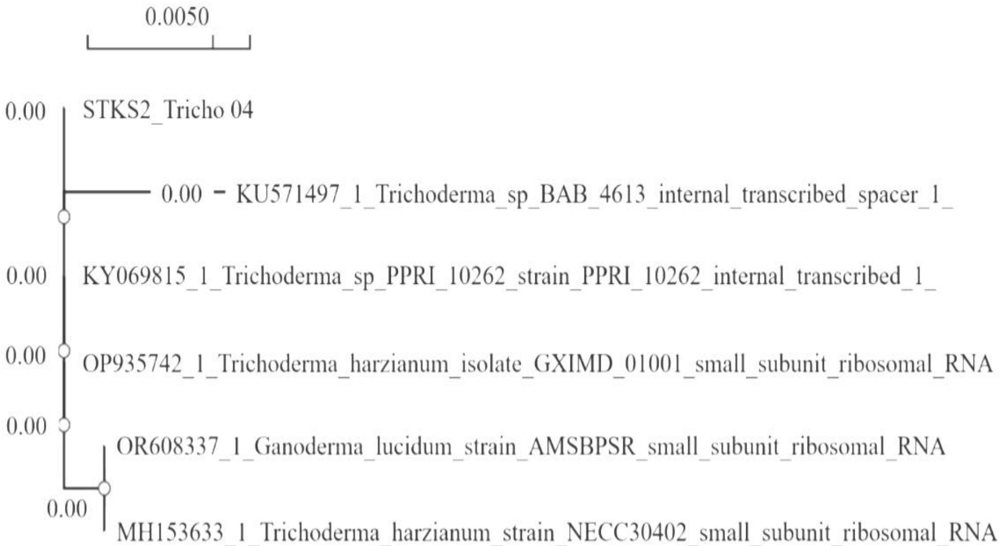

Figure 2. Phylogenetic tree based on ITS-1 rDNA sequences showing the placement of *Trichoderma* 04 (STKS_Tricho 04) within the *T. harzianum* clade. Bootstrap values indicate strong branch support

In vitro antagonism assay

The level of inhibition exerted by *Trichoderma* spp. against *P. infestans* exhibited a highly significant difference. According to the 5% DMRT results, *Trichoderma* 04 demonstrated greater effectiveness, resulting in the highest percentage of inhibition against *P. infestans* (Table 1). The lowest inhibition percentage was achieved by *Trichoderma* 02. However, in general, all *Trichoderma* species assessed had very high antagonistic abilities (above 70%) against *P. infestans*. Visual examination of the dual culture assay showed that all *Trichoderma* isolates inhibited *P. infestans* through competitive interaction. The colonies of *Trichoderma* expanded rapidly toward the pathogen and restricted its radial growth by occupying available space and resources. No lysis zones or clear contact inhibition boundaries were observed, indicating that antagonism occurred primarily through competition. Representative observations from two isolates are presented in Figure 3, as all five isolates exhibited the same competitive inhibition pattern.

Field evaluation of *T. harzianum* trichocompost for controlling potato late blight and enhancing yield

Among the five *Trichoderma* isolates tested in vitro, *Trichoderma* 04 demonstrated the highest inhibition rate against *P. infestans*, achieving 78.2% inhibition. Based on this superior antagonistic activity and subsequent morphological and molecular identification, *Trichoderma* 04 was classified as *T. harzianum*. Therefore, only this isolate was selected for further evaluation under field conditions.

The effectiveness of *T. harzianum*-enriched trichocompost in suppressing late blight disease in potatoes is illustrated in Figures 4.A-B. Application of trichocompost two weeks before planting resulted in the longest incubation period of late blight (17.7 days), significantly higher than the control (7.7 days), application at planting (12.7 days), and application two weeks after planting (9.3 days).The field efficacy of trichocompost in controlling late blight reached 49.18% when applied two weeks before planting (T1), followed by 36.06% at the time of planting (T2), and 24.27% when applied two weeks after planting (T3). These results demonstrate that earlier application leads to stronger disease suppression. In addition to disease suppression, the impact of *T. harzianum* trichocompost on yield parameters, including the number of tubers and average tuber weight, is presented in Table 2.

Table 1. Percentage inhibition (%) of *P. infestans* by *Trichoderma* spp.

No	*Trichoderma* isolates	Percentage inhibition[1)]
1.	*Trichoderma* 01	72.3 a
2.	*Trichoderma* 02	71.5 a
3.	*Trichoderma* 03	76.3 b
4.	*Trichoderma* 04	78.2 c
5.	*Trichoderma* 05	73.1 a

Note: [1)]: Numbers marked by distinct letters differ significantly (P<0.05) according to the DMRT test

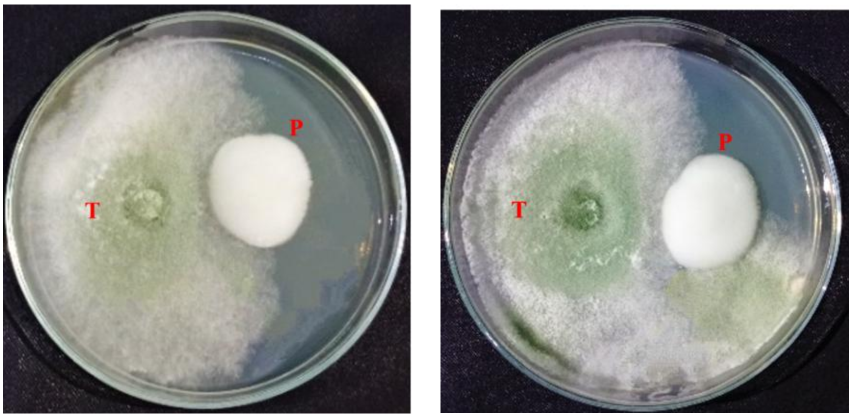

Figure 3. Competitive inhibition of *P. infestans* (P) by *Trichoderma* spp. (T) in dual culture

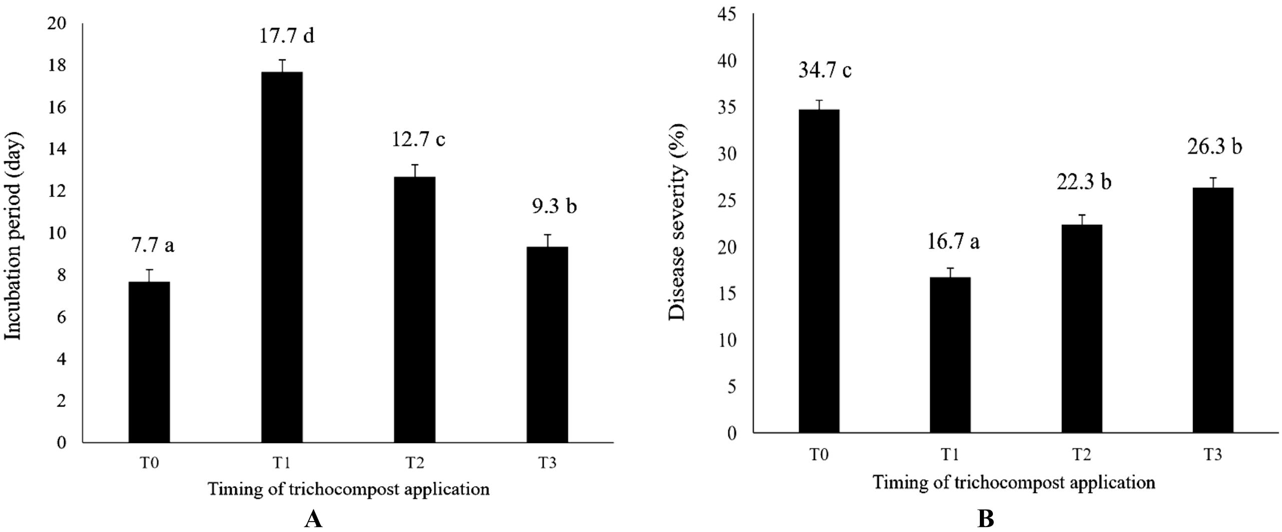

Figure 4. Effect of *T. harzianum* trichocompost on: A. Disease incubation period, B. Disease severity

Table 2. Effect of trichocompost *T. harzianum* on the number of tubers and tuber weight[1)]

Treatments	Number of tubers	Tuber weight (g)
T0: No trichocompost application (control)	5.87±0.12 a	79.00±0.20 a
T1: Application of trichocompost two weeks before planting	7.60±0.17 a	101.67±0.21 b
T2: Application of trichocompost at the time of planting	6.75±0.15 a	85.00±0.20 a
T3: Application of trichocompost two weeks after planting	6.71±0.10 a	84.33±0.25 a

Note: [1)]: Means within the same column followed by different letters are significantly different at P<0.05 according to DMRT

Discussion

The successful isolation of five *Trichoderma* species from the rhizosphere of healthy potato plants indicates that these beneficial fungi are naturally present and well adapted to the soil environment. The variations in their colony color, texture, and conidial form reflect natural diversity among isolates, which often influences their antagonistic ability. This diversity is important because it provides options for selecting strains with the strongest biocontrol potential, as also reported by Bouziane et al. (2016) and Purwantisari et al. (2021).

All five isolates showed strong inhibitory effects against *P. infestans*, with inhibition levels exceeding seventy percent. This result supports previous findings that *Trichoderma* species are effective biological control agents against late blight and other soilborne pathogens. The ability of *Trichoderma* to suppress pathogen growth is generally linked to mechanisms such as mycoparasitism, competition for nutrients, enzyme secretion, and antibiosis (Rokaya et al. 2023).

Among the tested isolates, one consistently produced the highest inhibition rate, showing its potential as a promising candidate for further testing under field conditions. The superior performance of this isolate reflects the well-known variability among *Trichoderma* strains reported in earlier studies. Chen et al. (2024) demonstrated that different *Trichoderma* isolates can display markedly variable antagonistic behaviors against pathogens such as *Pythium* and *Globisporangium*, even when grown under the same laboratory conditions. Stange et al. (2024) also found that the interaction strategies of *Trichoderma*, including active overgrowth and pathogen avoidance, depend strongly on both the strain and the target pathogen. In a similar way, Guzmán-Guzmán et al. (2025) reported that ecological fitness, enzyme production, and biocontrol performance vary widely among strains, particularly under dryland stress. These findings are consistent with the present results and reinforce the importance of selecting and testing local isolates for biological control. The evidence strongly supports the selection of *Trichoderma* 04 as a leading candidate for future field application in late blight management

This field study was conducted in the highland drylands of South-Central Timor, a region characterized by Entisol soils that are inherently infertile and low in organic matter. The agricultural landscape here is marked by sporadic rainfall, limited irrigation infrastructure, and persistent pathogen pressure, making cultivation especially challenging. Most smallholder farmers in the area do not use chemical fertilizers or fungicides due to high costs and poor availability, creating a strong demand for sustainable, low-input alternatives. Despite the absence of rainfall during the latter part of the growing season (September), daily dew in the highlands provided a vital moisture source that helped crops survive without irrigation. Rainfall data further emphasize the environmental constraints: June recorded six rainy days totaling 119 mm, July had ten days with 61 mm, and August had only five days with 26 mm (Central Statistics Agency 2023). This brief and erratic wet season underscores the importance of resilient plant- and soil-health strategies in tropical drylands.

In this study, the application of *T. harzianum* trichocompost produced encouraging results under real farmer field conditions. The T1 treatment, where trichocompost was applied two weeks before planting, proved the most effective. It extended the late blight incubation period from 7.47 days in the control to 17.67 days and reduced disease severity from 34.77% to 17.67%, resulting in an efficacy of 49.18%. Although this value was lower than the 78.2% inhibition observed under laboratory conditions, the field outcome is still meaningful, especially considering the natural variability and challenges present in open field environments (Khatun et al. 2021; Islam et al. 2022). These results show that trichocompost can help slow disease development and lessen symptom severity in a practical production setting. It is important to note that while *T. harzianum* is known in the literature to suppress pathogens through several biological pathways, including competition, antibiosis, and plant defense stimulation (Tyśkiewicz et al. 2022), this study did not measure those mechanisms directly. Therefore, the exact mode of action in this field trial remains unknown and would benefit for further investigation in future work.

Such discrepancies between laboratory and field results are well-documented. They can be attributed to environmental variability, fluctuating soil moisture, and microbial interactions, factors particularly pronounced in Entisol soils, which lack strong structure and retain little water. Despite these limitations, the T1 treatment produced measurable yield benefits. Although the increase in tuber number per plant was not statistically significant, it showed a numerical improvement from 5.87 to 7.60 per plant. In contrast, average tuber weight increased significantly, rising from 79.00 g to 101.67 g. These results highlight the potential dual benefits of trichocompost in suppressing disease and enhancing yield components. Together, the findings indicate a clear relationship between disease suppression and yield performance, where treatments that lowered late blight severity, particularly T1, also produced higher tuber weight and number. Similar positive effects of

Trichoderma-based compost on soil biological function and crop productivity have been reported in previous studies (Asghar and Kataoka 2021; Wei et al. 2024). Further validation with larger plot sizes and increased replication is recommended to strengthen this preliminary observation under dryland field conditions.

Treatments T2 (applied at planting) and T3 (two weeks after planting) also offered improvements, albeit less than T1. This highlights the importance of application timing; early application provides *T. harzianum* more time to colonize the rhizosphere before the onset of pathogen pressure (Mitiku and Eshete 2017). In smallholder systems that depend entirely on organic inputs and ambient moisture, even modest yield increases can significantly improve food security and livelihoods.

Mechanistically, *T. harzianum* suppresses pathogens through multiple modes of action: it competes for nutrients and space (Bae et al. 2017; Naher et al. 2018), produces cell wall–degrading enzymes such as chitinase and glucanase (Adnan et al. 2019), and releases antifungal compounds that inhibit pathogen development (Elsherbiny et al. 2020). Additionally, it parasitizes harmful fungi (Mukhopadhyay and Kumar 2020) and stimulates systemic resistance in host plants, enhancing tolerance to both biotic and abiotic stress (Kai et al. 2018; Guo et al. 2022; Tyśkiewicz et al. 2022).

Beyond disease control, *T. harzianum* contributes to soil fertility by enhancing microbial diversity, accelerating the decomposition of organic matter, and improving nutrient cycling, especially nitrogen, phosphorus, and potassium, which are typically deficient in Entisols (Ahmed et al. 2019; Wang et al. 2019; Mazen 2021; Flores and Leon 2024; Peña et al. 2025). The positive effects of *Trichoderma* spp. on agricultural productivity in arid and semi-arid regions have been well-documented. These fungi enhance crop yields, improve soil structure, and modulate soil microbial communities. For example, *Trichoderma* combined with NPK fertilizers significantly improved mustard yields compared to untreated controls, where biofertilizers alone had minimal effect (Islam et al. 2023). Similar benefits have been reported for other vegetables, including cucumber and tomato, when using *Trichoderma*-enriched biofertilizers (Haque et al. 2012). A review by Zhu et al. (2022) summarized the fungi's capacity to enhance physical, chemical, and biological soil properties, which is particularly valuable in degraded dryland soils. Furthermore, *Trichoderma*'s mycoparasitic behavior supports healthier plant growth by suppressing soil-borne pathogens (La Spada et al. 2020; Abdullah et al. 2021).

To enhance potato productivity in SCT, several strategies should be explored: applying trichocompost at higher doses or more frequently during the crop cycle; combining it with other organic amendments like composted manure or leguminous cover crops; and using *Trichoderma* strains that are locally adapted. Participatory on-farm trials and cost benefit analyses are also essential to promote adoption and inform future policy.

The number of tubers set by a potato plant is largely determined by its genetic makeup, even though environmental and agronomic factors can modulate that potential. In our study, all treatments used the same potato variety, and trichocompost application did not produce a statistically significant difference in tuber number (Table 2). This suggests that genetic factors likely defined the inherent capacity for tuber initiation, which remained relatively stable across treatments. Recent Genome-Wide Association Study research supports this interpretation, showing that specific genomic regions regulate tuber number (Gautam et al. 2024). While potential limits tuber initiation, the improved soil microbial activity and nutrient availability associated with trichocompost likely enhanced tuber bulking rather than tuber set, helping explain the significant increase in tuber weight observed in the T1 treatment. Trichocompost may have contributed to these improvements through microbial enrichment and enhanced nutrient cycling. The activity of *T. harzianum* and associated beneficial microbes accelerates organic matter decomposition and promotes nutrient mineralization, increasing the availability of N, P, and K in nutrient -poor Entisols. These processes are supported by recent evidence showing that Trichoderma strains produce phytohormones and biomolecules that enhance nutrient uptake, root growth, and overall plant vigour (Reghmit 2023). This improved nutrient supply likely supported greater root activity and bulking, contributing to the higher tuber weight recorded in T1 treatment.

In contrast, tuber weight responded significantly to the timing of *T. harzianum* trichocompost application. The T1 treatment, application two weeks before planting, yielded significantly heavier tubers compared to the control and other treatments. This effect is likely due to improved soil structure, enhanced nutrient availability, and beneficial microbial interactions stimulated by the trichocompost. Studies have shown that *Trichoderma*-enriched bioformulations can significantly increase tuber weight and overall yield under stress conditions by improving nutrient uptake and plant resiliency (Ashar et al. 2024; Napolitano et al. 2024).

This study clearly demonstrates that *T. harzianum*-enriched trichocompost is effective in suppressing late blight and improving potato productivity under tropical dryland conditions in SCT. The application of trichocompost at a rate of 30 tons per hectare, particularly when administered two weeks before planting (T1), significantly extended the incubation period of *P. infestans* from 7.47 to 17.67 days, and reduced disease severity from 34.77% to 17.67%. In addition, yield components improved, with tuber number increasing from 5.87 to 7.60 per plant and average tuber weight rising from 79.00 g to 101.67 g compared with the untreated control. These outcomes highlight the dual function of trichocompost as both a biocontrol agent and a soil amendment, offering valuable benefits in Entisol-dominated dryland that are typically low in organic matter and water-holding capacity. Overall, the field results confirm our initial hypothesis that *T. harzianum* trichocompost can suppress late blight and enhance potato yield under the challenging dryland conditions of SCT.

Building on the positive results of this study, the application of *T. harzianum* trichocompost two weeks before planting shows strong potential for broader adoption in tropical dryland highland regions. This application timing proved particularly effective, offering a practical, affordable, and environmentally sustainable strategy for smallholder farmers who often face challenges in accessing chemical inputs and reliable irrigation. The improvements observed in disease suppression and yield performance underscore the value of trichocompost in enhancing crop resilience under dry and nutrient-poor conditions.

From a practical perspective, the ability of *T. harzianum* trichocompost to prolong disease incubation and enhance tuber yield under-low input conditions has important implications for farmers in tropical drylands. By reducing reliance on synthetic fungicides and external fertilizer, this approach provides a cost-effective and ecologically sustainable option for smallholder farmers. It supports improved soil health, lower production costs, and greater resilience in resource-limited environments, making it particularly valuable for dryland communities that depend on organic inputs and limited water availability.

This study provides initial evidence that *T. harzianum* trichocompost can help reduce late blight and improve potato yields under dryland highland farming conditions in SCT. While promising, these results are from a single site and season, so further trials across different locations and seasons are needed to confirm consistency. Future research should also assess long-term soil health and economic benefits, and explore combining trichocompost with other organic materials to enhance effectiveness. Scaling up this approach will require participatory farmer validation to ensure that technology align with local practices, resource availability, and farmer priorities. Farmer engagement through training and filed demonstrations will be essential for practical adoption. From a policy perspective, integrating trichocompost-based biocontrol into regional agricultural development strategies, such as dryland intensification programs and soil restoration initiatives could support wider implementations. Supporting bio-based soil amendments and community-level composting efforts can strengthen soil health, build climate-resilient production systems, and improve farmer livelihoods in tropical dryland regions. Such integration would also enhance the adaptability and long-term sustainability of dryland farming systems. In summary, *T. harzianum* trichocompost presents a promising strategy to strengthen food production systems in tropical drylands, contributing to both environmental restoration and improved farmer livelihoods.

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Diversity and microclimatic patterns of vascular plant communities in cave-associated karst microhabitats of Ngantap Cave, Central Java, Indonesia

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Abstract. *Paramesti H, Sheliana MS, Hapsari M, Hasan MT, Susatio R, Jumari, Suharno, Setiawan AD. 2025. Diversity and microclimatic patterns of vascular plant communities in cave-associated karst microhabitats of Ngantap Cave, Central Java, Indonesia. Intl J Trop Drylands 9: 169-180.* Karst ecosystems are characterized by strong environmental heterogeneity driven by limestone geomorphology, shallow soils, and localized microclimatic variation. Within these systems, caves play an important role in shaping surrounding terrestrial habitats by generating gradients in light availability, humidity, and air movement. Despite their ecological significance, vegetation associated with cave-related microhabitats outside the cave interior remains poorly documented in tropical karst regions, including Indonesia. This study examines vascular plant communities associated with cave-related microhabitats around Ngantap Cave, Wonogiri District, Central Java, Indonesia, part of the Gunung Sewu UNESCO Global Geopark. Vegetation sampling was conducted using line transects across three cave-associated microhabitat zones: entrance, cliff, and twilight. A total area of 1,800 m² was surveyed, and all vascular plant individuals were recorded and classified by species, family, growth form, and origin status (native, introduced, cultivated). Microclimatic parameters, including air temperature, relative humidity, light intensity, and wind speed, were measured to characterize environmental gradients among zones. Community structure was analyzed using Shannon–Wiener diversity, Simpson dominance, and Pielou evenness indices within a descriptive–comparative framework. A total of 41 vascular plant species belonging to 22 families and comprising 1,736 individuals were recorded. Herbaceous species and ferns dominated cave-associated assemblages, whereas shrubs and small trees were less frequent, and large canopy trees were absent. Species richness and diversity were highest in the entrance zone and declined toward the twilight zone, which supported only a limited number of shade- and humidity-tolerant taxa. Microclimatic conditions exhibited clear and directional gradients, with increasing relative humidity and decreasing light intensity and air movement from the entrance to the twilight zone. Introduced and cultivated species were present but largely confined to entrance areas, reflecting historical tourism-related activities rather than ongoing biological invasion. These findings demonstrate that cave-associated microhabitats support distinct plant communities structured by fine-scale environmental filtering and provide baseline ecological information essential for conserving microhabitat diversity in tropical karst ecosystems.

Keywords: Cave-associated habitat, karst ecosystem, microclimate, vascular plants, vegetation zonation

INTRODUCTION

Karst ecosystems are characterized by highly heterogeneous geomorphology, shallow and discontinuous soils, and strong limitations in water and nutrient availability, making them among the most environmentally constrained terrestrial systems in the tropics (Ford and Williams 2007; Goldscheider and Drew 2007). Limestone dissolution processes generate complex landforms, including cliffs, sinkholes, fissures, and caves, resulting in pronounced spatial variability in substrate stability, moisture retention, and light availability over short distances. This extreme heterogeneity creates sharp ecological gradients at fine spatial scales and imposes strong environmental filters on plant establishment and persistence, often producing distinctive vegetation structures and specialized plant assemblages (Clements et al. 2006; White et al. 2019; Aprilia et al. 2021).

Caves constitute a critical component of karst systems not only as subterranean habitats but also as drivers of localized microclimatic gradients in their surrounding environments. Cave entrances and adjacent limestone surfaces modify air circulation, humidity regimes, and solar radiation, creating transitions from exposed and thermally variable conditions to shaded and persistently humid microhabitats (Badino 2010; Culver and Pipan 2014). These cave-induced gradients frequently extend beyond the cave interior and influence nearby terrestrial habitats that remain functionally linked to the cave system despite not being fully aphotic.

Areas surrounding cave entrances therefore function as ecological transition zones between surface karst landscapes and subterranean environments. Compared with open karst terrain, cave-associated microhabitats often exhibit reduced temperature fluctuations, higher relative humidity, lower light availability, and limited air movement (Badino 2010). Such conditions generate environments that differ markedly from both exposed karst surfaces and true cave interiors, potentially supporting distinct plant assemblages shaped primarily by microclimatic filtering rather than by broader landscape-scale processes. Despite this ecological significance, vegetation associated with cave-related microhabitats outside the cave interior remains poorly documented in tropical karst regions, particularly in Southeast Asia.

Vegetation patterns in tropical karst landscapes are generally shaped by edaphic stress, water scarcity, and the physical instability of limestone substrates. Exposed karst areas are commonly dominated by drought-tolerant trees, shrubs, and climbers, whereas herbs and ferns occupy rock crevices, shaded surfaces, and small soil pockets where moisture availability is relatively higher (Clements et al. 2006; Huang et al. 2022). Structural heterogeneity is a defining feature of karst vegetation, with sharp contrasts among open hills, cliff faces, and sheltered depressions occurring at very fine spatial scales.

Vascular plants inhabiting karst environments exhibit a range of morphological and physiological adaptations, including reduced stature, clonal growth, shade tolerance, and efficient water-use strategies (Porembski and Barthlott 2000; Huang et al. 2022). Ferns and members of the family Araceae are particularly associated with humid and shaded karst microhabitats, where stable moisture availability and reduced irradiance favor their growth (Parris et al. 2010). Climbers and epiphytes further contribute to vegetation complexity by exploiting vertical rock surfaces and existing vegetation, thereby enhancing habitat heterogeneity in limestone landscapes.

Vegetation associated with cave surroundings differs markedly from that of open karst landscapes. While exposed karst habitats are typically dominated by woody species adapted to high irradiance and seasonal drought, cave-associated microhabitats tend to support herbaceous- and fern-rich assemblages that benefit from reduced environmental stress and more stable microclimatic conditions (Poulson and White 1969; Culver and Pipan 2019). These contrasts highlight the ecological importance of cave-associated habitats as distinct components within karst vegetation mosaics rather than marginal extensions of surrounding landscapes.

Indonesia hosts extensive tropical karst landscapes across Java, Sulawesi, and eastern Indonesia, with the Gunung Sewu region of southern Java recognized as a UNESCO Global Geopark. Previous vegetation studies in Gunung Sewu and adjacent areas have largely focused on floristic inventories, forest structure, or land-use impacts at landscape scales (Whitten et al. 1996; Supriatna et al. 2017). Studies conducted in Pacitan, Gunungkidul, and Kebumen document karst flora diversity but generally emphasize open karst hills, forest remnants, or land-use gradients rather than cave-associated microhabitats. Consequently, fine-scale vegetation patterns linked to cave-related microhabitats remain poorly understood in Indonesia, particularly in the Wonogiri sector of the Gunung Sewu karst, where cave surroundings such as those of Ngantap Cave have received little focused scientific attention.

This study provides the first microhabitat-scale assessment of vascular vegetation associated with cave environments outside the cave interior in the Wonogiri sector of the Gunung Sewu karst, Central Java, Indonesia. The study documents species composition and growth-form structure, compares diversity and dominance among entrance, cliff, and twilight zones, and examines vegetation–microclimate relationships using a descriptive approach. The findings supply baseline ecological data that enhance understanding of karst ecosystem complexity and inform conservation and management of cave-associated microhabitat diversity. It is hypothesized that plant species richness, diversity, and growth-form composition decline from the cave entrance toward cliff and twilight zones in response to decreasing light availability and increasing humidity, resulting in distinct microhabitat-specific assemblages.

MATERIALS AND METHODS

Study area

The study was conducted in the surroundings of Ngantap Cave, Wonogiri District, Central Java, Indonesia (8° 04.8515' S, 110° 54.2506' E). Administratively, the site is located within the southern karst belt of Central Java, which forms part of the Gunung Sewu karst region. Geographically, this area lies within the tropical monsoon climate zone, characterized by distinct wet and dry seasons that strongly influence vegetation dynamics and microclimatic conditions.

Ngantap Cave is situated within the Gunung Sewu UNESCO Global Geopark, a landscape recognized for its extensive limestone formations, high geodiversity, and ecological significance. The karst system in this region is dominated by limestone hills, cliffs, sinkholes, and subterranean drainage networks formed through long-term dissolution processes (Ford and Williams 2007). These geomorphological features create strong environmental heterogeneity, particularly in terms of substrate depth, surface stability, and water availability, which in turn shape vegetation structure and species distribution.

The immediate surroundings of Ngantap Cave are characterized by steep limestone cliffs, shaded rock faces, and narrow entrance areas, with minimal development of flat terrain. Historically, the cave and its surroundings were used as a local tourism site; however, declining visitor numbers have resulted in limited maintenance and reduced human disturbance in recent years. This condition has allowed semi-natural vegetation to persist and regenerate around the cave system, including both native species and cultivated or introduced plants associated with earlier tourism activities. The combination of karst geomorphology and reduced anthropogenic pressure makes the Ngantap Cave area suitable for examining vascular plant communities associated with cave-related microhabitats (Figure 1).

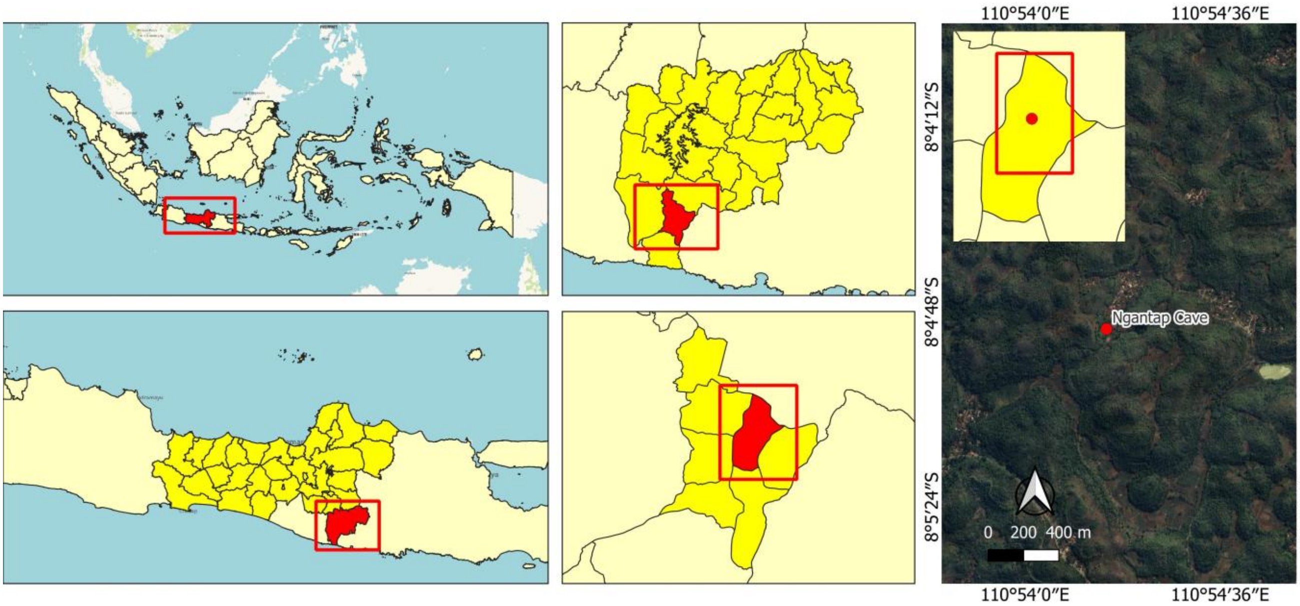

Figure 1. Research location map of Ngantap Cave and surrounding karst microhabitats in Central Java, Indonesia

Cave-associated microhabitat zoning

Vegetation sampling was organized according to cave-associated microhabitat zones defined based on geomorphological position, light availability, and microclimatic conditions. Three zones were distinguished: the entrance zone, the cliff zone, and the twilight (humid) zone. This zonation follows ecological principles commonly applied in cave and karst studies to capture environmental gradients extending outward from cave openings (Badino 2010; Culver and Pipan 2014), with emphasis on habitats that remain functionally influenced by cave morphology and airflow but are located outside the cave interior.

The entrance zone refers to areas directly adjacent to the cave opening that receive partial to full sunlight for part of the day. These areas experience greater temperature fluctuation, higher light intensity, and lower relative humidity compared to more cave-influenced zones, while still being affected by air exchange with the cave interior. The cliff zone comprises vertical or steeply inclined limestone surfaces surrounding the cave, characterized by shallow or absent soil, high surface roughness, and intermediate light conditions dominated by diffuse or reflected radiation due to microtopographic shading. Vegetation in this zone is typically restricted to rock crevices and small soil pockets, resulting in a dominance of stress-tolerant herbs, ferns, and climbers.

The twilight (humid) zone is defined as shaded areas located further from direct sunlight but still outside the cave interior. Within the context of this study, the twilight zone represents the most light-limited and humid microhabitat recorded, characterized by very low irradiance, minimal air movement, and relatively stable microclimatic conditions. These areas receive weak, diffused light and maintain high relative humidity due to reduced evaporation and close functional linkage to cave airflow. Such conditions favor shade-tolerant vascular plants, particularly ferns and members of Araceae, which are commonly associated with moist karst microhabitats.

Importantly, this study does not include open karst plains, agricultural land, or flat forested areas located away from the cave system. By restricting sampling to these three cave-associated zones, the analysis explicitly targets microhabitats that are environmentally filtered by cave-related geomorphology and microclimate, rather than broader karst landscapes influenced primarily by surface processes.

Vegetation sampling design

Vegetation sampling was conducted using a line transect method to capture fine-scale variation in species composition across cave-associated microhabitats. This method is widely applied in heterogeneous environments such as karst landscapes, where vegetation distribution is strongly influenced by microtopography and substrate discontinuity (Kent 2012). Transects were established separately within each defined microhabitat zone (entrance, cliff, and twilight) to ensure balanced spatial representation.

In each zone, three line transects measuring 50 m × 4 m were laid parallel to local geomorphological features, resulting in a total of nine transects. The total sampled area covered 1,800 m². Transect placement avoided overlap and followed accessible natural contours without modifying the substrate. All vascular plant individuals occurring within transect boundaries were recorded, regardless of size class, to capture the full spectrum of growth forms present in cave-associated habitats.

Individual plants were defined as distinct, physically separated entities. For clonal or creeping species, individuals were counted based on visible ramets when separation was clear in the field. Each recorded species was classified into growth form categories, including fern, herb, shrub, tree, climber, bamboo, and orchid, based on field-observed habitus. This classification emphasizes functional structure rather than strict life-form schemes, allowing direct comparison among microhabitat zones (Table 1).

Species identification was carried out through a combination of field observation and post-field verification. Preliminary identification was conducted in situ using regional floras, particularly *Flora of Java* (Backer and Bakhuizen van den Brink 1963-1968), supplemented by taxonomic references relevant to ferns and flowering plants of Java and Malesia (Holttum 1954; Piggott 1988; Parris et al. 2010). Scientific names were subsequently verified using authoritative online databases, including Plants of the World Online (POWO 2026, Royal Botanic Gardens, Kew; https://powo.science.kew.org) and the International Plant Names Index (IPNI 2026; https://www.ipni.org), to ensure nomenclatural consistency. Although accepted names from POWO and IPNI were consulted, several species are presented using names commonly applied in regional floristic and ecological studies of Java to ensure consistency with field identification and local literature. Final identifications were confirmed by cross-checking diagnostic morphological characters with published descriptions and verified images from these sources.

Microclimatic measurements

Microclimatic conditions were measured to characterize environmental variation among cave-associated microhabitat zones and to support a descriptive interpretation of vegetation patterns. Four key parameters were recorded: air temperature, Relative Humidity (RH), light intensity, and wind speed. These variables are commonly used to describe microclimatic gradients in karst and cave-related environments, as they directly influence plant physiological processes and habitat suitability (Badino 2010; Culver and Pipan 2014).

Measurements were conducted using portable field instruments. Air temperature and relative humidity were recorded with a digital thermo-hygrometer, light intensity was measured using a handheld lux meter, and wind speed was assessed using a portable anemometer. All instruments were calibrated according to manufacturer specifications prior to field deployment. Within each microhabitat zone, measurements were taken at multiple representative points along every vegetation transect to ensure adequate spatial coverage and direct correspondence between vegetation data and environmental conditions.

Data collection was carried out during daytime hours (approximately mid-morning to early afternoon) under comparable weather conditions to minimize the influence of short-term climatic variability. Along each transect, microclimatic readings were recorded at regular intervals, with sensors positioned at approximately 1 m above ground level to represent conditions experienced by the understory vegetation. For each microhabitat zone, measurements were conducted on the same sampling days to allow direct comparison among zones.

All measurements obtained from multiple points and transects within each zone were pooled and averaged to derive mean microclimatic values for the entrance, cliff, and twilight zones. These mean values were subsequently used to summarize environmental gradients and to support descriptive analyses of vegetation–microclimate relationships. Given the exploratory scope of the study and the limited spatial extent of the sampling area, microclimatic data were not subjected to inferential statistical testing but were interpreted comparatively among zones.

Data analysis

Vegetation data were analyzed to describe species diversity, dominance, and community structure across cave-associated microhabitat zones. Species abundance data obtained from transects were used to calculate standard diversity indices, including the Shannon–Wiener diversity index (H′), Simpson dominance index (D), and Pielou's evenness index (E). These indices are widely applied in vegetation ecology to summarize community complexity, dominance patterns, and the distribution of individuals among species (Magurran 2004; Kent 2012).

The Shannon–Wiener diversity index (H′) was calculated to represent overall species diversity by incorporating both species richness and relative abundance. Simpson's dominance index (D) was used to assess the extent to which communities were dominated by one or a few species, with higher values indicating greater dominance. Pielou's evenness index (E) was calculated to evaluate how evenly individuals were distributed among recorded species within each microhabitat zone. All indices were calculated separately for the entrance, cliff, and twilight zones to enable zone-specific comparison of community structure.

Interpretation of diversity indices followed commonly accepted ecological guidelines, where higher H′ values indicate greater diversity, higher D values reflect stronger dominance, and E values approaching 1 indicate more even species distributions (Magurran 2004). Rather than applying rigid categorical thresholds, index values were interpreted comparatively among zones to highlight relative differences in community structure.

Given the limited spatial extent of the study area, the small number of transects per zone, and the strong microhabitat-specific filtering inherent to cave-associated karst environments, the analysis adopted a descriptive–comparative approach without inferential statistical testing. Under such conditions, inferential statistics may provide limited ecological meaning and risk overstating generality. Accordingly, diversity indices and microclimatic data were used to support qualitative and comparative interpretation of vegetation patterns across cave-associated zones, emphasizing baseline documentation and ecological plausibility rather than hypothesis testing.

RESULTS AND DISCUSSION

Species composition and structural attributes

A total of 41 vascular plant species belonging to 22 families, comprising 1,736 recorded individuals, were documented across cave-associated microhabitat zones around Ngantap Cave (Table 1). Species richness and abundance were unevenly distributed among zones, with the entrance zone supporting the highest number of individuals, followed by the cliff zone, while the twilight zone contained only a very limited number of species and individuals.

A limited number of plant families taxonomically dominated the recorded flora. Asteraceae was the most species-rich family, contributing several herbaceous taxa commonly associated with disturbed or semi-open habitats. Fern families, particularly Thelypteridaceae, Pteridaceae, and Blechnaceae, were also well represented and were common in shaded and humid microhabitats associated with the cave system. Araceae contributed several species with creeping or climbing growth forms, while Fabaceae and Euphorbiaceae were represented by both herbaceous and woody taxa (Table 1).

Table 1. Species composition, family, growth form, and status

Species	Family	Growth form	Status
Celtis timorensis Span.	Cannabaceae	Tree	Native
Epipremnum pinnatum (L.) Engl.	Araceae	Climber	Native
Ficus callosa Willd.	Moraceae	Tree	Native
Thelypteris pozoi (C.Chr.) Morton	Thelypteridaceae	Fern	Native
Adiantum capillus-veneris L.	Pteridaceae	Fern	Native
Christella dentata (Forssk.) Brownsey & Jermy	Thelypteridaceae	Fern	Native
Christella parasitica (L.) H.Lév.	Thelypteridaceae	Fern	Native
Homalomena rubescens Kunth	Araceae	Herb	Native
Pilea angulata (J.R.Forst. & G.Forst.) Blume	Urticaceae	Herb	Native
Schismatoglottis calyptrata (Roxb.) Zoll. & Moritzi	Araceae	Herb	Native
Abrus precatorius L.	Fabaceae	Climber	Native
Acalypha brachystachya Hornem.	Euphorbiaceae	Herb	Native
Adiantum raddianum C.Presl	Pteridaceae	Fern	Introduced
Ageratum conyzoides L.	Asteraceae	Herb	Introduced
Ageratum houstonianum Mill.	Asteraceae	Herb	Introduced
Amphicarpaea bracteata (L.) Fernald	Fabaceae	Climber	Introduced
Bambusa vulgaris var. *vittata* (Aiton) A.Chev.	Poaceae	Bamboo	Cultivated
Blechnum orientale L.	Blechnaceae	Fern	Native
Caladium bicolor (Aiton) Vent.	Araceae	Herb	Cultivated
Casearia grewiaefolia Vent.	Salicaceae	Tree	Native
Centella asiatica (L.) Urb.	Apiaceae	Herb	Native
Christella normalis (C.Chr.) Holttum	Thelypteridaceae	Fern	Native
Chromolaena odorata (L.) R.M.King & H.Rob.	Asteraceae	Shrub	Introduced
Clidemia hirta (L.) D.Don	Melastomataceae	Shrub	Introduced
Codiaeum variegatum (L.) Rumph. ex A.Juss.	Euphorbiaceae	Shrub	Cultivated
Cordyline fruticosa (L.) A.Chev.	Asparagaceae	Shrub	Cultivated
Crassocephalum crepidioides (Benth.) S.Moore	Asteraceae	Herb	Introduced
Crinum asiaticum L.	Amaryllidaceae	Herb	Native
Davallia denticulata (Burm.f.) Mett.	Davalliaceae	Fern	Native
Dendrobium discolor var. *bromfieldii* (F.Muell.)	Orchidaceae	Epiphyte	Cultivated
Desmodium triflorum (L.) DC.	Fabaceae	Herb	Native
Diplazium esculentum (Retz.) Sw.	Athyriaceae	Fern	Native
Duranta erecta L.	Verbenaceae	Shrub	Cultivated
Litsea glutinosa (Lour.) C.B.Rob.	Lauraceae	Tree	Native
Manihot esculenta Crantz	Euphorbiaceae	Shrub	Cultivated
Melochia villosissima Blume	Malvaceae	Shrub	Native
Phytolacca acinosa Roxb.	Phytolaccaceae	Herb	Introduced
Polyalthia longifolia (Sonn.) Thwaites	Annonaceae	Tree	Cultivated
Samanea saman (Jacq.) Merr.	Fabaceae	Tree	Introduced
Synedrella nodiflora (L.) Gaertn.	Asteraceae	Herb	Introduced
Youngia japonica (L.) DC.	Asteraceae	Herb	Introduced

Note: Species nomenclature follows commonly used names in regional floristic studies and was verified against Plants of the World Online (POWO) and the International Plant Names Index (IPNI). Growth form classification is based on field-observed habitus, and species status (native, introduced, cultivated) follows regional floras and common usage in Java, Indonesia

In terms of growth form, herbaceous species constituted the largest proportion of recorded taxa, followed by ferns. Shrubs and small trees were present but comparatively less abundant, and large canopy tree species were absent from all sampling zones. Climbers, including both woody and herbaceous forms, contributed a smaller but ecologically notable component of the vegetation. Orchid representation was limited to a single cultivated epiphytic taxon. This structural pattern indicates a community dominated by low-stature vegetation adapted to shallow soils, rock crevices, and shaded limestone surfaces.

Species status classification revealed a mixed assemblage of native, introduced, and cultivated plants (Table 1). Native species accounted for the largest proportion of taxa and individuals, particularly among ferns and shade-tolerant herbs. Introduced species were mainly herbaceous taxa commonly associated with anthropogenic disturbance, whereas cultivated species consisted primarily of ornamental or food plants likely originating from earlier tourism-related planting or nearby human activity. Despite their presence, cultivated taxa contributed only a minor proportion of total abundance.

Spatially, most species were concentrated in the entrance and cliff zones, where higher light availability and substrate heterogeneity allowed the coexistence of multiple growth forms. In contrast, the twilight zone supported very few species and individuals, reflecting its low light intensity and persistently humid conditions. Representative species illustrating the range of growth forms and microhabitat associations observed in the study area are shown in Figure 2.

Spatial distribution of species across microhabitat zones

The spatial distribution of vascular plant species around Ngantap Cave showed clear variation among the three cave-associated microhabitat zones: entrance, cliff, and twilight (Table 2; Figure 3). Species richness and individual abundance were strongly concentrated in the entrance zone, which supported 31 species and 1,502 individuals, representing the majority of the recorded flora. This zone harbored a heterogeneous assemblage of herbs, ferns, shrubs, climbers, and small trees, coinciding with relatively higher light availability and greater substrate heterogeneity.

The cliff zone exhibited a distinct but substantially less diverse assemblage compared to the entrance zone. Only 6 species comprising 226 individuals were recorded in this zone. Species occurring here were largely restricted to taxa capable of establishing on steep limestone surfaces, rock crevices, and shallow soil pockets. Ferns and shade-tolerant herbs dominated the assemblage, while woody tree species were absent. Several species abundant in the entrance zone were not recorded on cliffs, indicating strong microhabitat filtering associated with substrate instability and limited soil development (Table 2).

In contrast, the twilight zone supported a highly restricted plant community. This zone contained only 4 species and 9 individuals in total. All recorded taxa were shade-tolerant and associated with persistently humid conditions, and no woody species were observed. Species richness in the twilight zone was markedly lower than in both the entrance and cliff zones, reflecting the combined constraints of low light availability and stable, humid microclimatic conditions.

Patterns of species presence and absence further emphasized differentiation among zones. Many herbaceous and introduced species were confined exclusively to the entrance zone and were absent from both the cliff and twilight zones. Conversely, a subset of fern species showed broader ecological tolerance, occurring in both entrance and cliff zones, although with marked differences in abundance. Overlap in species composition between the cliff and twilight zones was minimal, highlighting the distinct environmental conditions characterizing these habitats.

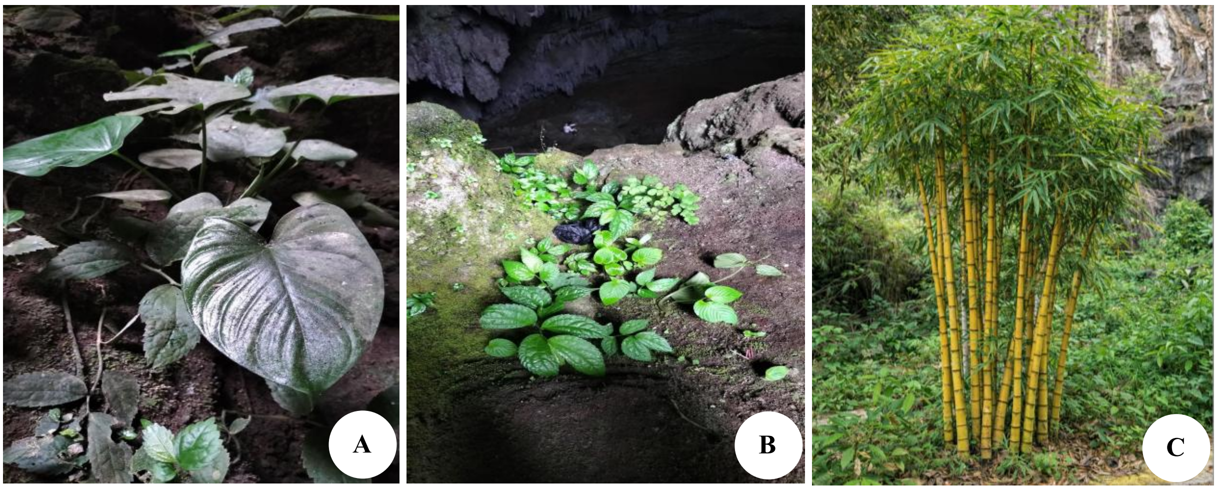

Figure 2. Representative vascular plant species across cave-associated microhabitat zones around Ngantap Cave, Wonogiri, Central Java, Indonesia. A. *Epipremnum pinnatum* in the twilight zone, B. *Pilea angulata* along the cliff zone, and C. *Bambusa vulgaris* var. *vittata* in the entrance zone

The entrance zone functioned as the primary reservoir of species richness within the cave-associated system, while the cliff zone represented a more specialized habitat supporting a reduced but distinctive assemblage. The twilight zone constituted the most environmentally restrictive microhabitat, supporting only a small subset of the regional species pool. Differences in species richness among zones are summarized in Figure 3, while detailed abundance data for each species across zones are presented in Table 2.

Diversity and dominance patterns among zones

Patterns of species diversity and dominance varied distinctly among the three cave-associated microhabitat zones around Ngantap Cave (Table 3). Quantitative indices revealed strong contrasts in community structure, reflecting differences in species richness, relative abundance, and the distribution of individuals among recorded species.

The entrance zone exhibited the highest Shannon–Wiener diversity index (H′ = 3.242), indicating substantially greater species diversity compared to the other zones. This zone also showed the lowest Simpson dominance value (D = 0.045), suggesting weak dominance and the absence of a single overwhelmingly abundant taxon. The high Pielou evenness value (E = 0.944) further indicates that individuals were relatively evenly distributed among species. Together, these values characterize the entrance zone as the most structurally complex and balanced plant community within the cave-associated system.

In contrast, the cliff zone displayed markedly lower diversity (H′ = 1.421) than the entrance zone. The Simpson dominance index was considerably higher (D = 0.283), indicating increased dominance by a limited number of species. The evenness value (E = 0.793) suggests a moderately uneven distribution of individuals, with several fern and herb taxa accounting for a large proportion of total abundance. These index values indicate stronger microhabitat filtering in the cliff zone, resulting in reduced diversity and increased dominance compared to the entrance zone.

The twilight zone showed the lowest overall diversity (H′ = 1.369), reflecting both low species richness and restricted total abundance. Although Simpson dominance remained relatively high (D = 0.259), the Pielou evenness index was very high (E = 0.987), indicating that the few species present occurred in relatively similar abundances, rather than being dominated by a single species. This combination reflects a simplified community structure shaped primarily by severe environmental constraints, rather than competitive exclusion.

The entrance zone supported the most diverse and structurally balanced plant community, whereas the twilight zone represented the most simplified assemblage characterized by low richness but high evenness among a small number of species. The cliff zone occupied an intermediate position between these two extremes. Diversity and dominance indices summarized in Table 3 provide a quantitative basis for subsequent discussion of ecological filtering and microhabitat specialization in cave-associated karst environments.

Table 2. Species abundance by microhabitat zone

Species	Zone		
	Entrance	Cliff	Twilight
Celtis timorensis	–	–	2
Epipremnum pinnatum	–	–	2
Ficus callosa	–	–	2
Thelypteris pozoi	–	–	3
Adiantum capillus-veneris	–	12	–
Christella dentata	–	60	–
Christella parasitica	–	50	–
Homalomena rubescens	–	5	–
Pilea angulata	–	90	–
Schismatoglottis calyptrata	–	9	–
Abrus precatorius	99	–	–
Acalypha brachystachya	88	–	–
Adiantum raddianum	18	–	–
Ageratum conyzoides	34	–	–
Ageratum houstonianum	19	–	–
Amphicarpaea bracteata	11	–	–
Bambusa vulgaris var. *vittata*	14	–	–
Blechnum orientale	40	–	–
Caladium bicolor	10	–	–
Casearia grewiaefolia	30	–	–
Centella asiatica	130	–	–
Christella normalis	69	–	–
Chromolaena odorata	78	–	–
Clidemia hirta	30	–	–
Codiaeum variegatum	59	–	–
Cordyline fruticosa	26	–	–
Crassocephalum crepidioides	17	–	–
Crinum asiaticum	87	–	–
Davallia denticulata	39	–	–
Dendrobium discolor var. *bromfieldii*	55	–	–
Desmodium triflorum	78	–	–
Diplazium esculentum	78	–	–
Duranta erecta	35	–	–
Litsea glutinosa	14	–	–
Manihot esculenta	56	–	–
Melochia villosissima	55	–	–
Phytolacca acinosa	22	–	–
Polyalthia longifolia	51	–	–
Samanea saman	25	–	–
Synedrella nodiflora	90	–	–
Youngia japonica	45	–	–
Total	1502	226	9

Note: Values indicate the number of individuals recorded per species in each microhabitat zone; "–" denotes absence

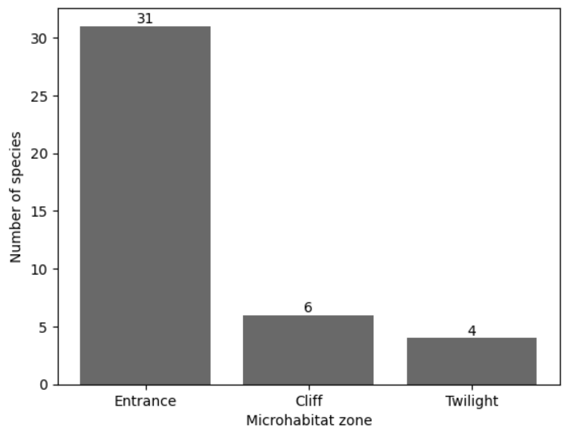

Figure 3. Species richness across cave-associated microhabitat zones

Microclimatic characteristics of cave-associated zones

Microclimatic conditions measured around Ngantap Cave showed clear and consistent differentiation among the entrance, cliff, and twilight zones, reflecting strong environmental gradients within the cave-associated system (Table 4). Variations were evident across all measured parameters, including Relative Humidity (RH), air temperature, light intensity, and wind speed, indicating a progressive transition from exposed and dynamic conditions at the entrance to increasingly shaded, humid, and climatically stable environments toward the twilight zone.

Relative humidity increased along the cave-associated gradient from the entrance zone toward the twilight zone. The entrance zone recorded the lowest mean RH value (76.68%), consistent with greater exposure to solar radiation and higher air movement. The cliff zone exhibited intermediate humidity levels (77.98%), likely reflecting partial shading and reduced evaporation on vertical limestone surfaces. The twilight zone maintained the highest RH (82.56%), indicating persistently humid conditions associated with minimal air circulation and close functional linkage to cave airflow (Table 4).

Air temperature showed only minor variation among zones compared to humidity. The entrance zone recorded the highest mean temperature (29.8°C), corresponding to its greater exposure to direct sunlight. Temperatures in the cliff zone were slightly lower (29.2°C), while the twilight zone exhibited the lowest mean temperature (29.0°C). These small differences indicate effective thermal buffering within cave-associated microhabitats, particularly in shaded and partially enclosed zones.

Light intensity displayed the strongest and most pronounced gradient among all measured variables. The entrance zone received very high light levels (5746.67 lux), reflecting direct exposure to sunlight. Light intensity declined markedly in the cliff zone (1472.50 lux), where illumination was dominated by diffuse and reflected light rather than direct solar radiation. The twilight zone exhibited the lowest light intensity (37.00 lux), representing the most light-limited microhabitat due to strong shading, reduced sky exposure, and proximity to the cave interior. This clear reduction in irradiance from entrance to twilight zone highlights light availability as a primary abiotic gradient structuring cave-associated environment (Figure 4).

Wind speed was generally low across the study area but showed clear spatial variation among zones. The entrance zone experienced the highest mean wind speed (1.10 m/s), consistent with its openness and direct exposure to external airflow. Wind movement decreased sharply in the cliff zone (0.06 m/s) and was effectively absent in the twilight zone (0.00 m/s), reflecting strong sheltering effects of limestone formations and restricted air exchange near the cave interior.

These microclimatic patterns illustrate a coherent and directional shift from exposed, brighter, and more ventilated conditions at the entrance to darker, more humid, and climatically buffered environments in the twilight zone, reflecting a strong microhabitat gradient within the cave-associated landscape.

Table 3. Diversity and dominance indices

Microhabitat zone	Shannon-Wiener (H′)	Simpson dominance (D)	Pielou evenness (E)
Entrance	3.242	0.045	0.944
Cliff	1.421	0.283	0.793
Twilight	1.369	0.259	0.987

Table 4. Abiotic characteristics of cave-associated microhabitat zones

Microhabitat zone	Air temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Light intensity (lux)
Entrance	29.8	76.68	1.10	5746.67
Cliff	29.2	77.98	0.06	1472.50
Twilight	29.0	82.56	0.00	37.00

Note: Values represent mean measurements recorded during the sampling period. Microhabitat zones include the entrance, cliff, and twilight zones surrounding Ngantap Cave, Wonogiri, Central Java, Indonesia

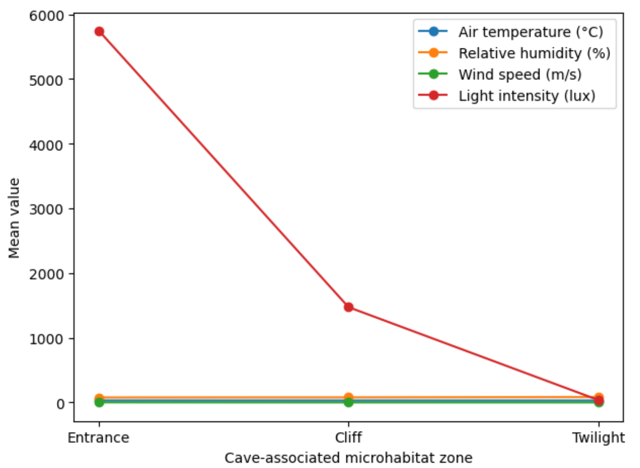

Figure 4. Microclimatic characteristics of cave-associated microhabitat zones (entrance, cliff, and twilight) around Ngantap Cave, Wonogiri, Central Java, Indonesia, based on mean air temperature, relative humidity, wind speed, and light intensity

Discussion

Ecological meaning of species composition and growth forms

The vascular plant communities recorded around Ngantap Cave are characterized by a clear dominance of herbaceous species and ferns, accompanied by a relatively low representation of shrubs and small trees, and the absence of large canopy-forming trees. This growth-form spectrum corresponds closely with the pronounced microhabitat heterogeneity and physical constraints of cave-associated karst environments, where shallow soils, extensive rock exposure, and discontinuous substrates limit the establishment of deep-rooted woody vegetation. Similar structural configurations have been reported from tropical karst systems in which vegetation patterns are governed more strongly by edaphic stress and microtopographic complexity than by successional age or stand development (Porembski and Barthlott 2000; Clements et al. 2006).

The prominence of ferns within the studied assemblages reflects their ecological affinity for shaded, humid, and structurally complex habitats. Ferns are particularly well adapted to limestone environments due to their ability to colonize rock crevices, tolerate thin or absent soil layers, and complete key life stages under low-light conditions. In the Ngantap Cave system, fern dominance was most evident in the cliff and twilight zones, where environmental constraints exclude most woody taxa, allowing pteridophytes to occupy microhabitats that are unsuitable for many seed plants. This pattern aligns with previous observations that ferns often dominate vegetation in humid karst microhabitats characterized by limited irradiance and high substrate instability (Parris et al. 2010; Watkins and Cardelús 2012).

Herbaceous angiosperms also constituted a substantial proportion of the recorded flora, particularly in the entrance zone. Many of these species exhibit flexible life-history strategies, rapid growth, and tolerance to fluctuating microclimatic conditions. Such functional traits are advantageous in ecotonal environments, where light availability, humidity, and disturbance intensity vary over short spatial scales. The entrance zone, functioning as a transition between open karst surfaces and more buffered cave-influenced habitats, therefore supports the coexistence of light-demanding herbs and shade-tolerant taxa, contributing to its comparatively high species richness.

The limited occurrence of shrubs and small trees, together with the complete absence of large canopy-forming species, further highlights the role of vertical habitat structure in shaping vegetation composition. In the study area, steep rock faces, narrow ledges, and unstable substrates restrict rooting depth and mechanical support, thereby constraining the development of tall woody growth forms. Instead, structural complexity is achieved through climbers and scrambling species, which exploit vertical rock surfaces and existing vegetation for support. This form of vertical stratification enhances habitat heterogeneity without leading to closed-canopy formation, a characteristic feature of karst landscapes with rugged topography (Huang et al. 2022).

The observed dominance of low-stature growth forms reflects a vegetation structure finely tuned to the physical and microclimatic conditions of cave-associated karst habitats. Rather than indicating an early or degraded successional stage, this assemblage represents a relatively stable configuration maintained by persistent environmental filtering at the cave–karst interface. The growth-form composition documented in this study, therefore, underscores the ecological importance of microhabitat heterogeneity and vertical structural constraints in shaping plant communities specifically associated with karst cave systems, distinguishing them from vegetation patterns reported in adjacent open karst forests or hill-slope environments.

Microhabitat filtering and zonation around cave systems

The differentiation of vegetation among entrance, cliff, and twilight zones around Ngantap Cave reflects a clear process of microhabitat filtering driven by gradients in light availability, substrate stability, and microclimatic conditions. These gradients do not produce a simple, continuous vegetation transition; instead, they generate discrete ecological compartments, within which only species possessing appropriate functional traits are able to establish and persist. Such compartmentalization is a characteristic feature of cave-associated karst systems, where abrupt changes in physical and microclimatic conditions occur over short spatial distances.

The entrance zone functions as a transitional habitat between open karst surfaces and cave-influenced environments. This zone exhibited the highest species richness and diversity, accommodating a wide range of growth forms, including herbs, ferns, shrubs, climbers, and small trees. The coexistence of multiple growth forms reflects relatively relaxed environmental filtering, resulting from intermediate light levels, moderate humidity, and heterogeneous substrates. Ecotonal environments such as cave entrances are widely recognized as biodiversity hotspots because overlapping environmental conditions allow taxa from adjacent habitat types to coexist (Poulson and White 1969; Culver and Pipan 2019). The patterns observed at Ngantap Cave are consistent with this framework, identifying the entrance zone as a key reservoir of plant diversity within the cave-associated system.

In contrast, the cliff and twilight zones function as more strongly filtered habitats. The cliff zone is characterized by steep limestone surfaces, shallow or absent soils, and high mechanical instability, which severely restricts plant establishment. Only species capable of anchoring within rock crevices, tolerating episodic water limitation, or exploiting vertical substrates were able to persist in this zone. Ferns and selected herbaceous taxa dominated the assemblage, reflecting their tolerance of physical stress and substrate discontinuity. Comparable vegetation patterns have been reported from karst cliffs elsewhere in the Gunung Sewu region, where plant communities are typically sparse and composed primarily of stress-tolerant growth forms (Porembski and Barthlott 2000; Parris et al. 2010).

The twilight zone represents the most strongly filtered microhabitat. It is characterized by very low light availability, high relative humidity, and minimal air movement, conditions that impose severe physiological constraints on vascular plants. Species richness and abundance were lowest in this zone, and community composition was restricted to a small subset of shade-tolerant taxa. This sharp reduction in diversity with declining light availability conforms closely to classical cave ecology models, which emphasize light as the primary limiting factor controlling biological organization near cave entrances (Poulson and White 1969; Badino 2010). Although no obligate cave-adapted vascular plants were recorded, the twilight zone nevertheless excludes most surface vegetation through persistent microclimatic filtering.

Comparisons with previous vegetation studies in the Gunung Sewu karst indicate that such fine-scale zonation is frequently overlooked. Most regional studies focus on open karst forests, slopes, or hilltops, where deeper soils permit the development of woody vegetation and canopy-forming trees. The Ngantap Cave system demonstrates that cave-associated microhabitats support plant assemblages that are structurally and compositionally distinct from surrounding karst landscapes, even over very short spatial scales. These findings underscore the importance of recognizing caves and their immediate surroundings as functionally unique ecological units within karst ecosystems, rather than treating them as marginal extensions of adjacent habitats.

Vegetation–microclimate relationships (descriptive)

Patterns of vegetation distribution around Ngantap Cave showed a close correspondence with measured microclimatic gradients, particularly relative humidity and light availability. Rather than implying direct causal relationships, these patterns represent functional alignment between plant growth forms and prevailing environmental conditions across cave-associated zones, consistent with descriptive ecological inference. The cave-associated microhabitats exhibited a clear and directional microclimatic gradient, characterized by decreasing light intensity and wind speed and increasing relative humidity from the entrance toward the twilight zone. Such correspondence is characteristic of karst systems, where microclimate operates as a dominant ecological filter shaping plant assemblages at fine spatial scales (Badino 2010; Culver and Pipan 2019).

Herbaceous species were most abundant in the entrance zone, where light intensity was highest, and relative humidity was lower than in the cliff and twilight zones. Many herbaceous taxa recorded in this zone exhibit flexible physiological strategies that allow tolerance of fluctuating irradiance and moisture regimes. These traits facilitate rapid growth and persistence in transitional environments, where microclimatic conditions vary both diurnally and seasonally. Consequently, the entrance zone supports a mixed assemblage of light-demanding and moderately shade-tolerant species, reinforcing its role as a microclimatic ecotone between exposed karst surfaces and cave-influenced habitats.

Ferns exhibited a pronounced affinity for zones characterized by higher relative humidity and lower light availability, particularly the cliff and twilight zones. Fern life cycles depend strongly on moist microenvironments for spore germination and gametophyte development, making them reliable indicators of humidity gradients. Their prevalence on shaded limestone crevices and persistently humid rock surfaces around Ngantap Cave is consistent with previous studies emphasizing the importance of stable moisture availability for pteridophyte persistence in karst landscapes (Parris et al. 2010; Watkins and Cardelús 2012). The increasing dominance of ferns from the cliff zone to the twilight zone reflects the combined influence of high humidity, low irradiance, and minimal air movement, particularly given the minimal temperature differences observed among zones.

Members of the family Araceae also showed a strong association with humid and shaded microhabitats. Araceous species typically possess broad leaves, thin cuticles, and high transpiration capacity, traits that are advantageous under conditions of high humidity and low evaporative demand. Their concentration on the cliff and especially the twilight zone corresponds closely with the most humid and light-limited conditions recorded in the study area, reinforcing their suitability as indicators of cave-influenced microhabitats. Comparable associations between Araceae and humid karst environments have been reported from other tropical limestone regions (Boyce et al. 2025).

In contrast, woody growth forms were largely restricted to zones with relatively higher light availability and more stable rooting substrates. The scarcity of shrubs and the absence of large trees in shaded and humid zones emphasize the combined constraints imposed by low irradiance, shallow soils, and limited mechanical stability. Reduced light availability limits photosynthetic potential, while persistently humid conditions and discontinuous substrates restrict structural support for woody stems, thereby constraining the establishment of tall growth forms in cliff and twilight microhabitats.

The vegetation–microclimate relationships documented in this study underscore the central role of increasing humidity, decreasing light availability, and reduced air movement in structuring cave-associated plant communities. Growth form distribution reflects adaptive responses to fine-scale microclimatic filtering rather than successional trajectories, highlighting the ecological importance of cave-associated microhabitats as distinct and environmentally restrictive components of tropical karst ecosystems.

Introduced and cultivated species in abandoned cave-tourism areas

The occurrence of introduced and cultivated plant species within cave-associated microhabitats around Ngantap Cave is best interpreted as a legacy of historical land use rather than as evidence of ongoing biological invasion. Several recorded taxa are widely used as ornamental or utilitarian plants in Java and are likely remnants of past planting associated with tourism facilities, site landscaping, or nearby human settlements. Their presence therefore reflects socio-ecological history and past management practices, rather than autonomous spread driven by invasive dynamics.

Abandoned or weakly managed tourism sites often function as transitional or semi-natural landscapes, where planted species persist alongside native vegetation under reduced disturbance and maintenance. In the Ngantap Cave area, declining visitor activity has resulted in minimal active management, allowing cultivated plants to survive and coexist locally with native taxa without further human intervention. Comparable patterns have been documented in abandoned recreational and cultural sites, where ornamental or planted species remain embedded within regenerating vegetation matrices (Hobbs et al. 2009; Kowarik 2011).

Spatially, introduced and cultivated species were largely restricted to the entrance zone, where light availability, substrate depth, and accessibility are more favorable for their establishment. These taxa were absent or extremely rare in the cliff and twilight zones, indicating strong environmental filtering that limits their persistence beyond relatively open and accessible microhabitats. Such spatial confinement suggests that these species are not actively expanding into cave-associated environments but are instead constrained by microclimatic conditions, substrate instability, and low light availability.

Importantly, none of the introduced or cultivated species exhibited dominance patterns characteristic of invasive behavior, such as numerical superiority, competitive exclusion, or spread across multiple microhabitat zones. Although some taxa are recognized as invasive in open or disturbed landscapes, their localized occurrence and low abundance in the study area indicate limited ecological impact within the cave-associated system. This distinction highlights the need to differentiate between species presence and functional ecological influence when evaluating non-native plants in karst environments.

From a conservation perspective, abandoned cave-tourism areas represent hybrid landscapes in which natural regeneration interacts with anthropogenic legacies. The persistence of cultivated species does not necessarily threaten native-dominated microhabitats but instead underscores the importance of context-sensitive management. Conservation strategies should prioritize the protection of environmentally restrictive zones, such as cliffs and twilight areas, while monitoring long-term species dynamics rather than implementing immediate removal of non-native taxa without evidence of ecological impact.

Limitations and implications for karst conservation

Several limitations should be acknowledged when interpreting the findings of this study. First, sampling was restricted to the immediate surroundings of a single cave system, intentionally focusing on fine-scale, cave-associated microhabitats. While this approach allows detailed ecological characterization, it limits direct extrapolation to other karst environments that may differ in geomorphology, disturbance history, or regional climatic context within the Gunung Sewu karst.

Second, data collection was conducted within a limited temporal window and did not encompass seasonal variability. In tropical karst systems, both microclimatic conditions and vegetation dynamics can differ substantially between wet and dry seasons, potentially influencing species presence, abundance, and growth-form expression. Consequently, the patterns documented here should be interpreted as a snapshot of vegetation–microclimate relationships rather than a representation of annual or long-term dynamics.

Third, the study adopted a descriptive–comparative analytical framework without inferential statistical testing. This choice reflects the limited number of transects per zone and the strong, non-random environmental filtering inherent in cave-associated microhabitats, where assumptions required for inferential analyses are difficult to satisfy. Although this limits statistical generalization, the approach is appropriate for baseline documentation and ecological interpretation at the microhabitat scale.

Despite these constraints, the study provides important baseline information on vascular plant communities associated with cave-related karst microhabitats, an ecological component that remains underrepresented in Indonesian karst research. By explicitly distinguishing entrance, cliff, and twilight zones, the results demonstrate that vegetation patterns around caves are structured by fine-scale environmental gradients rather than by broader landscape processes alone. This distinction has direct implications for karst conservation planning, particularly in areas subject to tourism development or land-use change. Recognizing cave-associated microhabitats as functionally distinct units supports more targeted management strategies that prioritize the protection of environmentally sensitive zones and help maintain the ecological integrity of karst systems.

In conclusion, this study shows that vascular plant communities associated with Ngantap Cave are primarily structured by fine-scale microhabitat variation and cave-related microclimatic gradients rather than by broader karst landscape patterns. A total of 41 vascular plant species from 22 families, comprising 1,736 individuals, were recorded across cave-associated habitats. Community composition was dominated by herbaceous plants and ferns, while shrubs and small trees were scarce and large canopy trees were absent, reflecting constraints imposed by shallow soils, rocky substrates, and limited light availability. Distinct spatial differentiation was evident among microhabitat zones. The entrance zone supported the highest species richness and abundance (31 species; 1,502 individuals), with high diversity (H′ = 3.242), low dominance (D = 0.045), and high evenness (E = 0.944). In contrast, the cliff zone harbored only 6 species and 226 individuals, with lower diversity (H′ = 1.421) and higher dominance (D = 0.283). The twilight zone represented the most restrictive habitat, supporting just 4 species and 9 individuals, characterized by low diversity (H′ = 1.369) but high evenness (E = 0.987). These patterns closely followed microclimatic gradients, particularly a sharp decline in light intensity from the entrance to the twilight zone, accompanied by increasing humidity. Introduced and cultivated species were largely restricted to the entrance zone, reflecting historical land use rather than active invasion. The findings highlight cave surroundings as functionally distinct ecological units that warrant explicit consideration in karst conservation and management.

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Short Communication: Biocultural patterns of medicinal plant use in the Gunung Sewu Karst of Central Java, Indonesia

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[2]Faculty of Medicine, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia
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Abstract. *Wibowo CNP, Azizah CKG, Rizka DR, Maharani DS, Susatio R, Yasa A, Jumari, Saensouk S, Setyawan AD. 2025. Short Communication: Biocultural patterns of medicinal plant use in the Gunung Sewu Karst of Central Java, Indonesia. Intl J Trop Drylands 9: 181-191.* Karst landscapes represent environmentally constrained systems characterized by shallow soils, limited water availability, and strong seasonal variability, conditions that shape both ecological processes and human livelihoods. In such settings, traditional medicinal plant use constitutes an important biocultural adaptation that supports household health and resilience. Despite the ecological and cultural significance of karst regions, ethnobotanical studies integrating medicinal plant use with biocultural adaptation frameworks remain limited, particularly in the Gunung Sewu Karst of Central Java, Indonesia. This study aims to document medicinal plant diversity and to analyze patterns of plant use in relation to karst environmental constraints. Ethnobotanical data were collected through semi-structured interviews, field observations, and direct plant identification in two karst villages of the Gunung Sewu Karst Region. A descriptive analytical approach was applied to classify plant use, preparation methods, application routes, and treated ailments. A total of 25 medicinal plant species belonging to 16 families were recorded. Zingiberaceae was the most represented family, reflecting both ecological suitability and cultural familiarity. Medicinal plant use was dominated by herbaceous species, with leaves and rhizomes as the primary plant parts utilized. Decoction and oral administration were the most common preparation and application methods, while treated ailments mainly comprised mild to moderate conditions related to digestion, respiration, skin health, and musculoskeletal pain. The observed patterns indicate that ecological filtering, sustainable harvesting practices, and household-based healthcare strategies shape medicinal plant use in the Gunung Sewu Karst. By explicitly linking growth forms, harvested plant parts, and preparation methods to karst environmental constraints, this study demonstrates that traditional medicinal practices function as a coherent biocultural adaptation rather than isolated cultural remnants. These findings contribute to ethnobotanical research by highlighting the adaptive role of local knowledge systems in karst environments and underscore their relevance for community-based conservation and sustainable health strategies.

Keywords: Biocultural adaptation, ethnobotany, karst landscape, medicinal plants, traditional knowledge

INTRODUCTION

Karst landscapes are widely recognized as environmentally extreme systems characterized by shallow soils, high surface rock exposure, rapid subsurface water infiltration, and pronounced seasonal water scarcity. These conditions impose strong ecological constraints on vegetation growth, agricultural productivity, and the availability of natural resources for human communities (Ford and Williams 2007; Day 2010). In tropical regions, karst ecosystems support distinctive assemblages of flora and fauna adapted to drought stress, nutrient limitation, and heterogeneous microhabitats, resulting in high levels of ecological specialization (Goldscheider et al. 2020). Consequently, human livelihoods in karst areas are closely intertwined with environmental conditions, shaping unique land-use systems, subsistence strategies, and knowledge practices.

Within such constrained environments, biocultural knowledge emerges as an adaptive response to long-term interactions between humans and their surroundings. Traditional ecological knowledge, including plant use, management practices, and seasonal resource allocation, plays a critical role in maintaining household resilience under persistent environmental stress (Gadgil et al. 1993; Berkes 2012). In karst landscapes, where infrastructure development and access to biomedical services may be limited, communities often rely on locally available biological resources to meet subsistence and healthcare needs. This reliance promotes the retention and intergenerational transmission of plant-based knowledge that reflects both ecological availability and culturally embedded preferences (Caillon et al. 2017; Toledo et al. 2018).

The Gunung Sewu Karst of Central Java, Indonesia, represents one of the largest and most geomorphologically complex karst regions in Southeast Asia. Despite its designation as a UNESCO Global Geopark, communities inhabiting this landscape continue to face structural challenges related to water access, soil fertility, and economic marginalization. Under such conditions, biocultural knowledge is not merely a cultural legacy but a functional system that supports everyday survival. Understanding how medicinal plant use operates within this biocultural framework is therefore essential for interpreting human–environment interactions in karst ecosystems.

Traditional medicinal plant use constitutes a central component of ethnobotanical systems in environmentally marginal landscapes. In drylands and karst regions, plant-based remedies frequently serve as primary or complementary healthcare resources due to limited access to formal medical facilities and the high cost of pharmaceutical treatments (Albuquerque et al. 2014). Medicinal plant selection in such environments is strongly influenced by species availability, growth form, regeneration capacity, and ease of harvesting, resulting in characteristic patterns dominated by herbaceous species, renewable plant parts, and simple preparation methods such as decoction (Voeks 2004; Gaoue et al. 2017).

In Indonesia, ethnobotanical research has documented extensive medicinal plant knowledge across lowland forests, agroforestry systems, and montane regions (Sujarwo et al. 2014; Silalahi et al. 2015). However, karst landscapes remain comparatively underrepresented in ethnobotanical studies, despite their ecological distinctiveness and socio-environmental vulnerability. Existing studies from karst regions globally suggest that medicinal plant use reflects both ecological filtering and cultural innovation, producing selective plant repertoires adapted to dry and rocky conditions (Pieroni and Quave 2014; Ferreira-Junior and Albuquerque 2018).

Several ethnobotanical studies have examined medicinal plant use in karst landscapes of southern Java, including Pacitan District (Ammar et al. 2021), Gunung Kidul (Nahdi and Kurniawan 2019), and the Menoreh Karst Area (Igustita et al. 2023). These studies consistently report a high reliance on Zingiberaceae, leaf- and rhizome-based remedies, and decoction as the dominant preparation method. Nevertheless, most focus primarily on species inventories and utilization patterns, with limited integration of ecological context, growth-form composition, and harvesting strategies as adaptive responses to karst-specific constraints. Comparative insights across adjacent karst systems also remain limited, particularly at the household scale.

The present study addresses this gap by examining medicinal plant use as a form of biocultural adaptation in karst villages of the Gunung Sewu Karst Region, Wonogiri District, Central Java. Rather than treating medicinal plants solely as pharmacological resources, this study situates plant use within the broader context of ecological limitation, livelihood strategies, and knowledge transmission. The objectives are to document the diversity of medicinal plants used by local communities, analyze patterns of use in relation to growth forms and harvested plant parts, and interpret these patterns within a biocultural adaptation framework. By integrating ecological characteristics of karst landscapes with ethnobotanical data, this study contributes to a more nuanced understanding of human–environment interactions and provides insights relevant to biodiversity conservation, cultural heritage preservation, and sustainable healthcare strategies in environmentally marginal landscapes. Medicinal plant use in the Gunung Sewu Karst is structured by karst-specific environmental constraints, resulting in a selective dominance of herbaceous species, preferential use of renewable plant parts (leaves and rhizomes), and simple preparation methods (primarily decoction) that function as adaptive, household-based healthcare strategies.

MATERIALS AND METHODS

Study area

The study was conducted in the Gunung Sewu Karst Region, Indonesia, a tropical karst landscape extending across parts of Wonogiri, Gunungkidul, and Pacitan Districts. This region is characterized by extensive limestone formations, rugged topography, and a dense network of sinkholes, caves, and subterranean drainage systems that strongly influence surface hydrology and land use patterns (Figure 1). Surface water availability is highly seasonal, with prolonged dry periods that constrain agricultural activities and household water access.

The environmental conditions of the Gunung Sewu Karst are defined by shallow and discontinuous soils, high rock exposure, and limited soil moisture retention, characteristics typical of limestone landscapes in southern Java (Haryono and Day 2004; Aprilia et al. 2021). These constraints shape vegetation structure, favoring drought-tolerant species, herbaceous plants, and taxa capable of regenerating under nutrient-poor conditions, as widely observed in karst ecosystems of Java and Indonesia (Prabowo et al. 2024; Nahdi and Kurniawan 2019). Local livelihoods are predominantly based on rain-fed agriculture, homegardens, and small-scale livestock rearing, with strong dependence on locally available biological resources for food, medicine, and daily subsistence, a pattern consistently documented in karst communities of Gunung Sewu and adjacent regions (Ammar et al. 2021).

Fieldwork was carried out in two karst villages, Gebangharjo and Glinggang, located within the Wonogiri District of the Gunung Sewu Karst, Central Java, Indonesia. These villages were selected due to their long-established settlement history, active reliance on traditional plant-based practices, and proximity to karst landforms that limit access to conventional health services. The combination of environmental constraints and sustained traditional knowledge makes these villages representative sites for examining biocultural adaptation in karst landscapes.

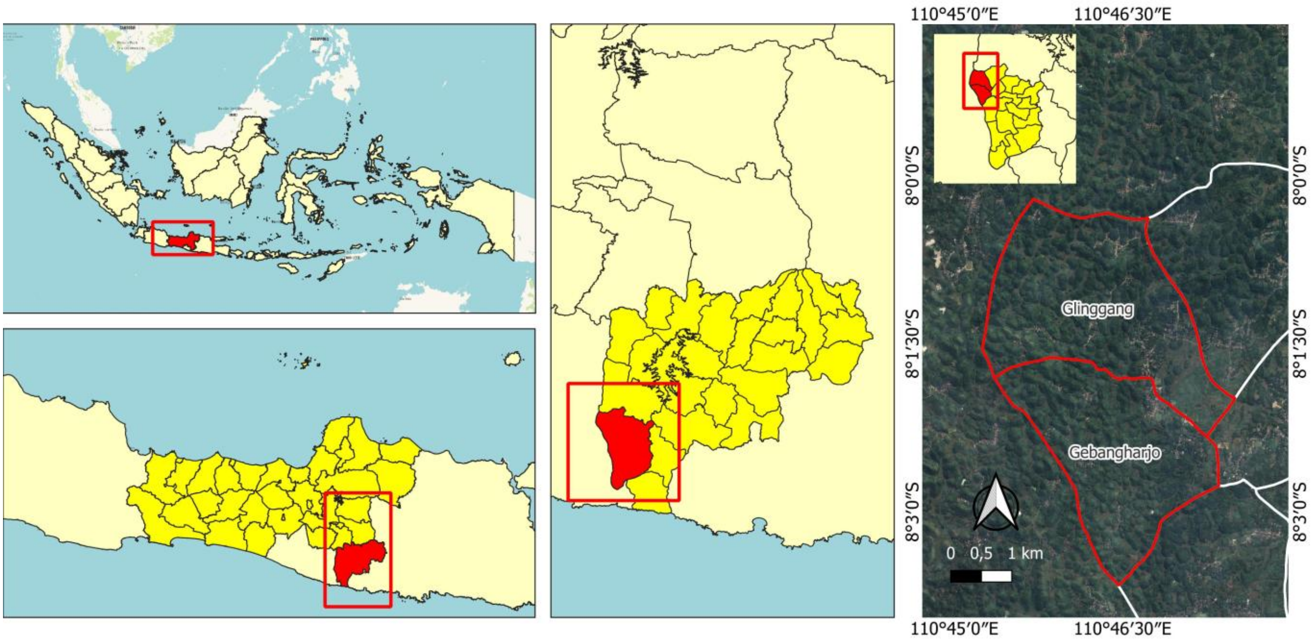

Figure 1. Location of the study area in the Gunung Sewu Karst, Central Java, Indonesia, showing the position of Gebangharjo and Glinggang Villages within the karst landscape

Data collection and ethnobotanical survey

Ethnobotanical data were collected through a combination of semi-structured interviews, field observations, and informal discussions conducted between local researchers and community members, an approach widely applied in ethnobotanical research to capture both documented practices and contextual knowledge (Martin 1995; Albuquerque et al. 2014; Jadid et al. 2020). Informants were selected using purposive sampling, targeting individuals recognized within the community as having knowledge of traditional medicinal plant use, including elderly residents, household caregivers, and local herbal practitioners. This approach ensured that information gathered reflected long-term experiential knowledge rather than incidental plant use, consistent with established ethnobotanical sampling principles (Tongco 2007; Kubiciel-Lodzińska 2021).

Semi-structured interviews were employed to document medicinal plant species, local names, plant parts used, preparation methods, routes of application, and ailments treated. Interviews were conducted in the local language to facilitate clear communication and minimize misinterpretation, as recommended in cross-cultural ethnobotanical studies (Alexiades 1996; Albuquerque et al. 2014). Open-ended questions allowed informants to elaborate on usage practices, contextual meanings, and perceived effectiveness of remedies, while maintaining consistency across interviews. Demographic characteristics of informants, including age group, gender, education level, and primary occupation, were recorded to contextualize knowledge distribution within the community (Table 1), following standard ethnobotanical documentation frameworks (Martin 1995; Navia et al. 2021).

Field observations accompanied interviews to verify plant identity, habitat, and harvesting practices. Plants cited by informants were directly observed in homegardens, agricultural fields, or surrounding karst vegetation. When possible, observations focused on harvesting intensity, plant availability, and regeneration patterns. This triangulation of interview data and field observation strengthened data reliability and ensured that reported medicinal uses were grounded in actual local practices rather than recalled knowledge alone, a procedure commonly recommended to reduce recall bias in ethnobotanical surveys (Alexiades 1996; Albuquerque et al. 2014; Kunwar et al. 2022).

Plant identification and nomenclature

Medicinal plant species were identified through direct field observation based on morphological characters, including growth form, leaf shape, stem structure, inflorescence, and reproductive traits. Field identification was supported by standard regional floras, particularly *Flora of Java* Volumes I-III (Backer and Bakhuizen van den Brink 1963-1968), which remain authoritative references for plant taxonomy in Java. Additional identification guidance was obtained from regional ethnobotanical and botanical literature relevant to tropical Southeast Asia.

To ensure nomenclatural consistency and taxonomic validity, all scientific names used in this study follow currently accepted names as recognized by major global plant taxonomic databases. Scientific names were standardized based on the Plants of the World Online (POWO; https://powo.science.kew.org) and the Global Biodiversity Information Facility (GBIF; https://www.gbif.org), which compile up-to-date taxonomic treatments and synonymy. Where local or literature-based names corresponded to historical or alternative nomenclature, these were cross-checked against accepted names to avoid the use of outdated or ambiguous taxa.

Synonyms encountered during identification were verified through these databases and are reported only when necessary to clarify taxonomic interpretation or to align local nomenclature with accepted scientific usage. This approach ensures that species names presented in the manuscript are taxonomically valid, internationally recognizable, and comparable with other ethnobotanical studies, while maintaining consistency with regional floristic references.

Data analysis

Ethnobotanical data were organized and analyzed using descriptive approaches to summarize patterns of medicinal plant use within the study area. Reported medicinal uses were first classified into major categories based on the type of ailment treated, plant part used, preparation method, and route of application. This classification facilitated comparison across species and households and allowed the identification of dominant use patterns at the community level (Martin 1995; Alexiades 1996).

Descriptive analysis was applied to quantify the relative contribution of plant families, growth forms, and plant parts used in traditional medicinal practices. Species frequency and use information were tabulated to support transparent presentation of results, while avoiding inferential statistics that require assumptions beyond the scope of the study. Proportional values were calculated to express the distribution of preparation methods, application routes, and disease categories across the recorded species, providing a clear overview of medicinal plant utilization trends (Albuquerque et al. 2014).

All analyses were conducted using simple tabulation and percentage calculations to ensure methodological clarity and reproducibility. This approach is appropriate for exploratory ethnobotanical studies aimed at documenting local knowledge systems and identifying biocultural patterns rather than testing causal hypotheses (de Medeiros et al. 2012).

RESULTS AND DISCUSSION

Demographic characteristics of respondents

A total of 36 respondents representing different genders, age groups, educational backgrounds, and occupations participated in this study (Table 1). The demographic composition reflects the social structure of karst village communities, where traditional knowledge of medicinal plants is unevenly distributed across age and social roles. Informants were predominantly adults, particularly those in the 36-45 years group (27.5%, n = 13) and 56-65 years (20.0%, n = 8), indicating that ethnomedicinal knowledge is mainly retained among individuals with long-term experience in household management and daily subsistence activities.

Both male and female respondents contributed information on medicinal plant use, with female respondents comprising a larger proportion (55.0%, n = 22) compared to male respondents (35.0%, n = 14). Women played a more prominent role in reporting medicinal plant use related to household healthcare, childcare, and food preparation, reflecting their central involvement in domestic health practices. Older respondents generally demonstrated broader knowledge of plant diversity, preparation techniques, and traditional applications, whereas younger respondents aged 15-25 years and 26-35 years each represented only 7.5% (n = 3) of the total sample, suggesting more limited familiarity with traditional medicinal practices.

Educational backgrounds varied among respondents, with the majority having completed senior high school (37.5%, n = 16) or elementary school (32.5%, n = 13). Fewer respondents reported junior high school education (15.0%, n = 6), and only one respondent had attained a university-level education (2.5%, n = 1). These patterns indicate that formal education level does not directly correspond with the depth of ethnobotanical knowledge, which appears to be more strongly associated with lived experience and intergenerational knowledge transmission rather than institutional schooling.

Overall, occupational profiles were dominated by farming and informal livelihood activities closely associated with the karst environment. This demographic context provides an important foundation for interpreting patterns of medicinal plant use and knowledge distribution observed in the Gunung Sewu Karst communities (Table 1).

Diversity of medicinal plant species

A total of 25 medicinal plant species belonging to 16 families were recorded from the karst villages studied (Table 2). The documented species represent a diverse assemblage of plants utilized in household-based traditional medicine under karst environmental constraints. Despite this overall taxonomic diversity, medicinal plant use was unevenly distributed across plant families, indicating selective reliance on taxa that are both ecologically suited to karst conditions and culturally embedded in local health practices.

Table 1. Demographic characteristics of respondents in the Gunung Sewu Karst, Central Java, Indonesia (n = 36)

Parameter	Specification	Freq.	Percentage
Gender	Male	14	35.0%
	Female	22	55.0%
Age (years)	15-25	3	7.5%
	26-35	3	7.5%
	36-45	13	27.5%
	46-55	4	10.0%
	56-65	8	20.0%
	66-75	5	12.5%
Education	Elementary school	13	32.5%
	Junior high school	6	15.0%
	Senior high school	16	37.5%
	University	1	2.5%

The family Zingiberaceae was the most dominant, contributing 8 species (32.0% of the total recorded species). Members of this family were widely cited for their medicinal applications, particularly for digestive disorders, body warming, fatigue reduction, and general health maintenance. The prominence of Zingiberaceae reflects the ecological suitability of rhizomatous herbs to shallow, rocky soils, as well as their cultural familiarity, since many species are commonly cultivated in homegardens and are easily accessible throughout the year. The family Lamiaceae ranked second, represented by 3 species (12.0%), followed by 13 families each represented by a single species (4.0% per family), resulting in a long-tail distribution of medicinal plant diversity (Figure 2).

In terms of growth forms, the recorded medicinal plants comprised herbaceous species (13 species, 52.0%), trees (7 species, 28.0%), climbers (3 species, 12.0%), shrubs (1 species, 4.0%), and succulent herbs (1 species, 4.0%). Herbaceous plants were thus the most frequently utilized growth form, particularly rhizomatous taxa from the Zingiberaceae, which were commonly prepared as decoctions for internal use. Several species were repeatedly mentioned by multiple informants, indicating their key role in the local medicinal system. These include widely cultivated rhizomatous herbs, climbers used primarily for febrile conditions, and tree species whose leaves or fruits are incorporated into household remedies.

The documented species comprised both cultivated plants maintained in homegardens and species obtained from surrounding karst vegetation, indicating a mixed sourcing strategy. This combination of deliberate management and opportunistic use allows households to maintain access to medicinal resources while adapting to the ecological limitations of the karst environment.

The diversity of medicinal plant species recorded in this study reflects a biocultural repertoire shaped by ecological constraints, accessibility, and accumulated traditional knowledge rather than random exploitation of available flora. The selective dominance of particular families and growth forms highlights adaptive patterns of medicinal plant use in the Gunung Sewu Karst landscape.

Table 2. Medicinal plant species used by local communities in the Gunung Sewu Karst, Indonesia (n species = 25)

Family	Scientific name	Local name	Growth form
Acanthaceae	*Strobilanthes crispa* (L.) Blume	*Kejibeling*	Shrub
Aloeaceae	*Aloe vera* (L.) Burm.f.	*Lidah buaya*	Succulent herb
Annonaceae	*Annona squamosa* L.	*Srikaya*	Tree
Basellaceae	*Anredera cordifolia* (Ten.) Steenis	*Binahong*	Climber
Campanulaceae	*Hippobroma longiflora* (L.) G.Don	*Kitolod*	Herbaceous
Fabaceae	*Cassia siamea* Lam.	*Johar*	Tree
Lamiaceae	*Ocimum basilicum* L.	*Kemangi*	Herbaceous
Lamiaceae	*Orthosiphon aristatus* (Blume) Miq.	*Kumis kucing*	Herbaceous
Lamiaceae	*Plectranthus amboinicus* (Lour.) Spreng.	*Bangun-bangun*	Herbaceous
Lauraceae	*Persea americana* Mill.	*Alpukat*	Tree
Meliaceae	*Swietenia mahagoni* (L.) Jacq.	*Mahoni*	Tree
Menispermaceae	*Tinospora crispa* (L.) Hook.f. & Thomson	*Brotowali*	Climber
Moraceae	*Antiaris toxicaria* Lesch.	*Upas*	Tree
Moringaceae	*Moringa oleifera* Lam.	*Kelor*	Tree
Piperaceae	*Piper betle* L.	*Sirih*	Climber
Poaceae	*Cymbopogon citratus* (DC.) Stapf	*Serai*	Herbaceous
Rutaceae	*Citrus aurantiifolia* (Christm.) Swingle	*Jeruk nipis*	Tree
Zingiberaceae	*Alpinia galanga* (L.) Willd.	*Lengkuas*	Herbaceous
Zingiberaceae	*Curcuma aeruginosa* Roxb.	*Temu ireng*	Herbaceous
Zingiberaceae	*Curcuma longa* L.	*Kunyit*	Herbaceous
Zingiberaceae	*Curcuma zanthorrhiza* Roxb.	*Temulawak*	Herbaceous
Zingiberaceae	*Curcuma zedoaria* (Christm.) Roscoe	*Kunyit putih*	Herbaceous
Zingiberaceae	*Kaempferia galanga* L.	*Kencur*	Herbaceous
Zingiberaceae	*Zingiber officinale* Roscoe	*Jahe*	Herbaceous
Zingiberaceae	*Zingiber officinale* var. *rubrum*	*Jahe merah*	Herbaceous

Growth forms and plant parts used

Medicinal plant use in the Gunung Sewu Karst showed clear patterns related to plant growth forms and harvested plant parts, reflecting adaptive strategies under karst environmental constraints. Herbaceous species constituted the dominant growth form, accounting for 52.0% of the recorded medicinal plants (13 of 25 species), followed by tree species at 28.0% (7 species) (Table 2; Figure 3.A). Climbers contributed 12.0% (3 species), while shrubs and succulent herbs were each represented by a single species (4.0% each). The dominance of herbaceous plants indicates a preference for taxa that are easily cultivated, regenerate rapidly, and are able to persist under shallow soils and limited moisture conditions typical of karst landscapes.

Tree species, although fewer in number, played a complementary role in traditional medicine, particularly through the use of leaves or fruits that can be harvested without causing permanent damage to the plant. Climbers were used more selectively and were often associated with specific medicinal applications, while shrubs and succulent herbs contributed only marginally to the overall medicinal repertoire. The relatively low representation of woody growth forms likely reflects both ecological constraints and practical harvesting considerations in rocky karst terrain.

Analysis of plant parts used revealed a strong reliance on renewable plant organs (Figure 3.B). Leaves were the most frequently harvested plant part, comprising 50.0% of recorded uses, owing to their year-round availability, ease of collection, and minimal impact on plant survival. Rhizomes represented the second most commonly used plant part (30.8%), particularly among herbaceous species in the Zingiberaceae, and were closely associated with decoction-based remedies for internal ailments. Other plant parts were used less frequently, including fruits (7.7%), flowers (3.8%), stems (3.8%), and roots (3.8%), typically for specific therapeutic purposes.

Taken together, these patterns indicate that a balance between therapeutic effectiveness and sustainable harvesting practices shapes medicinal plant use in the Gunung Sewu Karst. The predominance of herbaceous species and renewable plant parts such as leaves and rhizomes reflects a biocultural adaptation that minimizes ecological impact while maintaining access to essential household healthcare resources.

Preparation methods, applications, and treated ailments

Traditional medicinal plant use in the Gunung Sewu Karst is characterized by a limited number of preparation techniques and application routes, reflecting practical adaptation to household conditions and environmental constraints. Decoction was the dominant preparation method, accounting for 80.0% of all recorded uses (20 of 25 species) (Table 3; Figure 4.A). This method was applied to a wide range of plant parts, including leaves, rhizomes, stems, and fruits, enabling the extraction of bioactive compounds using simple equipment and readily available water sources. Other preparation techniques were reported less frequently, including crushing (12.0%, 3 species) and raw consumption (8.0%, 2 species), and were generally associated with specific plant species and targeted ailments.

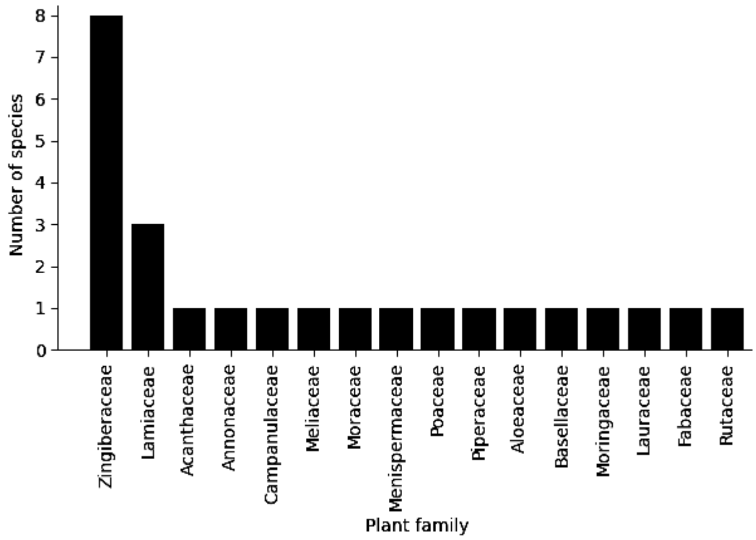

Figure 2. Diversity of medicinal plant species recorded in the Gunung Sewu Karst, Central Java, Indonesia, illustrating family-level composition and dominant plant families

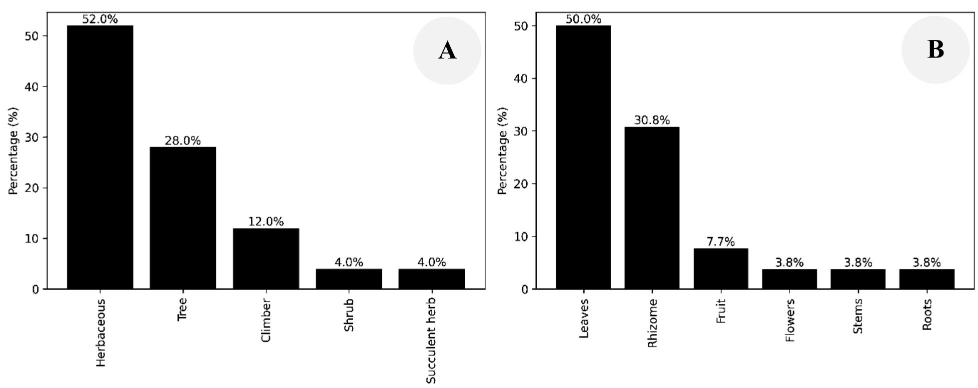

Figure 3. Distribution of growth forms and plant parts used in traditional medicinal practices in the Gunung Sewu Karst, Central Java, Indonesia, expressed as percentages of the total recorded species. A. Growth forms of medicinal plant species, B. Plant parts used

Oral administration overwhelmingly dominated the application routes, representing 88.0% of reported uses (22 of 25 species) (Figure 4.B). This pattern indicates that medicinal plants are primarily used for internal health maintenance and treatment of systemic conditions. Topical application was reported for only 8.0% of species (2 species), mainly for treating burns, wounds, or envenomation, while eye drops accounted for 4.0% (1 species) and represent a highly specific, culturally embedded practice involving fresh plant material. The distribution of preparation methods and application routes demonstrates a strong preference for techniques that are easy to perform, require minimal processing, and can be readily integrated into daily household routines.

The ailments treated using medicinal plants were largely mild to moderate health conditions commonly encountered in everyday life (Figure 5). Respiratory ailments were the most frequently reported category (16.0%, 4 species), including cough, cold, and flu, followed by digestive disorders (12.0%, 3 species), such as stomach ache and appetite enhancement, and skin-related conditions (12.0%, 3 species), including burns, wounds, and rashes. General health maintenance, including body warming and non-specific herbal remedies, accounted for 12.0% (3 species) of recorded uses. More specialized treatments, such as remedies for postpartum care, fever, anemia, or snake bite, were reported less frequently but remain culturally significant within the local medical system.

The dominance of decoction-based preparation and oral application, coupled with the emphasis on treating common ailments, highlights the role of medicinal plants as a first-line healthcare resource in karst villages. These practices reflect the functional integration of traditional medicine into household health strategies rather than reliance on specialized or ritualized treatments.

Discussion

Biocultural adaptation in karst environments

The patterns of medicinal plant use documented in the Gunung Sewu Karst reflect a clear form of biocultural adaptation shaped by long-term interactions between local communities and an environmentally constrained landscape. Karst environments are characterized by shallow soils, rapid subsurface drainage, seasonal water scarcity, and pronounced microhabitat heterogeneity, all of which limit plant establishment and strongly influence local resource management strategies (Ford and Williams 2007; Day 2010). Under such conditions, biocultural knowledge functions as an adaptive system that integrates ecological constraints with culturally embedded practices, enabling households to maintain resilience under persistent environmental stress (Gadgil et al. 1993; Berkes 2012).

Table 3. Preparation methods, application routes, and diseases treated using medicinal plants in the Gunung Sewu Karst, Central Java, Indonesia

Scientific name	Plant part used	Preparation method	Application	Treated ailment
Strobilanthes crispa (L.) Blume	Leaves	Crushed	Oral	General herbal medicine
Aloe vera (L.) Burm.f.	Leaves	Crushed	Topical	Burns
Annona squamosa L.	Leaves	Decoction	Oral	Stomach ache
Anredera cordifolia (Ten.) Steenis	Leaves	Decoction	Oral	Wound healing
Hippobroma longiflora (L.) G.Don	Leaves	Raw	Eye drops	Sore eyes
Cassia siamea Lam.	Leaves	Decoction	Oral	Malaria
Ocimum basilicum L.	Leaves	Raw	Oral	Bad breath
Orthosiphon aristatus (Blume) Miq.	Flower	Crushed	Oral	Skin rash, itching, nosebleed
Plectranthus amboinicus (Lour.) Spreng.	Leaves	Decoction	Oral	Flu
Persea americana Mill.	Leaves	Decoction	Oral	Hypertension
Swietenia mahagoni (L.) Jacq.	Fruit	Decoction	Oral	Postpartum care
Tinospora crispa (L.) Hook.f. & Thomson	Stem	Decoction	Oral	Fever
Antiaris toxicaria Lesch.	Leaves	Decoction	Topical	Snake bite
Moringa oleifera Lam.	Leaves	Decoction	Oral	Anemia
Piper betle L.	Leaves	Decoction	Oral	Cough
Cymbopogon citratus (DC.) Stapf	Leaves	Decoction	Oral	Cold
Citrus aurantiifolia (Christm.) Swingle	Fruit	Raw	Oral	Cough
Alpinia galanga (L.) Willd.	Rhizome	Decoction	Oral	Stomach ache
Curcuma aeruginosa Roxb.	Rhizome	Decoction	Oral	Menstrual pain
Curcuma longa L.	Rhizome	Decoction	Oral	General herbal medicine
Curcuma zanthorrhiza Roxb.	Rhizome	Decoction	Oral	Appetite enhancer
Curcuma zedoaria (Christm.) Roscoe	Rhizome	Decoction	Oral	Antioxidant
Kaempferia galanga L.	Rhizome	Decoction	Oral	Muscle pain
Zingiber officinale Roscoe	Rhizome	Decoction	Oral	Body warming
Zingiber officinale var. *rubrum*	Rhizome	Decoction	Oral	Antioxidant

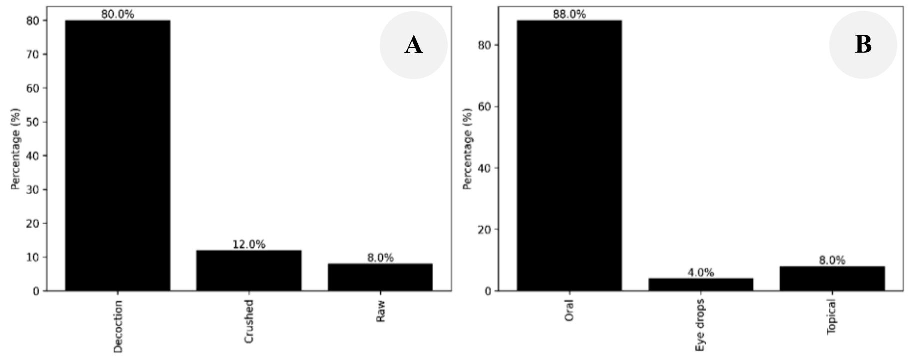

Figure 4. Preparation and application methods of medicinal plants used by local communities in the Gunung Sewu Karst, Central Java, Indonesia, showing the dominance of decoction-based preparation and oral administration. A. Preparation methods, B. Application routes

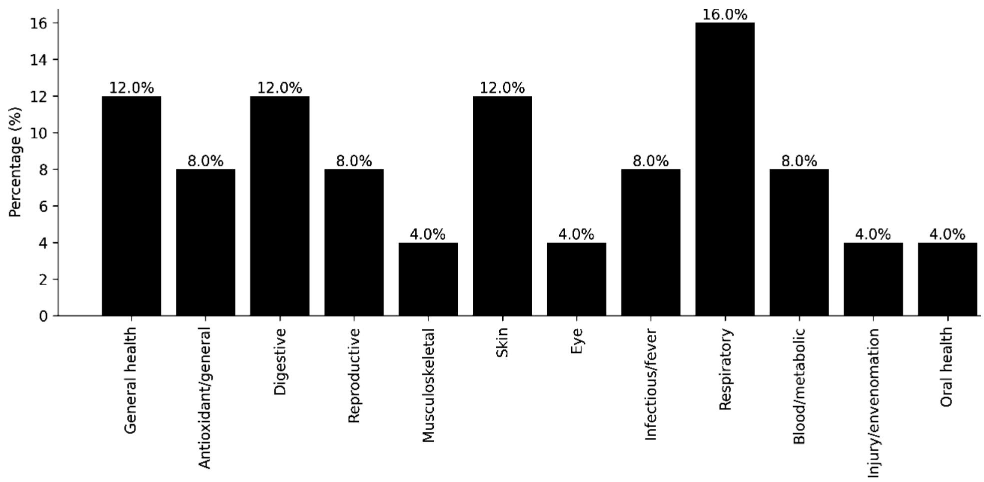

Figure 5. Categories of ailments treated using medicinal plants in the Gunung Sewu Karst, Central Java, Indonesia, highlighting the predominance of treatments for mild to moderate health conditions

The dominance of herbaceous medicinal plants, accounting for 52.0% of the recorded species, together with the preferential use of renewable plant parts such as leaves (50.0%) and rhizomes (30.8%), illustrates a strategic response to the ecological limitations of karst environments (Figure 5). Herbaceous taxa are favored due to their rapid growth, ease of cultivation in shallow and rocky soils, and strong regenerative capacity following harvesting, making them reliable resources in landscapes where woody vegetation is less accessible or slower to recover. Tree species, although contributing a smaller proportion (28.0%), played a complementary role, while climbers (12.0%), shrubs (4.0%), and succulent herbs (4.0%) represented more specialized components of the local medicinal flora. Similar dominance of herbaceous species has been reported from other karst and dryland regions, where medicinal plant selection is shaped by ecological filtering and long-term cultural adaptation processes (Voeks 2004; Gaoue et al. 2017; Pieroni and Quave 2014; Quave and Pieroni 2015).

The strong reliance on leaves as the primary harvested plant part further reflects adaptive harvesting strategies that minimize ecological impact while ensuring continuous access to medicinal resources. Leaf harvesting is widely recognized as a sustainable practice in traditional medicine systems, particularly in environments where intensive exploitation of roots, bark, or woody tissues could result in rapid resource depletion (Cunningham 2001; de Albuquerque et al. 2014). In the Gunung Sewu Karst, this pattern suggests the presence of an implicit conservation ethic embedded within everyday medicinal practices rather than reliance on formalized management regulations.

Rhizome use, especially among herbaceous taxa of the Zingiberaceae, represents a complementary adaptive strategy that balances therapeutic effectiveness with accessibility. Rhizomatous species are commonly cultivated in homegardens, thereby reducing pressure on wild populations and reinforcing the integration of medicinal plant use into household agroecological systems. Comparable patterns have been documented in karst-influenced agroecosystems of southern China and mainland Southeast Asia, where medicinal plants are actively maintained within managed landscapes as part of local health and subsistence strategies (Srithi et al. 2009; de Medeiros et al. 2012).

These findings demonstrate that medicinal plant use in the Gunung Sewu Karst is not random but constitutes a coherent biocultural adaptation to environmental limitation. The novelty of this study lies in explicitly linking growth-form composition and harvested plant parts to karst ecological constraints, thereby framing traditional medicinal practices as adaptive responses rather than isolated cultural traditions. This perspective contributes to a growing body of biocultural research emphasizing the critical role of local knowledge systems in sustaining human well-being in environmentally marginal landscapes (Caillon et al. 2017; Sterling et al. 2017).

Ecological constraints and medicinal plant selection

Ecological constraints inherent to karst landscapes play a decisive role in shaping medicinal plant selection and use. The dominance of herbaceous species documented in the Gunung Sewu Karst (52.0% of recorded species) reflects strong environmental filtering imposed by shallow soils, high rock exposure, limited nutrient availability, and pronounced seasonal drought. Under such conditions, herbaceous plants are ecologically favored over woody taxa because they require less soil depth, exhibit shorter growth cycles, and are able to rapidly exploit transient moisture availability following rainfall events (Ford and Williams 2007; Goldscheider et al. 2020). These ecological traits directly influence which plant species remain accessible to local communities and are subsequently incorporated into traditional medicinal systems.

Herbaceous dominance in medicinal plant repertoires has been widely documented in environmentally constrained systems, including karst, dryland, and mountainous regions. Studies from karst areas in the Mediterranean, the Balkans, and Southeast Asia consistently report medicinal knowledge concentrated on fast-growing herbs and climbers that occur close to settlements and along disturbed microhabitats (Srithi et al. 2009; Pieroni and Quave 2014). In the Gunung Sewu Karst, the prevalence of herbaceous medicinal plants suggests a selective process in which ecological availability and cultural preference converge, reinforcing the adaptive nature of medicinal plant use under resource limitation rather than random exploitation of the surrounding flora.

Sustainable harvesting practices further mediate medicinal plant selection in karst environments. The strong reliance on leaves as the primary harvested plant part (50.0% of recorded uses) reflects an implicit strategy to minimize ecological impact while maintaining therapeutic efficacy. Leaf harvesting is generally less destructive than the extraction of roots, bark, or whole plants, allowing individuals to continue growing and contributing to future harvests (Cunningham 2001; Gaoue et al. 2017). In karst landscapes, where edaphic limitations and water scarcity may constrain plant regeneration, such practices are particularly important for ensuring long-term availability of medicinal resources.

The integration of medicinal plants into homegardens and other managed spaces further supports sustainable use under ecological constraints. Many herbaceous species with medicinal value are deliberately cultivated or semi-managed near households, reducing dependence on wild populations and buffering against environmental variability. Comparable management strategies have been documented in karst-influenced agroecosystems of China, Thailand, and Vietnam, where medicinal plant cultivation functions simultaneously as a conservation measure and a household health strategy (de Medeiros et al. 2012; Ferreira-Junior and Albuquerque 2018). Together, these patterns indicate that medicinal plant selection in the Gunung Sewu Karst is shaped not only by ecological constraints but also by culturally embedded practices that promote sustainable and resilient resource use.

Comparison with other karst and non-karst regions

Comparative analysis indicates that medicinal plant use in the Gunung Sewu Karst shares important structural similarities with ethnobotanical systems documented in other karst regions, while simultaneously exhibiting distinctive local characteristics. Studies from Mediterranean karst landscapes and the Balkan Peninsula consistently report a strong reliance on herbaceous species and leaf-based remedies, reflecting convergent adaptive responses to shallow soils, limited water retention, and high substrate heterogeneity (Pieroni and Quave 2014; Quave and Pieroni 2015). Comparable patterns have also been observed in karst areas of southern China and mainland Southeast Asia, where medicinal plant repertoires are shaped by ecological filtering, proximity to settlements, and long-term cultural familiarity with locally available taxa (Srithi et al. 2009; de Medeiros et al. 2012).

Within Java, ethnobotanical studies conducted in karst landscapes adjacent to Gunung Sewu, including Pacitan District and Gunung Kidul, reveal similar functional patterns despite differences in species richness. Research from Pacitan karst villages documented a larger number of medicinal plant species, yet reported comparable dominance of Zingiberaceae, frequent use of leaves and rhizomes, and decoction as the principal preparation method (Ammar et al. 2021). Likewise, studies from Gunung Kidul emphasize herb-based *jamu* formulations and household-level reliance on cultivated or semi-cultivated species, reflecting parallel adaptive strategies under karst soil constraints (Nahdi and Kurniawan 2019). These similarities suggest that ecological limitation, rather than floristic availability alone, plays a decisive role in shaping medicinal plant use across southern Javanese karst systems.

The medicinal plant system of the Gunung Sewu Karst is nevertheless distinguished by its strong integration of cultivated and semi-cultivated species within household spaces. Compared with karst landscapes in coastal settings, such as the Prigi Bay area in Trenggalek—which represents a coastal karst system influenced by marine humidity, deeper colluvial soils, and agroforestry-oriented homegardens—Gunung Sewu exhibits a more constrained yet selectively managed plant repertoire. While studies from Prigi report high medicinal plant diversity embedded in complex homegarden structures (Agustina et al. 2022), the Gunung Sewu Karst favors fewer, functionally reliable species adapted to drier inland karst conditions. This contrast highlights how variation within karst types (inland versus coastal karst) further shapes biocultural strategies of medicinal plant selection and management.

In contrast to non-karst forest-based ethnobotanical systems in Indonesia—such as lowland rainforests and montane ecosystems—where medicinal plant use often includes a higher proportion of woody species and harvesting of bark or roots (Sujarwo et al. 2014; Silalahi et al. 2015), the Gunung Sewu Karst supports a simpler vegetation structure. This structural limitation promotes medicinal practices that emphasize functional efficiency, accessibility, and renewable plant parts rather than maximizing taxonomic richness. Similar patterns have been observed in other environmentally marginal systems, where ethnobotanical knowledge prioritizes species that are consistently available and easy to manage under variable environmental conditions (Voeks 2004; Gaoue et al. 2017).

The distinctiveness of the Gunung Sewu Karst, therefore, lies not merely in its species composition but in the way biocultural knowledge mediates between ecological scarcity and household healthcare needs. Unlike some karst regions where traditional medicinal practices are declining due to urbanization or increased reliance on biomedical healthcare, communities in the Gunung Sewu Karst continue to actively apply plant-based remedies as part of everyday health management. This persistence reflects both cultural continuity and ongoing environmental necessity. By situating Gunung Sewu within a comparative framework that includes inland karst, coastal karst, and non-karst systems, this study underscores its value as a model landscape for understanding how biocultural adaptations emerge, persist, and remain functionally relevant under long-term ecological constraint (Caillon et al. 2017; Sterling et al. 2017).

In conclusion, this study documents medicinal plant use in the Gunung Sewu Karst as a biocultural adaptation shaped by long-term interaction between local communities and an environmentally constrained landscape. A total of 25 medicinal plant species belonging to 16 families were recorded, with clear dominance of herbaceous taxa (52.0%) and a marked reliance on Zingiberaceae (32.0% of recorded species). Medicinal practices preferentially utilized renewable plant parts, particularly leaves (50.0%) and rhizomes (30.8%), reflecting adaptive harvesting strategies suited to shallow soils, seasonal water scarcity, and limited nutrient availability characteristic of karst environments. These patterns indicate ecological filtering in combination with culturally embedded strategies that emphasize accessibility, renewability, and household-based healthcare.

Preparation and application patterns further support this adaptive interpretation. Decoction was the dominant preparation method (80.0% of species), and oral administration accounted for 88.0% of reported uses, indicating that medicinal plants primarily function as first-line household healthcare resources. Rather than representing isolated cultural traditions, medicinal plant practices in Gunung Sewu constitute a coherent system that integrates ecological constraint, sustainable harvesting, and intergenerational knowledge transmission. By explicitly linking growth forms, harvested plant parts, and preparation methods to karst environmental conditions, this study advances a biocultural perspective on ethnobotany in marginal ecosystems. These findings contribute to ethnobotanical research by highlighting karst landscapes as important yet underexplored settings for biocultural adaptation.

This study is limited by its descriptive analytical approach, restricted geographic scope (two villages), and moderate sample size (36 respondents), which constrain broader generalization and prevent causal inference. In addition, the temporal dynamics of knowledge transmission and changes in medicinal plant use were not assessed. Future research should incorporate comparative studies across multiple karst systems, longitudinal analyses of knowledge change, and quantitative indices (e.g., use value, fidelity level) to strengthen inference. Integrating ethnobotanical data with ecological monitoring and socio-economic assessment will further clarify how traditional medicinal knowledge contributes to resilience, conservation, and sustainable healthcare strategies in environmentally marginal karst landscapes.

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