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THE EFFECT OF FARMERS' PARTICIPATION, THE ROLE OF FACILITATORS AND THE ROLE OF GOVERNMENT ON SOCIAL FORESTRY PERFORMANCE

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THE EFFECT OF FARMERS' PARTICIPATION, THE ROLE OF FACILITATORS, AND THE ROLE OF GOVERNMENT ON SOCIAL FORESTRY PERFORMANCE. This study aims to determine the effect of farmer participation, the role of facilitators, and the role of government on social forestry performance, and to determine the role of farmer group performance in mediating the effect of farmer participation, the role of facilitators, and the role of government on social forestry. This research uses a mixed-method approach that combines quantitative and qualitative research. The research instrument used was a questionnaire compiled with a five-point Likert scale. The sample size in this research was 198 respondents who were farmer groups holding social forestry permits, facilitators, and the Walanae Forest Management Unit. Data were analyzed using the SEM-PLS method with the help of Smart PLS software version 3.0. The results showed that farmer participation and the role of facilitators had a positive and significant effect on the performance of farmer groups and social forestry. Directly, the role of government did not have a significant effect on the performance of farmer groups, but had a positive and significant effect on the performance of social forestry. There is a tendency for the role of government to be more influential through other mechanisms. The performance of farmer groups can mediate the participation of farmers, the role of facilitators, and the role of government in improving the performance of social forestry. The benefits of this research not only contribute to improving the performance of social forestry, but also to the development of more inclusive, sustainable, and community-based forest management, so it is expected to be used as a recommendation for relevant parties in efforts to improve the performance of social forestry.

Keywords: Farmer participation, the role of facilitators, the role of government, social forestry performance.

PENGARUH PARTISIPASI KELOMPOK TANI, PERAN PENDAMPING DAN PERAN PEMERINTAH TERHADAP KINERJA PERHUTANAN SOSIAL. Penelitian ini bertujuan untuk mengetahui pengaruh partisipasi petani, peran pendamping dan peran pemerintah terhadap kinerja perhutanan sosial serta mengetahui peran kinerja kelompok tani dalam memediasi pengaruh partisipasi petani, peran pendamping dan peran pemerintah terhadap kinerja perhutanan sosial. Penelitian ini menggunakan pendekatan metode campuran yang menggabungkan penelitian kuantitatif dan kualitatif. Instrumen penelitian yang digunakan adalah kuesioner yang disusun dengan skala likert lima poin. Ukuran sampel dalam penelitian ini berjumlah 198 responden yang merupakan kelompok tani pemegang izin perhutanan sosial, pendamping dan Kesatuan Pengelolaan Hutan Walanae. Data dianalisis menggunakan metode SEM-PLS dengan bantuan perangkat lunak Smart PLS versi 3.0. Hasil penelitian menunjukkan bahwa partisipasi petani dan peran pendamping berpengaruh positif dan signifikan terhadap kinerja kelompok tani dan perhutanan sosial. Secara langsung peran pemerintah tidak berpengaruh secara signifikan dengan kinerja kelompok tani tetapi berpengaruh positif dan signifikan terhadap kinerja perhutanan sosial. Ada kecenderungan peran pemerintah lebih berpengaruh melalui mekanisme lain. Kinerja kelompok tani dapat memediasi partisipasi petani, peran pendamping, dan peran pemerintah dalam meningkatkan kinerja perhutanan sosial. Manfaat penelitian ini tidak hanya berkontribusi pada peningkatan kinerja perhutanan sosial, tetapi juga pada

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pengembangan pengelolaan hutan yang lebih inklusif, berkelanjutan, dan berbasis masyarakat sehingga diharapkan dapat dijadikan sebagai rekomendasi bagi para pihak terkait dalam usaha meningkatkan kinerja perbutanan sosial.

Kata kunci: Partisipasi petani, peran pendamping, peran pemerintah, kinerja perbutanan sosial

I. INTRODUCTION

Social Forestry is a system of sustainable forest management in state forest areas or private forests/customary forests carried out by communities around the forest (Damanhuri, 2021; Laksemi et al., 2019; Salim et al., 2018; Syahputra, 2021; Moeliono et al., 2023). The aim of social forestry is to provide legal rights/permits to local community groups to manage previously inaccessible state forests, with the aim of economic, ecological, and social improvement (Mahardika et al., 2021; Puspitasari et al., 2019; Sumanto, 2009; Herrawan et al., 2022). The social forestry program in Indonesia includes 5 (five) schemes, namely: Village Forest Management, Community Forest, Community Plantation Forest, Customary Forest, and Forestry Partnership. During the 2015-2019 period, the government allocated 12.7 million hectares of land for the social forestry program (Suhartini, 2009), and starting in 2023, it is targeted to have 7,380,000 ha of legal access land with the addition of 23,400 social forestry facilitators. Until 2030, it is targeted that 17,000 social business groups and partnerships will be developed through the social forestry program. These groups are expected to accommodate underprivileged communities around the forest to develop and ultimately improve their welfare. Until January 2024, the number of management permits for social forestry was 9,719 units involving 1,287,710 families with an area of 6,447,102.42 ha. For South Sulawesi Province, the national target was 473,401 ha, which was realized until the end of 2023, covering an area of 217,174.83 ha. The number of permits that have been issued is 924 permits, consisting of 92 village forest management business permits, 419 community forest utilization business permits, 378 community plantation forest utilization business permits, 26 forestry partnerships, and 9 customary forests. The

number of social forestry permits in Soppeng Regency is 5 village forest management business permit schemes, 9 community forest utilization business permit schemes, and 4 community plantation forest utilization business permit schemes. (South Sulawesi Provincial Forestry Service, 2024).

Since the social forestry program was launched in 2015, until now it has not provided satisfactory results. This is due to the weak support of central and regional government policies (Affandi et al., 2019; Shaleh et al., 2019; Hermin et al., 2021; Rahayu et al., 2024), low human resource capacity (Harahap et al., 2021; Harimbawan et al., 2022; Sami, 2020), and the amount of business and capital, as well as the use of product processing technology, have not had a significant impact (Josy & Moeis, 2022). The lack of synergy between social forestry support programs, the number and budget of companions, institutional management challenges, and the quality of community human resources are the primary challenges to social forestry (Fitria et al., 2021; Mulyani et al., 2023; Mutaqin et al., 2022; Nandini et al., 2022; Salaka et al., 2020; Zulkarnain, 2021).

Referring to the Regulation of the Minister of Environment and Forestry No. 9 of 2021, the key actor in the implementation of the social forestry program is the government, while the main actor is the holder of the social forestry permit. In the theory of the relationship between principal and agent or agency theory, the government is positioned and plays a role as a principal (permit giver), while the facilitator and local community or customary law community are positioned as agents (receivers or executing permits) whose relationship is bound by an agreement or contract. In this contract, the agent has a normative, legal, or moral obligation to work best for the principal (Quinn, 2013). These actors have different

interests and powers and will behave according to their interests and powers (Reed et al., 2009).

Many studies on social forestry only focus on one aspect, such as the importance of farmer participation (Fatarin Lukito et al., 2023; Laksemi et al., 2019; Marasabessy, 2018; Nita Andelia Mandasari, 2016; Rochmayanto et al., 2006; Suhartini, 2009), the role of facilitators (Hardhiyanti, 2022; Mulyani et al., 2023), and the role of government (Firdaus, 2020; Fitria et al., 2021; Sami, 2020). However, this study takes a more comprehensive approach by combining the variables of farmer participation, the role of facilitators, and the role of government in one analysis. This study reveals the effect of farmer participation, the role of facilitators, and the role of government indirectly on the performance of social forestry through the performance of farmer groups first. Analysis of this mediation relationship has rarely been discussed in previous literature, which tends to see the direct effect between these factors and social forestry performance without delving deeper into the performance of farmer groups as an important component in the success of the program.

Research related to correlation analysis of farmer participation, the role of assistants, and the role of government with SEM modeling (Structural Equation Modeling) through a Partial approach Least Square (PLS) which is a statistical tool that aims to analyze the relationship between variables is still minimally done, it is considered important to conduct this study because it will be known which variables affect the performance of social forestry both directly and indirectly so that it can be mapped which variables should be intervened to maximize the performance of social forestry. In addition, the use of the SEM method plays a role in testing whether the performance of farmer groups significantly mediates the relationship between farmer participation, the role of assistants, and the role of government with social forestry performance. This means that SEM can measure how much the performance of farmer groups contributes to strengthening or

weakening the effects of these variables. Thus, SEM is able to handle complex models, analyze latent variables, test direct and indirect effects, and provide an evaluation of the overall model suitability. With SEM, researchers can gain a more comprehensive understanding of how each factor affects the performance of social forestry and provide strong empirical evidence to support research conclusions. The benefits of this study are benefits of this research are not only to contribute to the improvement of social forestry performance, but also to the development of more inclusive, sustainable, and community-based forest management, so that it is expected to serve as a recommendation for relevant parties in an effort to improve social forestry performance.

II. MATERIAL AND METHOD

A. Research sites

This research was conducted in Soppeng Regency (119° 42' 23.16" to 120° 26' 27.17" East Longitude and 3° 39' 48.82" to 4° 32' 46.46" South Latitude) with a distance of 180 km from the provincial capital of South Sulawesi and can be reached in 5 hours. Soppeng Regency is included in the working area of Forest Management Unit (FMU) Walanae, which is located in Soppeng Regency, South Sulawesi Province, Indonesia. The working area of FMU Walanae has a management area of 64,592 Ha, consisting of protected forest covering an area of 39,396 Ha, permanent production forest covering an area of 11,035 Ha, and production forest covering an area of $\pm 14,161$ Ha. The elevation range is 2 - 1500 m above sea level. The distribution of the number of social forestry permits that have been issued in Soppeng Regency is in 10 villages, including Pesse Village, Bila Village, Maddulang Village, Lalabata Rilau Village, Bulue Village, Tampaning Village, Patampanua Village, Mattabulu Village, Sering Village, and Umpungeng Village. The livelihoods of the people in Soppeng Regency are dominated by agricultural activities, with the main crop being rice and other side crops

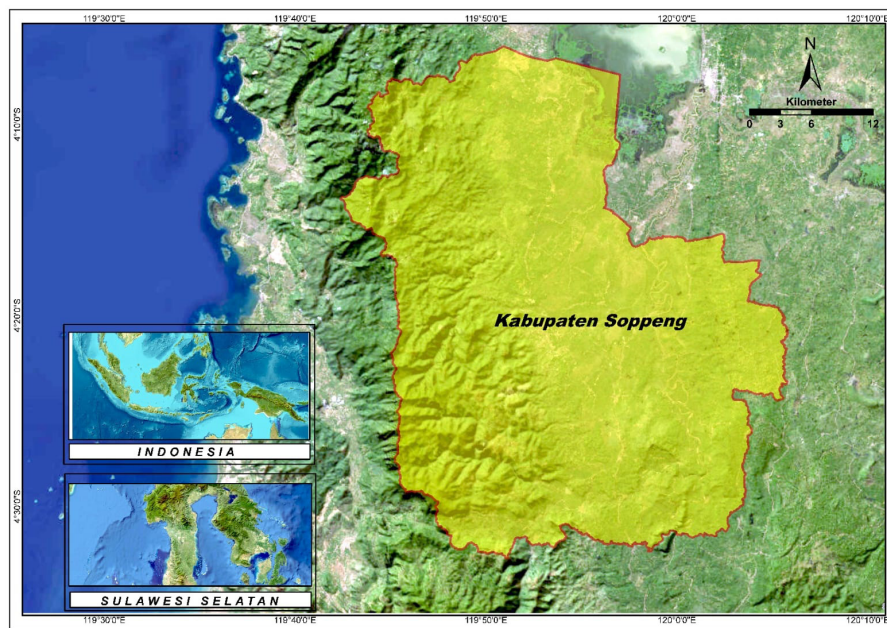


Figure 1. Map of research locations in Soppeng Regency, South Sulawesi Province, Indonesia

Table 1. Number of research respondents

No	Element	y
1.	Chairman, secretary, and treasurer (18 permit holders x 3 = 54 people)	54
2.	Members holding permits (18 permit holders x 3 people = 54 people)	54
3.	Chairperson of the social forestry business group = 72 people	72
4.	Head of Forest Management Unit = 1 person	1
5.	Head of Forest Protection and Community Empowerment Section = 1	1
6.	person	12
7.	Facilitators = 12 people	4
	Local Champion Companions = 4 people	
	Total	198

such as corn, soybeans, and green beans. Plantation commodities include candlenuts, cocoa, coconut, and cashew nuts. Apart from agriculture, the majority of people in Soppeng Regency raise cattle as their main livestock. A map of the research location can be seen in Figure 1.

B. Population and research sample

The population in this research is the number of farmers managing social forestry permits in Soppeng Regency, totaling 2,906 families spread across 3 sub-districts and 8 villages/sub-districts, consisting of 5 village forest management business Permit schemes, 9

community plantation forest utilization business permit schemes, and 4 community plantation forest utilization business permit schemes.

Respondents were selected purposively and included core group administrators, farmers who were actively involved and understood all stages of social forestry management, social forestry facilitators, the Head of Walanae Forest Management Unit, and the Head of Forest Protection and Community Empowerment Section of the Walanae Forest Management Unit. In addition, several local champion companions were included as respondents. These are local individuals who actively support social forestry implementation by

facilitating community initiatives, encouraging sustainable forest management practices, and assisting farmer groups in developing social forestry enterprises. Data were processed using a Likert scale to classify categories of farmer participation, the role of facilitators, the role of government, and the performance of social forestry. The total number of respondents interviewed was 198 people. The distribution of respondents is presented in Table 1.

C. Research variables

The variables used in this study were obtained from the results of field observations and literature studies from various studies/research that represent the relationship with the research topic. Based on this, the variables in this study are a combination of various variables used so that the results of the analysis in the study are more comprehensive.

The variables used in this study consist of exogenous variables (independent) and endogenous variables (dependent variables). Exogenous variables are farmer participation (X1), the role of facilitators (X2), and the role of government (X3). Endogenous variables are farmer group performance (Y1) and social forestry performance (Y2). The definition, parameters, and measurement categories of each variable, along with their measurement indicators, are as follows (Tables 2 to 6).

1. Farmer participation (X1) is the determination of the attitude and involvement of each individual's desires in the situation and conditions of their organization, so as to ultimately encourage the individual to participate in the achievement of the organization's goals, and take part in every shared responsibility (Syafii, 2002).
2. The role of facilitator (X2) is the role carried out by facilitators as a liaison with the community who run the business with external parties (Rumampuk et al., 2021)
3. The role of government (X3) is a government unit that is responsible for carrying out government duties (Firdaus, 2020)
4. Farmer Group Performance (Y1) is an assessment of farmer groups in institutional management, area management, and business management (Permenhut, 2018)
5. Social Forestry Performance (Y2) is an assessment (evaluation) activity intended to analyze to what extent physical and non-physical activities in the management of social forestry land in the short, medium, and long term have been in accordance with the mutual agreement between the parties (Pemerintah Republik Indonesia, 2021).

Table 2. Indicators definition, parameters, and categories of farmer participation measurements (Syairozi et al., 2019).

Indicator/Code	Definition	Parameter	Measurement Scale
Planning/PP1	Intensity of respondent involvement in social forestry planning	The value of respondent presence in social forestry planning	Ordinal scale
Implementation/PP2	Intensity of respondent involvement in the implementation of social forestry	Respondent activity values in implementing social forestry	Ordinal scale
Monitoring and evaluation/PP3	Intensity of respondent involvement in monitoring and evaluation in social forestry	The value of respondent attendance in monitoring and evaluation in social forestry	Ordinal scale
Services (Labor)/PP4	The intensity of respondents' involvement in the form of labor in social forestry activities	Respondent intensity value in the form of labor in social forestry activities	Ordinal scale

Indicator/Code	Definition	Parameter	Measurement Scale
Ideas/PP5	The intensity of respondent involvement in the form of ideas/concepts/thoughts in social forestry activities	The value of respondents' presence in the form of ideas/concepts/thoughts in social forestry activities	Ordinal scale
Material/PP6	The intensity of respondent involvement in the form of materials in social forestry activities	The value of respondents' presence in the form of materials in social forestry activities	Ordinal scale

Table 3. Indicators, definitions, parameters, and measurement scales of the variables of the role of the facilitator's role in social forestry (Rumampuk et al., 2021)

Indicator	Definition	Parameter	Measurement Scale
Enabling/ Pend_1	Facilitator activities to provide motivation and opportunities to respondents in social forestry activities	Respondents' assessment of the intensity of facilitator activities in facilitating social forestry activities	Ordinal scale
Reinforcement/ Pend_2	Facilitator activities to provide education and training to respondents in social forestry	Respondents' assessment of the intensity of facilitator activities in social forestry education and training	Ordinal scale
Protection/ Pend_3	Facilitator activities to provide advice to respondents and other stakeholders in bridging the interests of forest farmer groups and other stakeholders related to social forestry activities.	Respondents' assessment of the intensity of facilitator activities to provide advice to respondents and other stakeholders in bridging the interests of forest farmer groups and other stakeholders related to social forestry activities.	Ordinal scale
Supporters/ Pend_4	Facilitator activities for the development of respondents' businesses in social forestry activities	Respondents' assessment of the intensity of facilitator activities in supporting social forestry activities	Ordinal scale

Table 4. Indicators, definitions, parameters, and measurement scales of government role variables (Rochmayanto et al., 2006)

Indicator	Definition	Parameter	Measurement Scale
Regulator/ Pem_1	Government activities to create social forestry rules and mechanisms	Respondents' assessment of the intensity of government activities to create social forestry rules and mechanisms	Ordinal scale
Dynamycator/ Pem_2	Government activities to encourage respondents to participate in social forestry activities	Respondents' assessment of the intensity of government activities in socialization, mentoring, training, and field visits in social forestry activities	Ordinal scale
Facilitator/ Pem_3	Government activities become a driving force through funding in providing capital.	Respondents' assessment of the intensity of government activities through funding in providing capital according to farmers' needs.	Ordinal scale

Table 5. Indicators, definitions, parameters, and measurement scales for farmer group performance variables (Permenhut, 2018)

Indicator	Definition	Parameter	Measurement Scale
Manage area/ KK1 KK2 KK3 KK4	Intensity of respondent involvement in managing the area	Respondents' activities in managing the area. Activity: Territorial boundary layout Working block Social Forestry work plan Identification of potential	Ordinal scale
Manage institutions/ KL_1 KL_2 KL_3 KL_4	The intensity of respondents' involvement in managing forest farmer group institutions	Respondents' activities in managing institutions Activity: Organizational structure Articles of association/Bylaws Group meeting Cadre formation	Ordinal scale
Manage business/ KU_1 KU_2 KU_3 KU_4	The intensity of respondents' involvement in managing forest farmer group businesses	Respondents' activities in business management Activity: Business products Local marketing Business meeting Cooperation	Ordinal scale

Table 6. Indicators, definitions, parameters, and measurement scales of performance variables of social forestry (Pemerintah Republik Indonesia, 2021)

Indicator	Definition	Parameter	Measurement Scale
Administrative Aspects/ AP	Availability of social forestry planning documents	Availability of planning documents Activity: Legality of documents, planning, activities	Ordinal scale
Economic Aspects/ AE1 AE2 AE3	Intensity of realization of activities from an economic aspect	Realization of activities from an economic aspect Activity: Forest Resource Governance Management of timber forest products, non-timber forest products, and environmental services Utilization of natural resources and access to financial institutions and markets	Ordinal scale

Indicator	Definition	Parameter	Measurement Scale
Ecological Aspects/ AEK1 AEK2 AEK3 AEK4	Intensity of realization of activities from an ecological aspect	Realization of activities from an ecological aspect Activity: Area functions are maintained Land cover improvement Diversity of types of forest resource products Improvement of hydrological conditions	Ordinal scale
Social Aspects/ AS1 AS2 AS3	Intensity of realization of activities from social aspects	Realization of activities from a social aspect Activity: Group/community welfare Institutional strengthening Conflict Resolution	Ordinal scale

D. Data processing and analysis

This research uses a mixed-method approach that combines quantitative and qualitative research. Quantitative methods are used to analyze the effect of farmer participation, the role of facilitators, and the role of government as latent research variables and farmer group performance as an intervening variable to achieve social forestry performance, for which the Structural Equation Modeling (SEM) method used Partial Least Squares (PLS) software version 3.0. Qualitative methods are used to explain accurate and in-depth information to support verification and to draw conclusions. The data sources used are primary data sources, collected through in-depth interviews using a questionnaire tool, and secondary data obtained from literature studies and documentation studies produced by agencies that are related to research objectives, such as the Walanae forest management unit, the Central Bureau of Statistics, village governments, the Environment and Forestry Service, local governments, and so on.

The answer format in the questionnaire uses a Likert scale (Likert Summated Rating) with five answer alternatives, each answer alternative is scored as follows: a) very high/strongly supports the statement given a score of 5; b) high/supports the statement given a score of 4;

c) moderate given a score of 3; d) low supports the statement given a score of 2; e) very low/strongly does not support the statement given a score of 1.

Model evaluation in PLS consists of two stages, namely the evaluation of the outer model or the measurement model, and the evaluation of the inner model or the structural model (structural measurement). Outer model evaluation is the process of assessing the quality of latent variable measurement through indicators related to SEM analysis. Inner model evaluation is the process of assessing the effect of latent constructs. Inner model evaluation focuses on hypothesis testing involving the effect between latent constructs that have been measured well by their indicators (after outer model validation).

Evaluation of the outer model (measurement model) aims to determine the validity and reliability of latent variables and measuring variables. Validity tests are interpreted by looking at several things, including: convergent validity by looking at the Loading Factor and Average Variance Extracted (AVE) values, and discriminant validity by looking at the Fornell-Lacker and Cross Loading values. The reliability test is interpreted with the Composite reliability and Cronbach's Alpha values. The loading factor is used to assess the ability of each indicator to measure the variable to be

measured, so that a strong indicator is obtained to measure the variable. The loading factor value ≥ 0.7 is said to be ideal, meaning that the indicator is valid to measure the construct it forms. Convergent value measures the magnitude of the loading factor of each latent variable. Loading factors above 0.70 are highly recommended; however, loading factors above 0.50 can still be tolerated as long as the model is still in the development stage. The next test is to see the AVE value. The model requirement has good validity if the latent variable has a latent AVE > 0.5 . AVE value describes the amount of variance or diversity of manifest variables that a latent construct can have. The third discriminant validity test is by looking at the value of Fornell-Larcker. The requirement for a model to have good discriminant validity is that the correlation between the variable and the variable itself is not smaller than the correlation value between the latent variable and other latent variables. The fourth discriminant validity test is to look at the cross-loading value. A good cross-loading value is if the correlation value of the indicator with the variable itself is not greater than the correlation value between the indicator value and other variables. The measure of cross-loading is by comparing the correlation of the indicator with its construct

and the construct from other blocks (Hair et al., 2017)

Reliability is a coefficient value that indicates the level of data consistency. A study is said to be reliable if there is similarity in the data at different times. A measure that states a variable is said to be reliable if the variable has composite reliability and a Cronbach's Alpha value greater than 0.5.

Evaluation of the inner model (structural model) is carried out to see the relationship between latent constructs. Measures that can be used to evaluate the structural model (inner model) are R-square (R^2), Q-Square Predictive Relevance (Q^2), and Model Fit. The R^2 value is the coefficient of determination on the endogenous construct and the path parameter coefficient. R^2 is used to measure the predictive power of structural models. R^2 explains the influence of exogenous latent variables on whether endogenous variables have a substantive influence. The R^2 value is estimated between 0 and 1. The qualitative interpretation of Q^2 values is 0 (low influence), 0.25 (medium influence), and 0.50 (strong influence). The structural model of the effect of farmer participation, the role of facilitators, and the role of government on social forestry performance can be seen in Figure 2. The research hypothesis is that farmer

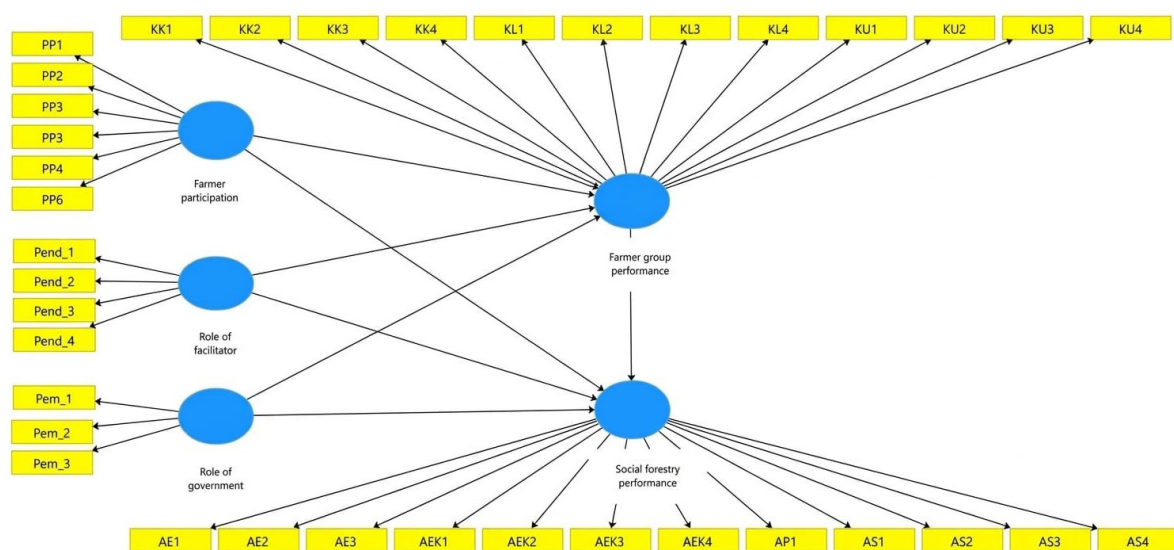


Figure 2. Relationship between the Conceptual Model of Farmer Participation, the Role of Facilitators, the Role of Government, and Social Forestry Performance

participation, the role of facilitators, and the role of government have a significant effect both directly and indirectly on social forestry performance.

III. RESULT AND DISCUSSION

A. Result

1. Outer Model Evaluation (Measurement Model)

The results of the outer model in Figure 3 show that several indicators are not valid to be used as a measure of the value of the

factor loading variable because they have a value of <0.7 , including indicators: PP6 (farmer participation in material form) with a value of 0.523; Social forestry performance AS1 (improving the welfare of groups/communities/villages/related parties)) with a value of 0.328, and social forestry performance AS4 (gender sensitivity) with a value of 0.263. These three indicators were removed from the measurement model, and remeasurement was done until they were valid, as shown in Figure 4 below:

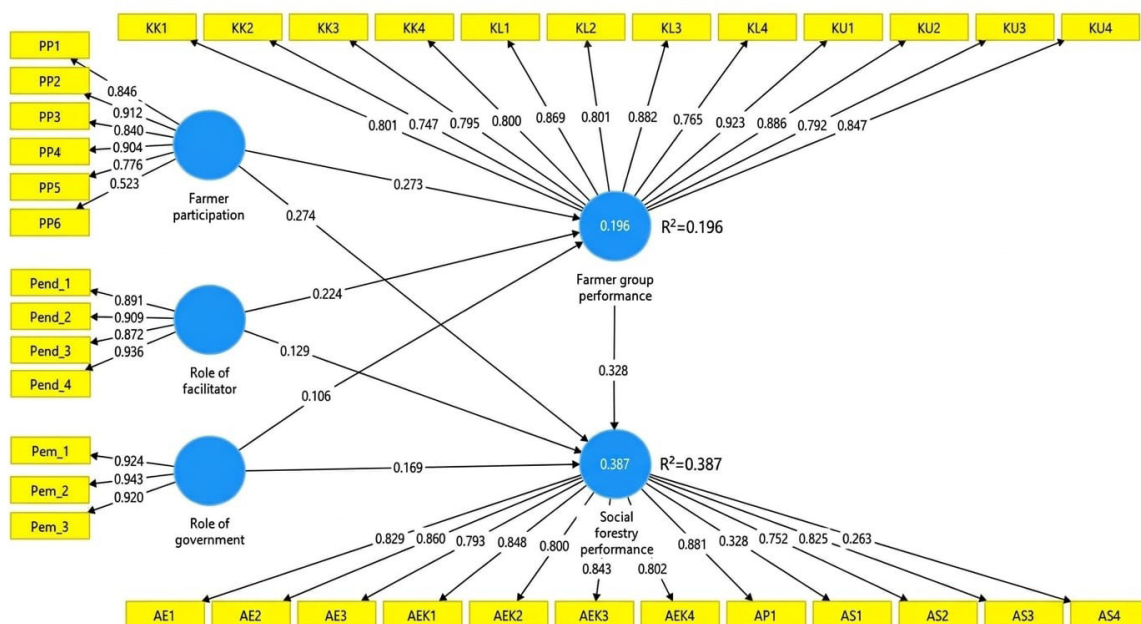


Figure 3. The initial measurement of the relationship between farmer participation, the role of facilitators, the role of government, and social forestry performance

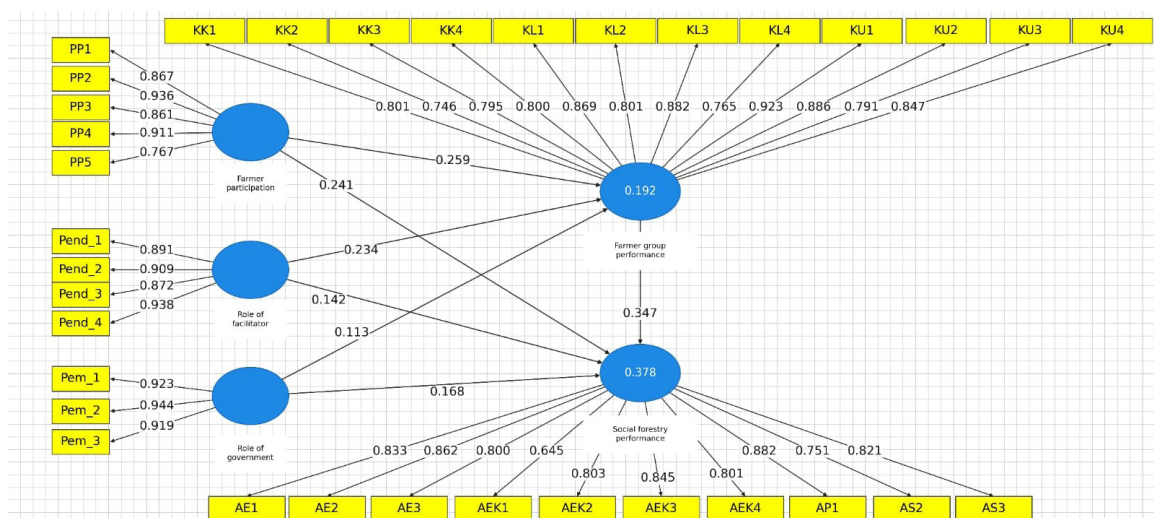


Figure 4. Remeasurement of the external model of the relationship between farmer participation, the role of facilitators, the role of government, and Social Forestry Performance

Based on Figure 4, all indicators used for each variable are valid because the outer loading values of the indicators are > 0.7 . The farmer participation variable uses five valid indicators, namely participation in planning (PP1), implementation (PP2), monitoring and evaluation (PP3), participation in service of labor (PP4), and ideas/concepts (PP5). The valid companion role variable is measured by indicators as an enabling function (Pend-1), as reinforcement (Pend-2), as protection (Pend-3), and as a supporter (Pend-4). The government role variable uses three valid indicators, namely the function as a regulator (Pem-1), the function as a dynamicator (Pem-2), and the function as a facilitator (Pem-3). The farmer group performance variable uses 12 valid indicators, namely territorial boundaries (KK1), work blocks (KK2), social forestry work plan (KK3), potential identification (KK4), organizational structure (KL_1), Articles of association/ Bylaws (KL_2), group meetings (KL_3), and cadre formation (KL_4), business products (KU_1), local marketing (KU_2), business meetings (KU_3), and cooperation (KU_4). The social forestry performance variables use ten valid indicators, namely the legality of activity planning documents (AP), forest resource governance (AE1), management of timber

forest products, non-timber forest products and environmental services (AE2), utilization of natural resources and access to financial institutions and markets (AE3), maintained area functions (AEK1), land cover improvement (AEK2), diversity of forest resource product types (AEK3), improvement of hydrological conditions (AEK4), institutional strengthening (AS2), and institutional strengthening (AS3).

The results of the path coefficient evaluation indicate a positive effect between the variables of farmer participation, the role of facilitators, and the role of government, with the performance of farmer groups and the performance of social forestry. The coefficient value of each path of farmer participation (0.259), the role of facilitators (0.234), and the role of government (0.113) on the performance of farmer groups; and the coefficient value of farmer participation (0.241), the role of facilitators (0.142), and the role of government (0.168) on the performance of social forestry.

Cross-loading value in Table 7 shows that each value of the exogenous and endogenous variables and their constituent indicators has a value > 0.70 and AVE > 0.50 , meaning that the correlation value between the variables and indicators has a positive and constructive effect.

Table 7. Results of validity tests (loading factor, AVE) and reliability tests (composite reliability and Cronbach's alpha) on the outer model of the effect of farmer participation, the role of assistants, the role of government, and social forestry performance.

Construct	Validity test		Reliability Test	
	Convergent Validity		Composite Reliability	Cronbac 's Alpha
Farmer Participation		0.757	0.940	0.920
- Planning (PP1)	0.867			
- Implementation (PP2)	0.936			
- Evaluation (PP3)	0.861			
- Services/labor (PP4)	0.911			
- Ideas/thoughts (PP5)	0.767			
Role of Facilitator		0.814	0.946	0.925
- Possible (Pend_1)	0.891			
- Strengthening (pend-2)	0.909			
- Protection (Pend_3)	0.872			
- Supporter (Pend_4)	0.936			

Construct	Validity test		Reliability Test	
	Convergent Validity		Composite Reliability	Cronbac 's Alpha
	Loading Factor	AVE		
Role of Government		0.862	0.949	0.923
- Regulators (Pem_1)	0.923			
- Dynamisator (Pem_2)	0.944			
- Facilitator (Pem_3)	0.919			
Farmer group performance		0.684	0.963	0.958
- Regional boundary arrangements (KK1)	0.801			
- Working block (KK2)	0.746			
- Social forestry work plan (KK3)	0.795			
- Potential identification (KK4)	0.800			
- Organizational structure (KL_1)	0.869			
- Basic household budget (KL_2)	0.801			
- Group meeting (KL_3)	0.882			
- Cadre formation (KL_4)	0.765			
- Business products (KU1)	0.923			
- Local marketing (KU2)	0.886			
- Business Meeting (KU3)	0.791			
- Cooperation (KU4)	0.847			
Social Forestry Performance		0.681	0.955	0.948
- Legality of documents, planning, activities (AP)	0.833 0.862			
- Forest resource management (AE1)				
- Management of wood, non-timber forest and environmental services (AE2)	0.800			
- Utilization of natural resources and access to financial institutions and markets (AE3)	0.845 0.803			
- Area function AEK1)	0.845			
- Improvement of land cover (AEK2)				
- Diversity of forest resource types and products (AEK3)	0.882			
- Improvement of hydrological conditions (AEK 4)	0.751 0.821			
- Institutional strengthening (AS2)				
- Conflict Resolution (AS3)				

Table 8. The cross-loading values for the outer model of the relationship between farmer participation, the role of facilitators, the role of government, and social forestry performance

	Farmer Participation	Role of Facilitator	Role of Government	Farmer Group Performance	Social Forestry Performance
PP1	0.867	0.354	0.058	0.310	0.397
PP2	0.936	0.289	0.039	0.304	0.397
PP3	0.861	0.394	0.204	0.352	0.392
PP4	0.911	0.316	0.053	0.337	0.407
PP5	0.767	0.213	-0.027	0.211	0.237
Pend_1	0.388	0.891	0.119	0.279	0.368
Pend_2	0.268	0.909	0.112	0.287	0.312

	Farmer Participation	Role of Facilitator	Role of Government	Farmer Group Performance	Social Forestry Performance
Pend_3	0.364	0.872	0.179	0.396	0.380
Pend_4	0.275	0.936	0.079	0.244	0.252
Pem_1	0.104	0.152	0.923	0.124	0.224
Pem_2	0.073	0.147	0.944	0.228	0.294
Pem_3	0.058	0.082	0.919	0.069	0.195
KK1	0.218	0.186	0.128	0.801	0.304
KK2	0.218	0.204	0.115	0.746	0.301
KK3	0.253	0.171	0.093	0.795	0.273
KK4	0.218	0.216	0.181	0.800	0.356
KL1	0.276	0.315	0.158	0.869	0.510
KL2	0.281	0.272	0.123	0.801	0.464
KL3	0.330	0.326	0.162	0.882	0.419
KL4	0.359	0.295	0.180	0.765	0.422
KU1	0.286	0.256	0.118	0.923	0.432
KU2	0.281	0.299	0.101	0.886	0.444
KU3	0.360	0.408	0.168	0.791	0.482
KU4	0.352	0.342	0.123	0.847	0.496
AE1	0.378	0.357	0.269	0.362	0.833
AE2	0.347	0.348	0.221	0.421	0.862
AE3	0.352	0.317	0.086	0.465	0.800
AEK1	0.412	0.350	0.278	0.476	0.845
AEK2	0.389	0.314	0.194	0.427	0.803
AEK3	0.457	0.398	0.213	0.533	0.845
AEK4	0.333	0.271	0.200	0.366	0.801
AP1	0.342	0.335	0.244	0.423	0.882
AS2	0.186	0.130	0.270	0.329	0.751
AS3	0.252	0.146	0.239	0.321	0.821

Table 9. The Fornell-Larcker values in the outer model of the relationship between farmer participation, the role of facilitator, the role of government, and social forestry performance

	Farmer Group Performance	Social Forestry Performance	Farmer Participation	Role of Government	Role of Facilitator
Farmer Group Performance	0.827				
Social Forestry Performance	0.503	0.762			
Farmer Participation	0.372	0.464	0.811		
Role of Government	0.168	0.273	0.109	0.929	
Role of Facilitator	0.345	0.373	0.389	0.142	0.902

Testing discriminant validity by looking at the Fornell-Larcker value and cross-loading. The correlation value between the latent variable and the variable itself is not smaller than that of other latent variables. The Fornell-Larcker values and cross-loading can be seen in Tables 7 and 8.

Table 8 shows that the cross-loading values on the original variable are higher compared to the cross-loading values on other variables. This means that the indicators used are more appropriate or relevant to measure their own variables rather than measuring other variables.

Table 9 shows that all correlation values between the variable values and the variable itself are greater than the correlation values between the variable values and other variables, so this test is valid. The reliability test in Table 3 shows the Composite Reliability and Cronbach's alpha values > 0.70 . This means that all indicators used to measure latent variables are reliable.

2. Inner Model Evaluation (Structural Model)

The R² analysis of farmer group performance were 0.192, as an endogenous variable correlated with the construct it formed. The latent variable of farmer group performance is influenced by exogenous variables (farmer participation, role of facilitator, role of government) by 19.2%. The endogenous variable of social forestry performance is influenced by exogenous variables (participation of farmers, role of facilitator, role of government) and farmers. The group performance variable was 37.8%, and the remaining 62.2% was influenced by other variables outside these variables and was not included in this research model. The adjusted R² value of the social forestry performance variable is 0.365 (> 0.33), so the influence of all exogenous constructs X1, X2, and X3 on Y1 is weak.

Table 10. R² value in the analysis of the relationship between farmer participation, the role of facilitator, the role of government, and social forestry performance.

	R Square	R Square Adjusted
Farmer Group Performance	0.192	0.179
Social Forestry Performance	0.378	0.365

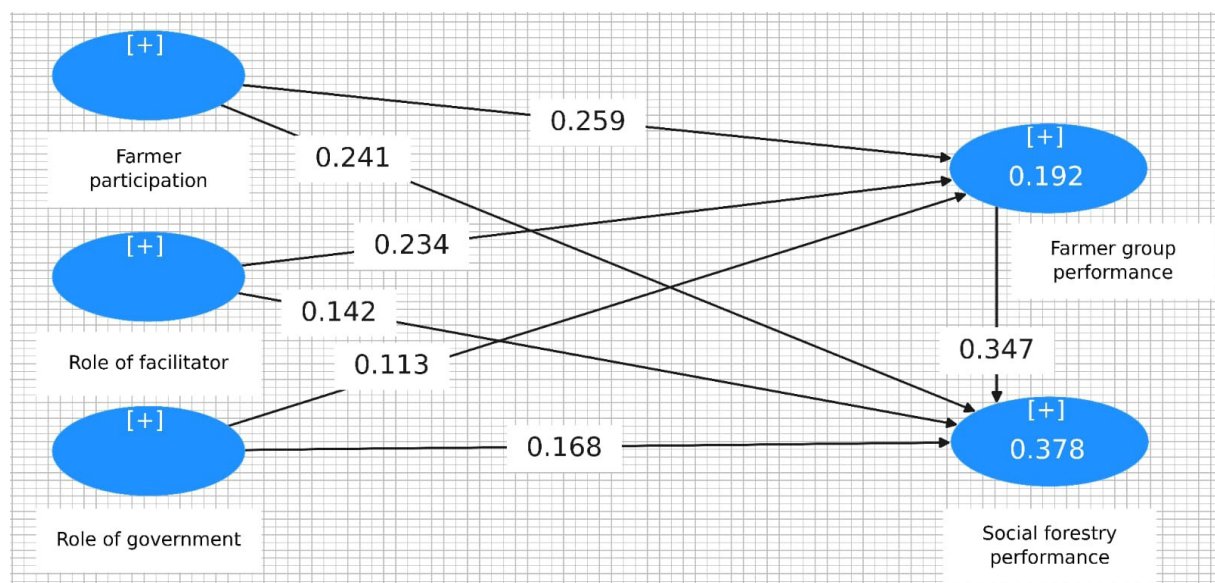


Figure 5. Results of the Bootstrapping Social Forestry Performance Model

The predictive relevance of Q-Square (Q²) for farmer group performance (0.122) and social forestry performance (0.244) is quite low (see Table 11). The performance value of farmer groups (Y1) = 0.122 indicates that the relevance of predictions is relatively small. Meanwhile, the performance of social forestry (Y2) = 0.244 indicates that the relevance of predictions is classified as moderate. This indicates that the predictive contribution of farmer group performance to social forestry performance is relatively limited. Although farmer group performance significantly influences social forestry performance, other factors outside the model may also play an important role in explaining the overall performance of social forestry.

This indicates that the predictive contribution of farmer group performance to social forestry performance is relatively limited. Although farmer group performance significantly influences social forestry performance, other factors outside the model may also play

an important role in explaining the overall performance of social forestry.

The NFI value of the model is 0.749 (74.9%) (see Table 12), indicating a moderate model fit. In SEM analysis, NFI values closer to 1 indicate a better model fit. Therefore, the obtained NFI suggests that the proposed model has an acceptable level of fit for explaining the relationships among the studied variables.

The NFI value of the model is 0.749 (74.9%) (see Table 12), indicating a moderate model fit. In SEM analysis, NFI values closer to 1 indicate a better model fit. Therefore, the obtained NFI value suggests that the proposed model has an acceptable level of fit for explaining the relationships among the studied variables.

3. Hypothesis test

Hypothesis testing uses a bootstrapping method simulation on the sample, which can be seen in Table 13. The indirect influence of exogenous and endogenous variables can be seen in Table 14.

Table 11. Predictive Relevance of Social Forestry Performance Model Output

	Q² (=1-SSE/SSO)
Farmer Group Performance	0.122
Social Forestry Performance	0.244

Table 12. Output of the Social Forestry Performance Fit Model

	Saturated Model	Estimated Model
Chi-Square	1822606	1822606
NFI	0.749	0.749

Table 13. Direct Influence on the Social Forestry Performance Model

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (O/STDEV)	P Values
Farmer Group Performance -> Social Forestry Performance	0.347	0.349	0.057	6,042	0,000
Farmer Participation -> Farmer Group Performance	0.259	0.261	0.069	3,783	0,000
Farmer Participation -> Social Forestry Performance	0.241	0.239	0.062	3,903	0,000

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (O/ STDEV)	P Values
Government Role -> Farmer Group Performance	0.113	0.110	0.064	1,766	0.078
Government Role -> Social Forestry Performance	0.168	0.170	0.054	3,115	0.002
Role of Facilitator-> Farmer Group Performance	0.234	0.239	0.070	3,346	0.001
Role of Facilitator-> Social Forestry Performance	0.142	0.141	0.061	2,341	0.020

Table 14. Indirect Influence on the Social Forestry Performance Model

Exogenous Variable	Endogenous Variable	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (O/ STDEV)	P Values
Farmer Participation	Social Forestry Performance	0.090	0.091	0.028	3,251	0.001
Government Role	Social Forestry Performance	0.039	0.038	0.023	1,712	0.088
Role of Facilitator	Social Forestry Performance	0.081	0.084	0.029	2,749	0.006

Table 15. Results of Bootstrapping Research on Social Forestry Performance Models in Soppeng Regency

	t-statistics (O/ STDEV)	p-value	Remark
Farmer Group Performance -> Social Forestry Performance	6,042	0,000	Important
Farmer Participation -> Farmer Group Performance	3,783	0,000	Important
Farmer Participation -> Social Forestry Performance	5,192	0,000	Important
Government Role -> Farmer Group Performance	1,766	0.078	Not significant
Government Role -> Social Forestry Performance	3,588	0,000	Important
Role of Facilitator -> Farmer Group Performance	3,346	0.001	Important
Role of Facilitator-> Social Forestry Performance	3,695	0,000	Important

The farmer participation variable influences social forestry performance through the farmer group performance variable, t-statistic value > t-table ($3.251 > 1.96$), and p-value of 0.001. The government role variable does not affect social forestry performance through the performance

of farmer groups (t-statistic value of 1.712), and a p-value of 0.088. The companion role variable has an indirect effect on social forestry performance through the farmer group performance variable, with a t-statistic of 2.749 and a p-value of 0.006.

B. Discussion

1. The Direct Effect of Farmer Participation Variables, The Role of Facilitators, The Role of Government on The Performance of Farmer Groups

Based on the research results, farmer participation has a significant direct effect on the performance of farmer groups. Farmer participation is more dominant in the implementation of SF activities from the beginning of submitting permit applications to the issuance of management permit decisions, preparing administrative files and documentation, participating in training, socialization and counseling, attending regular meetings, and managing cultivated land. Farmer participation in the implementation process is more in the form of services/labor, especially in managing land. The provision of seed assistance or assistance for productive economic tools provided by the government is a special attraction for farmers because this assistance belongs to farmers or becomes a group asset, thereby reducing the burden of production costs. Farmer participation in monitoring and evaluating activities is dominated by farmer group administrators who actively convey criticism, suggestions, and solutions; while other farmer group members follow farmers who are more knowledgeable and experienced.

One of the obligations for social forestry permit holders is to arrange the boundaries of the work area. Most of the permit holder groups in Soppeng Regency do not arrange the boundaries of the work area; they only understand and know the outer boundaries of the permits they obtain. Among the 18 permit holder groups, only farmer group Cempalagie has carried out a simple boundary arrangement carried out through participatory means by some group members and assisted by assistants and related agencies. The lack of funds and knowledge in mapping has caused the 17 other farmer groups to be unable to fulfill their obligations in accordance with the rules set by the government. Low levels of

education, lack of experience, and inadequate information available at the location can be overcome through socialization (Banuwa, 2018; Puspitasari et al., 2019; Rahman, 2021; Zulkifli et al., 2020). Before social forestry is implemented, widespread socialization is necessary. In addition, training is needed as an effort to increase knowledge and skills so that there is a change in the behaviour of permit holders (Marliyana, 2020; Supriyanto et al., 2021; Susilo & Nairobi, 2019). The training system implemented should use treatment that touches on the perception, self-concept, and values of the individual (Wijaya et al., 2020). In addition to requiring a long process, changing productive behaviour also requires reinforcement, repetition, and coaching (Solichin, 2006). Thus, it is hoped that farmers will have a higher spirit in managing their farming businesses, understand work situations, and be able to use new skills appropriately, and have a great attitude of confidence in solving problems related to their farming businesses (Djuku et al., 2021).

The role of facilitators for farmers holding social forestry management permits is needed in the research location because the community not only manages the land conventionally but also has to become social forestry entrepreneurs (Lawasi, 2022). Through support for assistance and facilitation from the government and business actors, the community can learn to independently manage social forestry land, starting from planning, developing potential biological resources, implementing business activities, protecting and securing forest ecosystems, and even monitoring and evaluation. Well-managed land will provide optimal benefits to the community, especially in improving welfare (Alivia et al., 2022).

The role of government does not have a significant effect on the performance of farmer groups. In the social forestry program, the role of government is realized through policies, regulations, and provision of resources such as funds or infrastructure. However, implementation in the field generally involves

facilitators as liaisons between the government and farmer groups. Because facilitators act as intermediaries, government support is not directly felt by farmer groups, but rather through facilitators who function as intermediaries. Facilitators interact directly with farmers in the field. Meanwhile, government policies or roles are only felt after being implemented by facilitators. This is in line with the results of this study that the performance of farmer groups is directly affected by the role of facilitators.

The government's bias is evident in the empowerment process, which has offered social forestry farmer groups access to productive economic tools and facilitators. However, not all facilitators met the specific needs of the groups. (Taroniarta & Yahya, 2022). The assistance provided by the government is not being utilized effectively, which negatively impacts farmer productivity. Since the issuance of the social forestry permit, there have been issues with the support provided. Some of the equipment given as assistance has been improper for their needs, rendering it inefficient and ineffective for use (Sami, 2020).

Government assistance provided in the form of mulberry seedlings for silkworm cultivation has not been successful in some locations due to unsuitable soil conditions. Therefore, government assistance programs should be better aligned with land suitability while taking ecological, economic, and social considerations into account (Najmi et al., 2019). Additionally, factors such as temperature, rainfall, altitude, and soil type must also be taken into account, as these are natural limitations that cannot be altered (Supriyanto et al., 2021).

For agricultural production, there are certain tools and equipment that cannot be utilized due to limitations in their power requirements. Many of these tools require a large electrical capacity that is not available to farmers in rural areas. Therefore, members of the farmer group need access to production tools that utilize appropriate technology, rather than those that

demand high electrical power and capacity.

Government policies are not always aligned with local needs and field conditions. As a result, farmer groups do not directly benefit from these policies because their implementation is sometimes not relevant to the local context. Therefore, the government needs to conduct consistent monitoring and evaluation of the assistance provided to social forestry permit holders to ensure that policies are implemented effectively and achieve the intended outcomes. The monitoring and evaluation mechanism for the policy does not work well, so problems in policy implementation are not immediately detected and corrected. As a result, the policy does not have a significant impact.

The effect between the performance of social forestry permit holder groups through area management, institutional management and business management with farmer participation, the role of facilitator and the role of the government is relatively low, lack of knowledge of permit holder farmers, limited assistance and minimal mapping costs from the government in arranging work area boundaries are obstacles (Harnadi, 2019), out of 18 permit holder groups only one group has arranged the outer boundaries of the work area.

The government needs to continue to encourage and provide fiscal instruments in the form of assistance and economic incentives to improve access to information, skills, appropriate technology, assistance, training and product development, post-harvest handling, commodity and product marketing, increase productivity and added value, obtain an efficient market chain, equalize product benefits, and obtain more benefits. In providing assistance, the government must also evaluate the needs of farmers and land that will be used as the location for recipients of assistance in order to determine its potential and characteristics so that the assistance program with the assistance items provided is appropriate (Shaleh et al., 2019).

2. Indirect Effect of Farmer Participation Variables, Role of Assistants, Role of Government on Farmer Group Performance

The effect of farmer group performance variables significantly mediates farmer participation and the role of assistants on social forestry performance, although the effect is low. This finding shows that to improve social forestry performance, one thing that must be done is to improve farmer group performance first through farmer participation and the role of assistants. This is in line with research (Istiqomah et al., 2021; Oktoyoki et al., 2023; Sami, 2020; Veriasa et al., 2023).

Farmer participation, the role of facilitators, and the role of the government have a low effect on the performance of social forestry through the performance of farmer groups in the prerequisite aspect; each group shows the availability of documents in the form of legality, both permit holder decrees and maps and planning documents. The main factor that encourages people to become social forestry permit holders is a sense of security in utilizing the forest, so that social forestry is considered a conflict resolution both with government officials and fellow farmer groups (Krisnantoro, 2019). Because legally the status of the land belongs to the state, but the community has the assumption that the land belongs to individuals and groups because they are considered to have maintained it, so that the forests they manage are maintained (Fitria et al., 2021).

The habit of farmers managing land using traditional and non-intensive methods, where the land is not cultivated optimally, only oriented to meet daily needs, so that the income of group members is still minimal, including contributing income to the wider community. The main factor that affects the level of farmer income is the high intensity of farmers in managing their crops and farmers who have large areas of land, not all of which can be cultivated due to limited labor (Mutaqin et al., 2022; Supriyanto et al., 2021).

3. Efforts to Improve Social Forestry Performance

The low performance of social forestry requires intervention and focus on factors that are more dominant in determining the success and failure of social forestry. This includes the main steps that can be taken as a result of the structural model proposed in this study (Figure 6). This will be able to provide a better solution because it can add to the explanation that the performance of farmer groups is absolutely necessary to achieve PS performance.

a) Improving knowledge, skills, independent attitudes and entrepreneurial abilities

The purpose of social forestry is to increase community capacity; failure to understand the social forestry program will reduce community participation (Pambudi, 2020), so that the benefits are not only felt by the group but also at the member level (Kaskoro, 2017). The social forestry permit holder group in Soppeng Regency knows about the social forestry program, and they are motivated to participate in it, but their knowledge is inadequate. Although knowledge and motivation are not the main factors (Adzkiya et al., 2023), the independent attitude and entrepreneurial skills of farmers are very important in participation efforts (Fauzan & Pradana, 2023; Indraningsih & Swastika, 2022; Mukti & Kusumo, 2021; Sa'diyah & Soetarto, 2021). Therefore, educating farmers to be independent and entrepreneurial is an important factor in increasing the success of social forestry (Nona & Sagajoka, 2021; Raharjo et al., 2020).

b) Encourage active involvement of farmers in production

Farmers in Soppeng Regency have historically faced challenges in managing their production results, which hampers their ability to enhance community productivity. Many farmers focus on processing semi-finished goods primarily for their household needs, with only a portion being sold to purchase items they are unable to produce themselves. This observation aligns with the findings of Fitri

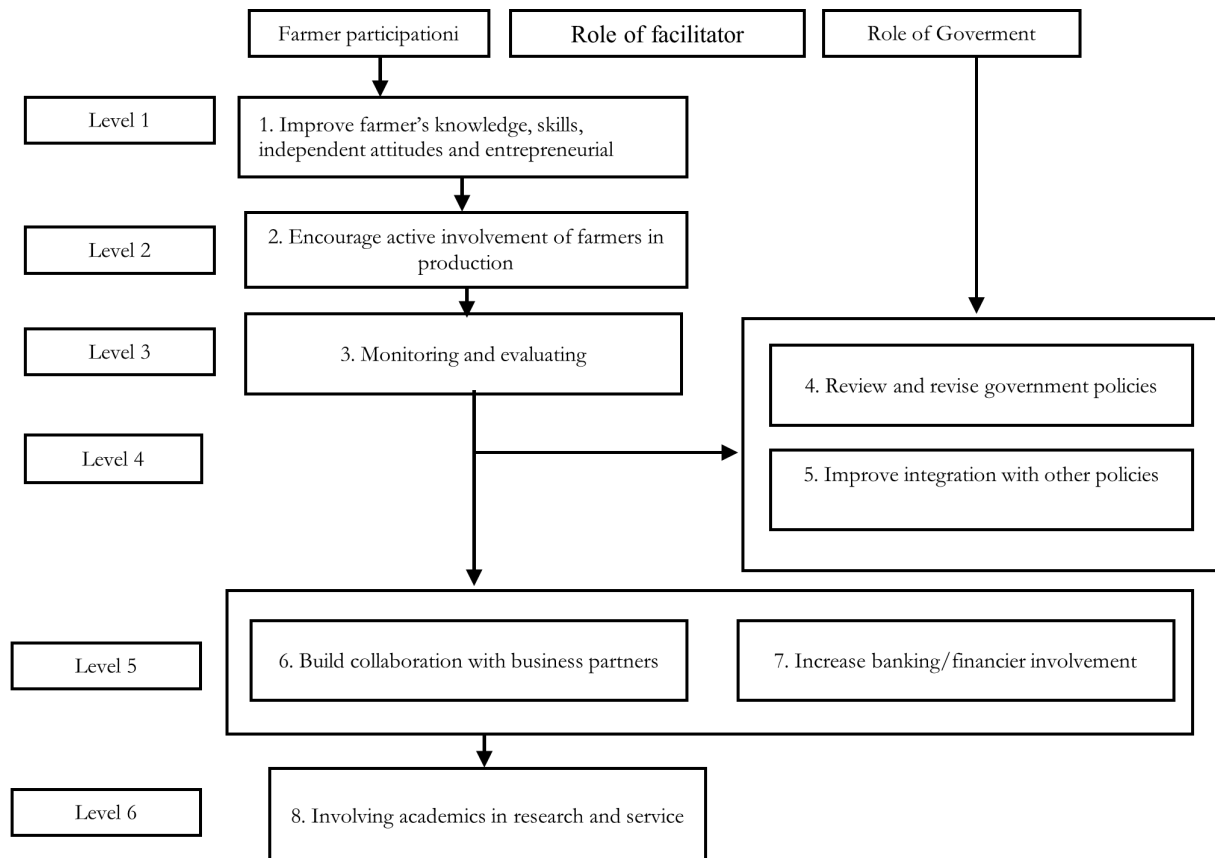


Figure 6. Efforts to Improve Social Forestry Performance in Soppeng Regency

et al. (2019), who stated that the amount of farmer income is only enough to meet daily needs. Therefore, changes in farmer behavior in producing public goods can provide new experiences and can improve production skills.

Production experience is very important to increase farmers' income, because it can affect farmers' motivation, attitude, and participation in social forestry management. The main issue is, what is the quality of the products produced by farmers (Hastanti, 2021) and how to maintain business sustainability (Manalu et al., 2022), and increase the farmer experience to produce public goods, not only oriented towards meeting production or food needs but also must improve people's standard of living (Wanimbo, 2019).

c) Monitoring and evaluation of activities

The government monitors and evaluates SF activities periodically to assess the effectiveness

of the assistance provided and make adjustments if necessary. Involving farmers in providing feedback on the assistance received can help the government improve assistance in the future.

d) Reviews and revisions of government policies

The implementation of social forestry regulations has not been optimally carried out; the obligation of farmer groups as holders of social forestry permits to arrange the boundaries of the work area and create boundary blocks cannot be carried out by permit holders. This is due to the limitations of farmer groups in using modern technology in mapping or geographic information systems in planning forest management, so that policy changes need to be made to periodically review and revise social forestry policies based on the results of monitoring and evaluation.

e) Improve integration with other policies

Lack of coordination between government agencies in Soppeng Regency has caused social forestry to run separately from rural development policies. Integration of policies with local governments and village governments will maximize local community economic empowerment and sustainable forest management.

f) Building collaboration with business partners

The group of social forestry permit holders is expected to be able to cooperate with retail companies, supermarkets, organic or environmentally friendly food retailers, food producers that produce processed non-timber forest products, pharmaceutical and cosmetic companies, and cooperatives. These parties can develop and enhance market production results using attractive packaging technology, selling products at prices affordable to the community, promoting with online brochures containing the uniqueness, and advertising the advantages and benefits of the products. These partners are expected to be able to build networks and carry out partnerships according to their respective roles (Kamaluddin & Tamrin, 2019). The lack of business partners for the farmer groups results in limited development of group businesses; therefore, cooperation with partners needs to be built. This will increase the types of group businesses so that it will have an impact on increasing work and business opportunities that can improve farmer welfare.

g) Increasing banking/financier involvement

License holders in Soppeng Regency have permits to manage forests as cultivated land; however, they face a lack of capital. This shortage of funding is a significant factor contributing to low forest yields (Sari, 2019). Therefore, it is essential to implement effective financial capital management in collaboration with third parties, specifically banks, to provide additional funding through smallholder business credit (Puspitasari et al., 2019).

h) Involving academics to play an active role in research and community service

Since the finding of *Rafflesia* sp. in the Anambas Islands from 2014 to 2025, there has not been a single form of scientific report. The involvement of academics in the development of social forestry is greatly needed by social forestry permit holders in Soppeng Regency. Research and community service provide knowledge and insight as well as improve the capacity of human resources (Wulandari et al., 2022), with policy-independent learning, an independent campus provides opportunities for students to assist farmer groups and provide solutions to problems faced by farmers so as to create independent farmer groups in the village (Yanuarsari et al., 2021).

IV. CONCLUSION

There is a significant effect between the farmer participation variable (0.259) and the role facilitator variable (0.234) on the performance of farmer groups, the government role variable does not have a direct effect on the performance of SF farmer groups, the government should conduct regular monitor and evaluate activities periodically to assess the effectiveness of SF implementation and make policy changes by reviewing and revising social forestry policies based on the results of monitoring and evaluation.

There is a significant effect between the farmer participation variable (0.241), the role of facilitator (0.142), the government role variable (0.168), and the performance of farmer groups (0.347) on social forestry performance. The performance of farmer groups contributes to mediating the relationship between farmer participation, the role of facilitators, and the role of government with social forestry performance. The predictive relevance of farmer group performance value (0.122) suggests that it is relatively small, whereas the predictive relevance of social forestry performance (0.244) indicates a moderate level of relevance. Although farmer group

performance significantly influences social forestry performance, its overall explanatory power within the model remains limited.

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REFERENCES

- Adzkiya, M. A. Z., Renanti, M. D., & Trison, S. (2023). Edukasi Dan Eksplorasi Pengolahan Kopi Di Perhutanan Sosial Desa Jambewangi, Kabupaten Banyuwangi. *Jurnal Abdi Insani*, 10(1), 212–223. <https://doi.org/10.29303/abdiinsani.v10i1.881>
- Alivia, E. T., Ati, N. U., & Abidin, A. Z. (2022). Implementasi Kelompok Usaha Perhutanan Sosial (KUPS) dalam Mengembangkan Wisata Siti Sundari (Studi Kasus Di Desa Burno Kecamatan Senduro Kabupaten Lumajang). *Respon Publik*, 16(9), 20–31.
- Banuwa, I. S. (2018). Strategi Implementasi Kebijakan Hutan Tanaman Rakyat Di Kph Gedong Wani. *Sosiohumaniora*, 20(1), 29–38.
- Boang Manalu, A. G., Subono, N. I., & Putri, R. D. D. G. S. (2022). Partisipasi Perempuan dalam Perhutanan Sosial: Studi Kasus di Lima Provinsi. *Jurnal Perempuan*, 27(1), 85–99. <https://doi.org/10.34309/jp.v27i1.666>
- Damanhuri, Y. A. (2021). Pemenuhan Hak Konstitusional untuk Warga Negara Indonesia melalui Program Perhutanan Sosial. *Dharmasiasya*, 1(3), 1655–1668.
- Djuku, S. U., Makaborang, Y., & Taranau, O. K. (2021). Jurnal Penelitian Kehutanan Bonita. *Jurnal Penelitian Kehutanan Bonita*, 4(2), 20–29.
- Fatarin Lukito, A., Padmaningrum, D., Studi Penyuluhan dan Komunikasi Pertanian, P., & Pertanian, F. (2023). *Partisipasi Petani Dalam Program Perhutanan Sosial Di Kecamatan Kemusu Kabupaten Boyolali*. 4(5), 32–46.
- Fauzan, N. A., & Pradana, A. (2023). Eksplorasi Kewenangan Pemerintah Desa Kulo Kabupaten Sidrap Di Bidang Pertanian : Peluang Dan Tantangan. *Jurnal Sulatan Riset Hukum Tata Negara*, 2(1), 1–14.
- Firdaus, R. (2020). Peran Pemerintah Daerah Sebagai Regulator, Dinamisator, Fasilitator, Dan Katalisator Dalam Pemberdayaan Petani Kakao Di Kabupaten Luwu Utara. *Jurnal Publik Administrasi*, 3(1), 32–40.
- Fitria, W., Suharjito, D., & Ekawati, S. (2020). Peran Kesatuan Pengelolaan Hutan (KPH) dalam Implementasi Perhutanan Sosial (Studi di KPH Produksi Kerinci, Provinsi Jambi dan KPH Lindung Sijunjung, Provinsi Sumatera Barat). *Jurnal Analisis Kebijakan Kehutanan*, 18(2), 145–160. <https://doi.org/10.20886/jakk.2021.18.2.145-160>
- Fitriani, Y., Aryadi, M., & Naparin, M. (2019). Kontribusi Sistem Agroforestry Terhadap Pendapatan Petani Hutan Kemasyarakatan (HKM) Suka Maju di Desa Tebing Siring Kabupaten Tanah Laut Contribution Of Agroforestry Systems Toward Revenue Of Community Forest Farmers Suka Maju in Tebing Siring Village. *Jurnal SYha Scienceae*, 02(5), 901–909.
- Harahap, M., Siregar, G., & Riza, F. V. (2021). Mapping the potential of village agricultural social economic improvement efforts in lubuk kertang village Kecamatan Berandan Barat Kabupaten Langkat. *Journal of Agribusiness Sciences*, 4(1), 8–14.
- Hardhiyanti, R. (2022). Pendampingan Kemitraan Pada UMK Kelompok Tani Hutan (KTH) Sadar Tani Muda Produk Madu. *ALMUJTAMAE: Jurnal Pengabdian Masyarakat*, 2(2), 139–142. <https://doi.org/10.30997/almujtamae.v2i2.5420>
- Harimbawan, P. H., Surata, I. N., & Ardana, P. S. (2022). (2022). Penegakan Hukum Pidana Kehutanan pada Kawasan Perhutanan Sosial (Studi pada Unit Pelaksana Teknis Daerah Kesatuan Pengelolaan Hutan Bali Barat). *Kertha Widya Jurnal Hukum*, 10(1), 156–183. <https://doi.org/10.36636/jogiv.v3i2.822>
- Harnadi, K. (2019). Model Penguasaan Tanah oleh Masyarakat Desa Margosari dan Penyelesaiannya pada Kawasan Hutan Lindung Register 22 Way Waya Kabupaten Pringsewu. *Cepalo*, 2(2), 85. <https://doi.org/10.25041/cepalo.v2no2.1765>
- Herrawan, H., Sirimorok, N., Nursaputra, M., Mas'ud, E. I., Faturachmat, F., Sadapotto, A., ... & Sahide, M. A. K. (2022). Commoning the state forest: Crafting commons through an

- Indonesian social forestry program. *Forest and Society*, 6(1), 20-39.
- Hermin, S. L., Sahide, M. A. K., & Supratman. (2021, June). The bureaucratic politics in developing Forest Management Unit (FMU) after the forestry decentralization in South Sulawesi province. In *IOP Conference Series: Earth and Environmental Science* (Vol. 788, No. 1, p. 012178). IOP Publishing.
- Indraningsih, K. S., & Swastika, D. K. S. (2022). Akselerasi Pembangunan Pertanian Wilayah Tertinggal melalui Penguatan Kapasitas Petani dan Kelompok Tani Acceleration of Agricultural Development in Disadvantaged Regions Through Strengthening the Capacity of Farmers and Farmers Groups. *Forum Penelitian Agro Ekonomi*, 39(2), 147–164.
- Istiqomah, Udiansyah, & Hamdani Fauzi. (2021). Kinerja Kelembagaan Kelompok Tani Hutan Pemegang Izin Perhutanan Sosial di Wilayah Kelola Kesatuan Pengelolaan Hutan Kayutangi The Institutional Performance of Forest Farmer Groups Holding Social Forestry Permits in the Management Area of the Kayutangi Fo. *Jurnal Sylva Scientee*, 04(3), 440–451.
- Jossy, M. ;, & Moeis, P. (2022). Dampak program perhutanan sosial terhadap pertumbuhan usaha dan deforestasi: bukti empiris dari Indonesia (Vol. 11, Issue 1).
- Kamaluddin, A. K., & Tamrin, M. (2019). Pemberdayaan Masyarakat Berbasis Potensi Lokal Melalui Skema Perhutanan Sosial Di Area Kph Ternate – Tidore. *Techno: Jurnal Penelitian*, 8(2), 308. <https://doi.org/10.33387/tk.v8i2.1350>
- Kaskoro, H. (2017). Impact of community forest program in protection forest on livelihood outcomes : A case study of Lampung Province, Indonesia. *Journal of Sustainable Forestry*, 36(3), 250–263. <https://doi.org/https://doi.org/10.1080/10549811.2017.1296774>
- Krisnantoro, D. (2019). Penyelesaian Permasalahan Klaim Sengketa Tanah Eigendom Verponding Melalui Hukum Konflik Agraria. AKSELERASI: *Jurnal Ilmiah Nasional*, 1(3), 9–24. <https://doi.org/10.54783/jin.v1i3.539>
- Laksemi, N. P. S. T., Sulistyawati, E., & . M. (2019). Sustainable Social Forestry in Bali (A Case Study at Hutan Desa Wanagiri). *Jurnal Sylva Lestari*, 7(2), 150. <https://doi.org/10.23960/jsl27150-163>
- Lawasi, M. A. (2022). Sebagai Formula Kebijakan Pemberdayaan Masyarakat Dalam Program Perhutanan Sosial Constructing Access , Assistance , and Innovation As a Community Empowerment Policy Formula in the Social. *JLANA: Jurnal Ilmu Administrasi Negara, Volume 20, Nomor 3 Desember 2022: 50-65 e-ISSN: 2714-55881 | p-ISSN: 1411-948X, 20, 51–65.*
- Mahardika, A., Muyani, H. S., Ilmu, J., Publik, A., Ilmu, F., Dan, S., Politik, I., Muhammadiyah, U., & Utara, S. (2021). Analisis Legalitas Perhutanan Sosial Dalam Meningkatkan Kesejahteraan Masyarakat Di Kabupaten Asahan. *Jurnal Administrasi Publik Dan Kebijakan (JAPK)*, 1(1), 1–9. <https://doi.org/10.30596/japk.v1i1.6484>
- Marasabessy, H. (2018). Kearifan Lokal Dalam Pengelolaan Hutan (Studi Kasus Kelembagaan Sasi Hutan Di Desa Kailolo Kecamatan Pulau Haruku Kabupaten Maluku Tengah). *Jurnal Hutan Pulau-Pulau Kecil*, 2(1), 49–69. <https://doi.org/10.30598/jhpk.2018.2.1.49>
- Marliyana, T. (2020). Pengorganisasian Kelompok Tani Dalam Memperjuangkan Perhutanan Sosial (Studi Kasus Pengorganisasian Stam Di Desa Mentasan, Kecamatan Kawunganten, Kabupaten Cilacap). *Jurnal Analisa Sosiologi*, 9, 376–395. <https://doi.org/10.20961/jas.v9i0.41369>
- Moeliono, M., Sahide, M. A. K., Bong, I. W., & Dwisatrio, B. (2023). Social forestry in Indonesia: Fragmented values, progress, contradictions, and opportunities. In *Social value, climate change and environmental stewardship: Insights from theory and practice* (pp. 117-138). Cham: Springer International Publishing.
- Muhaemin Shaleh, S., Insan Noor, T., Sulistyowati, L., & Setiawan, I. (n.d.). Efektivitas Bantuan Pemerintah (Suatu Kasus Program Upaya Khusus Pajale Penyediaan Sarana Kedelasi Desa Jatiwaras Kecamatan Jatiwaras Kabupaten Tasikmalaya, Jawa Barat).
- Mukti, G. W., & Kusumo, R. A. B. (2021). Pertanian Berkelanjutan : Sebuah Upaya untuk Memadukan Pengetahuan Formal dan Informal Petani (Kasus pada Petani Hortikultura di Provinsi Jawa Barat). *Jurnal*

- Pemikiran Masyarakat Ilmiah Berwawasan Agribisnis*, 7(2), 1141. <https://doi.org/10.25157/ma.v7i2.5135>
- Mulyani, S., Prakoso, T., Winarso, R., & Saputro, H. (2023). *Inisiasi Pembentukan Kelompok Usaha Perhutanan Sosial Menuju Desa Mandiri Ekonomi*. 14(3), 624–630.
- Mutaqin, D. J., Wahyuni, I., & Rahayu, N. H. (2022). Analisis Kegiatan Perhutanan Sosial dalam Peningkatan Kualitas Lingkungan dan Peningkatan Ekonomi Masyarakat Pasca Pandemi Covid-19. *Bappenas Working Papers*, 5(2), 159–175. <https://doi.org/10.47266/bwp.v5i2.135>
- Najmi, N. L., Al Jaktas, A. J., Suharno, S., & Fariyanti, A. (2019). Status Keberlanjutan Pengelolaan Perkebunan Inti Rakyat Kelapa Sawit Berkelanjutan Di Trumon, Kabupaten Aceh Selatan. *Forum Agribisnis*, 9(1), 53–68. <https://doi.org/10.29244/fagb.9.1.53-68>
- Nandini, R., Putri, B. G. R., Setiawan, S. N., Anggraeni, F., & Fedryansyah, M. (2022). Peran Pendamping Program Keluarga Harapan (Pkh) Dalam Upaya Resolusi Konflik Sosial Di Desa Genteng Kecamatan Sukasari, Kabupaten Sumedang. *Jurnal Kolaborasi Resolusi Konflik*, 4(1), 74. <https://doi.org/10.24198/jkrk.v4i1.38294>
- Nita Andelia Mandasari, M. (2016). Pengaruh Persepsi Dan Motivasi Terhadap Partisipasi Masyarakat Desa Hutan Dalam Pengelolaan Hutan Bersama Masyarakat (Phbm) Di Kawasan Bkph Guwo. *Journal of Public Policy and Management Review*, 5(4), 313–329.
- Nona, R. V., & Sagajoka, E. (2021). Peran Penyuluhan Pertanian Dalam Membentuk Perilaku Petani Di Kabupaten Ende. *Jurnal Ilmiah Ekonomi*, 11(2), 210–225. <https://doi.org/10.37478/als.v11i2.973>
- Oding Affandi, Hariadi Kartodihardjo, Bramasto Nugroho, S. E. (2019). Analisis Kelembagaan Implementasi Perhutanan Sosial di Provinsi Sumatera Utara. *Inovasi*, 16(2), 75–162. <https://doi.org/https://doi.org/10.33626/inovasi.v16i2.146>
- Oktoyoki, H., Pratama, B., Safnizar, S., & Himawan, R. (2023). Performansi Kelompok Tani Hutan (Kth) Dalam Pengelolaan Hutan Kemasyarakatan: Dimensi Kelola Kelembagaan, Kawasan, Dan Usaha. *Jurnal Hutan Pulau-Pulau Kecil*, 7(2), 210–220. <https://doi.org/10.30598/jhppk.v7i2.10824>
- Pambudi, A. S. (2020). The Development of Social Forestry in Indonesia: *The Journal of Indonesia Sustainable Development Planning*, 1(1), 57–66. <https://doi.org/10.46456/jisdep.v1i1.11>
- Pemerintah Republik Indonesia. (2021). *Peraturan Menteri Lingkungan Hidup dan Kehutanan Republik Indonesia Nomor 9 Tahun 2021 Tentang Pengelolaan Perhutanan Sosial* (pp. 1–268).
- Permenhut. (2018). Peraturan Menteri Lingkungan Hidup dan Kehutanan Republik Indonesia Nomor 89 Tahun 2018 Tentang Pedoman Kelompok Tani.
- Puspitasari, S. A., Saragih, H. J. R., & Navalino, R. D. A. (2019). Perhutanan Sosial alam Mendukung Pemberdayaan Masyarakat dari Perspektif Ekonomi Pertahanan (Studi Pada Desa Pantai Bakti Kecamatan Muara Gembong Kabupaten Bekasi). *Jurnal Ekonomi Pertahanan*, 5(1), 121–142. <http://jurnalprodi.idu.ac.id/index.php/EP/article/view/551>
- Quinn, J. . (2013). Teori Prinsipal Agen dalam Ilmu Politik. In *Prenada Media Group: Vol. 16*. <https://doi.org/10.24853/baskara.2.2.93-106>
- Raharjo, S. A. S., Hastanti, B. W., & Haryanti, N. (2020). Dinamika Kelembagaan Perhutanan Sosial di Wilayah Pehutani: Studi Kasus di KPH Telawa, Jawa Tengah. *Politika: Jurnal Ilmu Politik*, 11(2), 183–197. <https://doi.org/10.14710/politika.11.2.2020.183-197>
- Rahayu, S., Sakuntaladewi, N., Sumirat, B. K., Widyaningsih, T. S., Yusnikusumah, T. R., Muin, N., & Bisjoe, A. R. H. (2024). The role of local governments in supporting social forestry implementation in Indonesia: A social network analysis and evidence from Eastern Indonesia. *Forest and Society*, 8(1), 154–178.
- Rahman. (2021). Pendampingan Program Perhutanan Sosial Masyarakat Desa Hutan Burno Kabupaten Lumajang Menuju Pembangunan Berkelanjutan Indonesia 2030. *Islamic Management*, 3(2), 116. <https://doi.org/10.18326/imej.v3i1.115-132>
- Reed et al., 2009. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, 90(5), 1933–

1949. <https://doi.org/http://dx.doi.org/10.1016/j.jenvman.2009.01.001>
Schlager,
- Rochmayanto, Y., Frianto, D., & Nurrohmah, E. (2006). Analisis Partisipasi Pada Program Hutan Kemasyarakatan (Studi Kasus Di Koto Panjang, Riau). *Jurnal Penelitian Sosial Dan Ekonomi Kehutanan*, 3(3), 175–189. <https://doi.org/10.20886/jpsek.2006.3.3.175-189>
- Rumampuk, M., Tulus, F. M. G., & Kolondam, H. F. (2021). Kemampuan kerja fasilitator dalam pendampingan masyarakat di Desa Ranoketang Tua Kecamatan Amurang Kabupaten Minahasa Selatan. *JAP: Jurnal Administrasi Publik*, 7(110), 70–78.
- Sa'diyah, M., & Soetarto, E. (2021). Respon Masyarakat Desa Hutan Pasca Penetapan Forest Countryside Community Response After the Establishment of Social Forestry (Case: Kawasan Pengakuan dan Perlindungan Kemitraan Kehutanan (Kulin KK) in Harumansari Village, Kadungora Regency, Garut Distr. *Jurnal Sains Komunikasi Dan Pengembangan Masyarakat* |, 05(02), 220. <https://doi.org/10.29244/jskpm.v5i2.705>
- Salaka, F., Alviya, I., Y Suryandari, E., Nurfatriani, F., & Zahrul Muttaqin, M. (2020). the Effectiveness of Local Institutional Arrangement for Community Plantation Forest. *Jurnal Analisis Kebijakan Kehutanan*, 17(1), 75–92. <https://doi.org/10.20886/jakk.2020.17.1.75-92>
- Salim, M. N., Pinuji, S., & Utami, W. (2018). Reforma Agraria Di Kawasan Hutan Sungaitohor, Riau: Pengelolaan Perhutanan Sosial Di Wilayah Perbatasan. *BHUMI: Jurnal Agraria Dan Pertanahan VO* - 4, 4(2), 164.
- Sami, R. G. (2020). Implikasi Peraturan Menteri Lingkungan Hidup Nomor 83 Tahun 2016 Tentang Perhutanan Sosial Terhadap Swadaya Ekonomi *UNES Journal of Swara Justisia*, 4(2), 121–138. <http://swarajustisia.unespadaang.ac.id/index.php/UJSJ/article/view/158%0Ahttp://swarajustisia.unespadaang.ac.id/index.php/UJSJ/article/download/158/164>
- Shaleh, S. M., Noor, T. I., Sulistyowati, L., & Setiawan, I. (2019). Efektivitas Bantuan Pemerintah (Suatu Kasus Program Upaya Khusus Pajale Penyediaan Sarana Kedelai Desa Jatiwaras, Kecamatan Jatiwaras, Kabupaten Tasikmalaya, Jawa Barat). *Jurnal Agribisnis Terpadu*, 1(1), 262–277.
- Solichin, M. M. (2006). Belajar Dan Mengajar Dalam Pandangan Al-Ghazali. *Tadris*, 1(2), 138–153.
- Suhartini. (2009). Kajian Kearifan Lokal Masyarakat dalam Pengelolaan SDA dan lingkungan. *Seminar Nasional Penelitian, Pendidikan Dan Penerapan MIPA*, 206–218.
- Sumanto, S. E. (2009). Kebijakan pengembangan perhutanan sosial dalam perspektif resolusi konflik. *Jurnal Analisis Kebijakan Kehutanan*, 6(1), 13–25.
- Supriyanto, H., Sudarmo, S., & Setyowati, K. (2021). Implementation of Social Forestry in Perum Perhutani Kph Telawa. *Jurnal Analisis Kebijakan Kehutanan*, 18(1), 31–43. <https://doi.org/10.20886/jakk.2021.18.1.31-43>
- Susilo, S. Y., & Nairobi. (2019). Dampak Perhutanan Sosial Terhadap Pendapatan Masyarakat. *ISEI Economic Review*, III(1), 16–27. <http://jurnal.iseibandung.or.id/index.php/ier>
- Syafii, K. I. (2002). *Sistem Pemerintahan Indonesia*. Rineka Cipta.
- Syahputra, O. H. (2021). Masa Depan Kedaulatan Pangan: Dukungan Agroforestri dalam Produksi Pangan Melalui Perhutanan Sosial. *Prosiding Seminar Nasional Pertanian*, 6, 255–266. <https://ejurnalunsam.id/index.php/psn/article/view/4824>
- Syairozi, M., Rosyad, S., & Pambudy, A. P. (2019). Pemberdayaan Masyarakat Sebagai Pengguna Kosmetik Alami Beribu Khasiat Hasil Produk Tani Untuk Meminimalkan Pengeluaran Masyarakat Desa Wonorejo Kecamatan Glagah Kab. Lamongan. *Empowering: Jurnal Pengabdian Masyarakat*, 3(August 2019), 88. <https://doi.org/10.32528/emp.v3i0.2271>
- Taroniarta, S., & Yahya, N. H. (2022). Perempuan Pejuang Sutra di Kabupaten Wajo: Aktor Tunggal dan Tantangan Akses Program Perhutanan Sosial. *Jurnal Perempuan*, 27(1), 15–28. <https://doi.org/10.34309/jp.v27i1.650>
- Veriasa, T. O., Daxoko, B. T., Imron, N. A., & Santosa, A. (2023). Policy Brief: Memperbaiki Kinerja Perhutanan Sosial Menuju Keberlanjutan Hutan Jawa. *Pertanian, Kelautan, Dan Biosains Tropika*, 5(4).
- Wanimbo, E. (2019). Kehidupan Sosial Ekonomi Keluarga Petani dalam Meningkatkan Taraf Hidup (Studi di Desa Bapa Distrik Bogonuk Kabupaten Tolikara Propinsi Papua). *Journal of Social and Culture*, 12(3), 1–18.

- Wijaya, B., Fauzi, H., & Hafizianor, H. (2020). Kinerja Kelembagaan Kelompok Tani Hutan Kemasyarakatan Di Kabupaten Tanah Laut. **Jurnal Sylva Scientiae**, 3(1), 62–74.
- Wulandari, C., Bakri, S., Safe'i, R., Hilmanto, R., Pah, J. M., & Pangestu, P. (2022). Training for Strengthening the Human Resources Capacity Overcoming the Socio-Economic Impact on Social Forestry Farmers Due to the Covid-19 Pandemic at Pesawaran FMU, Lampung. *Repong Damar: Jurnal Pengabdian Kebutanan Dan Lingkungan*, 1(2), 136. <https://doi.org/10.23960/rdj.v1i2.6241>
- Yanuarsari, R., Asmadi, I., Muchtar, H. S., & Sulastini, R. (2021). Peran Program Merdeka Belajar Kampus Merdeka dalam Meningkatkan Kemandirian Desa. *Jurnal Basicedu*, 5(6), 6307–6317. <https://doi.org/10.31004/basicedu.v5i6.1828>
- Zulkarnain, A. A. (2021). Strategi Kebijakan Percepatan Perhutanan Sosial. *Journal of Governance Innovation*, 3(2).
- Zulkifli, A., Sari, F. M., & Prihati, P. (2020). Pendampingan Masyarakat Ekowisata Mangrove Sungai Bersejarah (MSB) Kayu Ara Permai Melalui Kebijakan Padat Karya di Masa Pandemi Covid-19. *Community Empowerment*, 6(1), 71–80. <https://doi.org/10.31603/ce.4395>

ENVIRONMENTAL MANAGEMENT STRATEGIES FOR ECONOMIC LOSSES DUE TO LANDSLIDES ON THE DIENG PLATEAU FOREST AREA

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ENVIRONMENTAL MANAGEMENT STRATEGIES FOR ECONOMIC LOSSES DUE TO LANDSLIDES ON THE DIENG PLATEAU FOREST AREA. The Dieng Plateau is an area known for its agricultural cultivation. However, excessive use of land for agriculture increases the potential for landslides that disrupt community activities. This research aims to determine the potential losses due to landslides on agricultural land and determine strategies for managing environmental damage due to landslides in the Dieng Plateau. Determination of sample locations was carried out using the purposive sampling method, while data collection used the accidental sampling method. Data analysis uses quantitative techniques and SWOT analysis is used to formulate environmental damage management strategies. The research results show that the greatest losses due to landslides occur during the harvest period. The observation location that has the greatest potential for loss is location 1 which is Dieng Kulon Village. As the years go by, the resulting losses will be greater. The appropriate environmental management strategy to implement is Planting of vegetation types that are beneficial for the environment, tourism and agriculture to improve environmental quality and improve community welfare, stricter monitoring of agricultural activities, and the formation of a disaster response team.

Keywords: Dieng, environment, economic losses, landslide, management strategies

STRATEGI MANAJEMEN LINGKUNGAN TERHADAP KERUGIAN EKONOMI AKIBAT BENCANA LONGSOR DI KAWASAN HUTAN DATARAN TINGGI DIENG. Dataran Tinggi Dieng merupakan salah satu kawasan yang dikenal dengan hasil budidaya pertanian. Akan tetapi pemanfaatan lahan untuk pertanian yang berlebihan meningkatkan potensi terjadinya bencana longsor yang mengganggu aktivitas masyarakat. Penelitian ini bertujuan untuk mengetahui potensi kerugian akibat bencana longsor pada lahan yang mengalami alih guna dan mengetahui strategi manajemen lingkungan akibat bencana longsor di Dataran Tinggi Dieng. Penentuan lokasi sampel dilakukan menggunakan metode purposive sampling, sementara pengumpulan data menggunakan metode accidental sampling. Analisis data menggunakan teknik kuantitatif dan analisis SWOT yang digunakan untuk merumuskan strategi manajemen lingkungan. Hasil penelitian menunjukkan bahwa kerugian terbesar akibat bencana longsor terjadi pada masa panen. Lokasi pengamatan yang memiliki potensi kerugian terbesar adalah lokasi pengamatan 1 yaitu Desa Dieng Kulon. Semakin bertambah tahun maka nilai kerugian yang dihasilkan akan semakin besar. Strategi manajemen lingkungan yang tepat dilakukan adalah pemanfaatan jenis-jenis vegetasi yang bermanfaat bagi lingkungan, wisata, dan pertanian untuk memperbaiki kualitas lingkungan dan meningkatkan kesejahteraan masyarakat, memantau aktivitas pertanian yang lebih ketat, serta membentuk tim tanggap bencana.

Kata kunci: Dieng, kerugian ekonomi, lingkungan, longsor, dan strategi pengelolaan

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I. INTRODUCTION

The Dieng Plateau is situated in two administrative regions: Wonosobo Regency and Banjarnegara Regency. It has an average elevation of 1,600 to 2,000 m above sea level, with daytime temperatures ranging from 15 to 20 °C and nighttime temperatures around 10 °C. The plateau is characterized by undulating to sloping topography. In Wonosobo Regency, the protected forest area spans approximately 4,598 ha, of which about 50 to 60% has been converted to agricultural land (Haty et al., 2021; Maya, 2022; Santosa, 2023; Wijaya et al., 2024). The Dieng Plateau is well known for its agricultural use due to its fertile soil and scenic landscape. However, excessive agricultural activities have a negative impact on the environment such as soil fertility loss, water pollution, deforestation, climate change, and pesticide pollution (Candan Demirkol, 2022; Rey-Romero et al., 2022; Waithaka, 2023). Forest encroachment by local communities for agriculture has disrupted the ecological balance of the region (Maesaroh & Suwarno, 2022). This will certainly have an impact on the balance of the ecosystem in the area. The forest area in the area is intended to protect the ecosystem from damage and potential natural disasters, because encroachment will eliminate the function of the forest as an ecosystem buffer.

The history of natural disasters caused by volcanoes and landslides in the Dieng area is still often found. Dieng, situated at an altitude of 2000–2500 m above sea level, is an active volcanic region, as evidenced by the continuous emission of sulfuric smoke from the Si Kidang crater (Rahayuningsih & Wati, 2023). The condition of the Dieng area which is vulnerable to disasters is still often found today. It was proven in previous research that the area prone to landslides with high potential reached 46.90% (Krisnandi et al., 2021). Whereas once the charm of the Dieng ecosystem was a protected forest. Land use then changed when residents' agricultural patterns switched to potato cultivation as a staple crop for Dieng farmers (Sahara et al., 2023).

Pradana et al. (2015) state that the Dieng Plateau has been dominated by potato farming. Mountainous areas with a slope of more than 40%, have been heavily exploited for potato plantation. Even more than 900 ha of protected forest in Wonosobo have been cleared (Swarnawati, 2018). Potato cultivation continues to increase every year. While this land-use change supports farmers' incomes, it significantly harms the environment. The area with a slope of more than 40% has been widely used for potato cultivation, resulting in the clearing of more than 900 ha of protected forest area (Santosa, 2022). Central Java potato production 2020 reached 269.476 thousand tons, 58% of which came from agriculture in Dieng (Badan Pusat Statistik Jawa Tengah, 2021). Besides potatoes, the most common vegetable crops grown by farmers as inter-crops are carrots (*Daucus carota*) and cabbage (*Brassica oleracea*) (Pujiwinarko et al., 2024). The dry land yield, in average per annum, tea 149.48 tons, coffee 689.00 tons, fruits 106,925 tons, varieties of cassava, peanuts, bean, and corn, 195,812, and varieties of vegetables including potatoes, 191,238 tons (Wahono & Puspitawati, 2021).

Tree species that are identical to productive plants that are usually planted in state forests managed by Perhutani, such as *Pinus merkusii* Jungh. & de Vriese, *Eucalyptus* sp., *Cupressus sempervirens* L. and *Schima wallichii* (DC.) Korth (Pujiwinarko et al., 2024). Potato farming is particularly vulnerable in the rainy season as potato plants wither quickly and are prone to landslides (Akmalia, 2022).

The utilization of forest areas as agricultural land certainly has a negative impact on the environment. For example, deforestation due to agricultural land expansion has occurred greatly in Vietnam, with a high proportion of forests being converted into agriculture, leading to a negative impact on the hydrologic regime in the large basin (Truong et al., 2022). Clear-cutting and other forestry practices inflict intense disturbances on forests, global warming, causing dramatic changes in the habitat available to support biodiversity, and

degradation of physical and rheological soil properties (Galindo et al., 2022; Lawrence & Vandecar, 2015; Tolimir et al., 2020; Wahyuni & Suranto, 2021). One of the impacts felt by the community is the frequent landslides on the Dieng Plateau that disrupt community activities. Massive agricultural activities accompanied by continuous tillage increase the potential for landslides due to land degradation. If landslides occur on the agricultural land itself, it will certainly cause greater losses than the income that the community earns from these activities.

Previous research indicates that the losses due to landslide events on agricultural land in Clapar Village, Banjarnegara, amount to 4 billion IDR (Mutia et al., 2018). Meanwhile, Retnowati (2014) reported that landslide occurrences on agricultural land in Kokap District, Special Region of Yogyakarta, resulted in estimated economic losses ranging from IDR 60,900,000.00 to IDR 220,460,000.00. Another study conducted by Dewangga (2018) on agricultural land in Girimulyo District, Kulonprogo, Yogyakarta, demonstrated that the potential economic losses incurred include: i) IDR 1,958,600 per hectare per year after the processing period, ii) IDR 2,288,700 per hectare per year after the planting period, iii) IDR 5,683,000 per hectare per year after the growing period, and iv) IDR 19,361,400 per hectare per year at the time of harvest. Predictions for economic losses in 2028 include: i) IDR 5,662,300 per hectare per year after the processing period, ii) IDR 6,616,600 per hectare per year after the planting period, iii) IDR 16,429,700 per hectare per year after the growth period, and iv) IDR 55,973,700 per hectare per year at the time of harvest.

Estimating economic losses from landslides in agricultural land located within or adjacent to protected forest zones is critical, as these areas exhibit higher environmental vulnerability and contribute significantly to disaster-induced degradation. Global landslide-related economic losses have risen sharply from approximately USD 50 billion annually in the 1980s to over

USD 200 billion in recent years, with the majority occurring in developing countries characterized by fragile infrastructure and weak disaster governance, causing both direct and indirect economic losses (Zhang et al., 2021; Marín-Rodríguez et al., 2024). Although numerous studies have focused on technical aspects such as susceptibility mapping and loss estimation (Elkhrachy et al., 2023; Shano et al., 2020; Zhao et al., 2023), most remain sectorally isolated and rarely integrate comprehensive environmental management frameworks. Estrella et al. (2016) and Renaud et al. (2016) emphasize that conventional engineering-based approaches often fail to deliver sustainable outcomes in mountain ecosystems because they neglect ecosystem functions and services. Consequently, systemic strategies rooted in Ecosystem-based Disaster Risk Reduction (Eco-DRR) and Adaptive Environmental Management—such as vegetative engineering, watershed restoration, and risk-informed land-use planning—are still underrepresented in landslide economic mitigation frameworks (Sneddon, 2022; Hossain et al., 2024).

This study adopts the Ecosystem-based Disaster Risk Reduction (Eco-DRR) framework (UNDRR, 2020; Sneddon, 2022) combined with Adaptive Environmental Management (Estrella et al., 2016; Renaud et al., 2016) as the core conceptual foundation. Eco-DRR explicitly recognizes healthy ecosystems (particularly forest and agroforestry systems) as cost-effective natural infrastructure that reduces landslide hazard, exposure, and vulnerability simultaneously, while adaptive management ensures continuous learning and adjustment of strategies in response to changing socio-ecological conditions. By integrating quantitative economic valuation, time-value-of-money projections, and SWOT-based strategy formulation within this dual framework, the research addresses the identified gap and provides a replicable model for highland tropical regions. Specifically, this study (1) quantifies current and future economic

losses due to landslides on the Dieng Plateau, (2) evaluates environmental damage linked to forest-to-agriculture conversion, and (3) formulates locally appropriate environmental management strategies to minimize long-term losses and enhance community resilience.

II. MATERIAL AND METHOD

A. Study Site

The research was conducted in the Dieng Plateau Protection Forest area which is located in two areas, namely Wonosobo Regency and Banjarnegara Regency. This research was conducted in Dieng Wetan Village and Sikunang Village, Kejajar District, Wonosobo Regency, and Dieng Kulon Village, Karangtengah Village, and Bakal Village, Batur District, Banjarnegara Regency. The area of Dieng Wetan is 282 ha, Sikunang 373.9 ha, Dieng Kulon 197 ha, Bakal 485 ha, and Karangtengah 48900 ha. Dieng Plateau has a rough topography in the form of hills and valleys with a slope of 87.5-92.4%. The area is at an altitude of $\pm 2,100$ m above sea level. The study site was selected

based on the research objective, namely forest areas that have undergone land-use conversion into agricultural land. The selection of the location was based on the bio-physical and administrative characteristics of the region to increase area diversity, thereby enabling the collection of comprehensive and representative data for spatial and ecological analyses. The selected research site is a forest area located on the Dieng Plateau. The research location is shown in Figure 1.

B. Methods

The tools used in this study were a camera, tally sheet, GPS, laptop, and writing materials. The materials used were administrative maps, forest area maps, land use maps, slope maps, and soil type maps. These maps were used to determine the observation locations by spatially analyzing the maps and determining the observation locations according to the specified characteristics. The characteristics of the observation location are forest areas that have been converted to agricultural land.

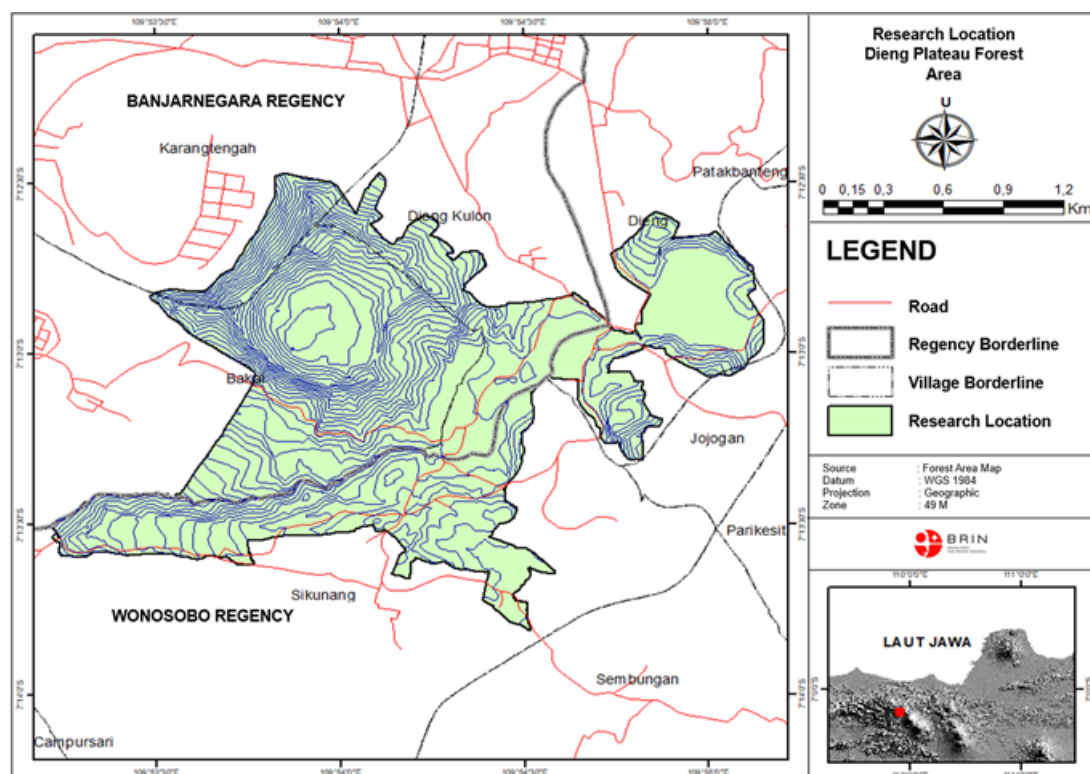


Figure 1. Research location in the Dieng Plateau Protection Forest area

The determination of study site selection used the purposive sampling method, which involved selecting locations with the condition that the forest area had undergone land conversion to agricultural land. The samples were determined using a spatial analysis method by applying an overlay technique to four types of maps: soil type maps, forest area maps, slope maps, and land use maps. Spatial analysis using the overlay technique was conducted to generate new information. The results of this spatial analysis produced 9 analytical units with different variations and characteristics. The sampling locations are the observation or data collection sites, which are divided into nine sampling locations with different characteristics. These nine sampling locations are distributed across five villages located within two administrative regions. The research location refers to the general study area, namely the forest area of the Dieng Plateau. The results of the spatial analysis of the research locations can be seen in Figure 2.

Data collection that used is accidental sampling technique. The selection of accidental sampling was based on field conditions and the characteristics of the research object. Agricultural lands resulting from forest land-use conversion are generally unevenly distributed, not formally documented, and difficult to identify spatially in advance. Therefore, accidental sampling was considered the most appropriate approach, as it allows respondents to be selected based on locations that are accessible and directly encountered in the field during the research period. Furthermore, this approach is relevant because the study aims to describe existing conditions rather than to achieve statistical generalization across the entire population. Accidental sampling enables efficient data collection under constraints of time, access, and limited preliminary information, while still capturing real variations in biophysical conditions and land management practices. Thus, this method is suitable for exploratory and descriptive studies.

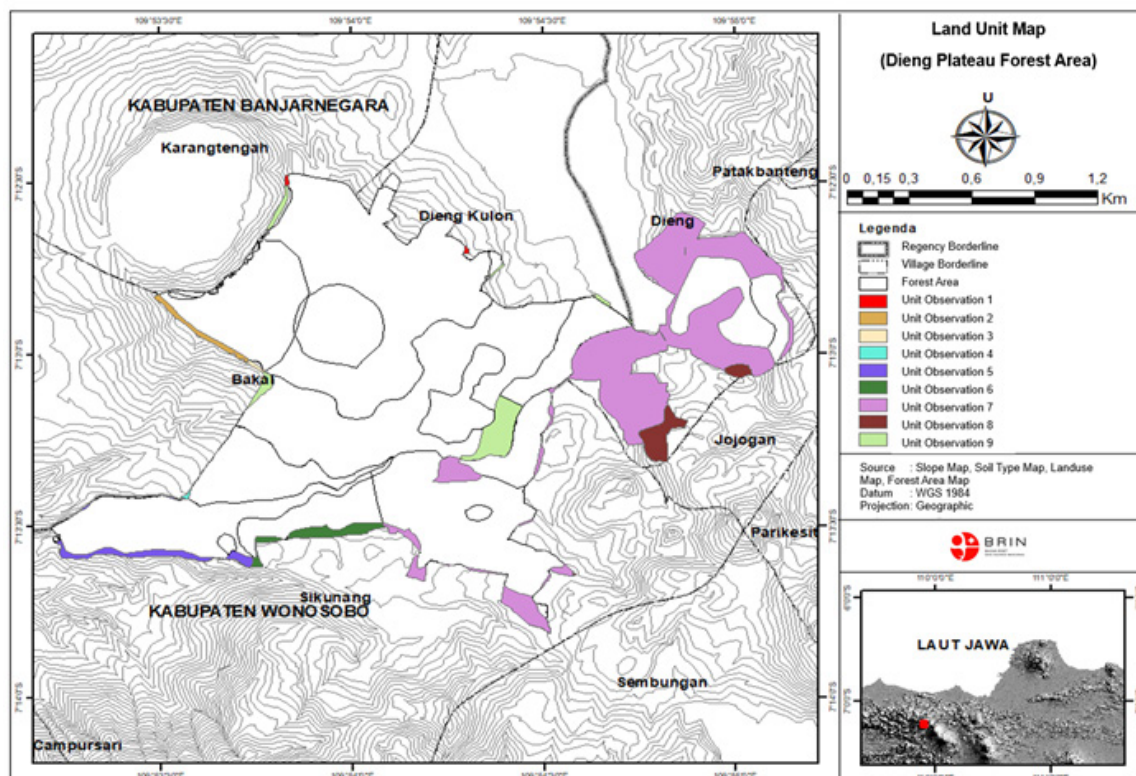


Figure 2. Land units map in the Dieng Plateau Protection Forest area

Samples were taken based on justifiable considerations, as long as they met the requirements. Requirements respondents were farmers and were on farm activities in the forest area. The respondents interviewed were those who were met accidentally at the sampling location, but the respondents selected were not just anyone, but rather those who were related to the research, namely farmers who were carrying out agricultural activities at the location. Before the interview was conducted, a validation was carried out on the respondents, following the steps for determining the respondents. First, to ensure that the respondent is a farmer. Second, to ensure that the respondent is carrying out agricultural activities in the forest area. Third, to ensure that the respondent is a cultivator or owner of the land. Fourth, to ensure how the respondent opens up the forest area. The number of respondents was not clearly determined beforehand. The number of respondents was determined by how many respondents could be met in the field during the data collection period. The total number of respondents was 22. Respondents are farmers who actively carry out agricultural activities in converted forest areas and 9.1% of respondents have experienced a landslides. Data collection conducted to respondents aims to collect information on land area, land ownership, land clearing techniques, land management, land management capital, and income obtained from crop production. The data was analyzed to determine the income and economic loss if landslide occurs on the land.

C. Analysis

1. Economic Valuation of Agriculture

The analysis of economic valuation of agriculture is conducted to determine the amount of income generated by the community from agricultural activities carried out in the Dieng Plateau forest area. The results of the economic valuation will show the amount of income obtained and its changes each year. Continuous land cultivation will result in a

decrease in land productivity due to erosion and a decrease in the ability of the land to provide nutrients for plants, so that there is a decrease in crop yields over time. The economic valuation of agriculture is calculated based on the income of agricultural businesses. Farm income is calculated by multiplying the crop yield per hectare by the average selling price and then subtracting the total production costs. The following formula is used to calculate farm income (Jarwinto et al., 2015).

1.1 Farm income

$$FI = SI - FE \dots\dots\dots(1)$$

where:

FI = farm income (IDR/year/hectare)

SI = sales income (IDR/year/hectare)

FE = farm expenses (IDR/year/hectare)

1.2 Sales income

$$SI = Y \times P \dots\dots\dots(2)$$

where:

SI = sales income

Y = production yield (kg/year/hectare)

P = average selling price (IDR/kg)

1.3 Farming expense

$$FE = Cs + Cf + Cp + Cl + Ct \dots\dots\dots(3)$$

where:

FE = farming expense

Cs = cost of seeds (IDR/year/hectare)

Cf = cost of fertilizer (IDR/year/hectare)

Cp = cost of pesticides (IDR/year/hectare)

Cl = labor cost (IDR/year/hectare)

Ct = cost of tools (IDR/year/hectare)

2. Estimation of Economic Losses Due to Landslides in Conversion Areas

The estimation of economic losses is carried out to determine the losses due to landslides so that the estimated losses can be obtained if a landslide occurs in the period 2019-2024. Due to the difference in time dimensions, the following formula is used to predict the economic losses due to landslides for the next 6 years (Kumalawati, 2005):

$$Fv = Po \times (1+i)^n$$

$$FI = SI - FE \dots\dots\dots(4)$$

where:

Fv = future value of money

Po = present value of money

i = interest rate

n = year n

Ct = cost of tools (IDR/year/hectare)

In this calculation, the current interest rate of 5.75% is used, based on the Bank Indonesia Rate. To assess the economic losses due to landslides, it is assumed that landslides occur at several times during the planting, growing, and harvesting seasons (Garcia-Chevesich et al., 2021; Kimura et al., 2023; Zhang et al., 2019). The assumed level of occurrence is total damage. This assumption is applied because of landslides on the slope like the Dieng Plateau usually causes severe physical damage to land structures, including landslides, which make land permanently unusable for agricultural production. The components calculated in analyzing each period differ according to the treatment required in that period. The results of this calculation can be used as a recommendation that forest areas should not be converted into agricultural land and should be better maintained as forest areas.

3. Analysis of Environmental Management Strategies on Economic Losses Due to Landslides

Economic assessment and estimate of lost use as inserting key in environmental management strategy analysis. SWOT analysis is a form of situational analysis that systematically identifies the strengths, weaknesses, opportunities, and

threats of an organization and its environment in order to formulate organizational strategies (Istiqomah & Andriyanto, 2017). The analysis is carried out by identifying problems in the form of a matrix to determine the strategy that is appropriate for the existing factors. The analytical approach using the SWOT analysis matrix can be seen in Table 1 (Sarsby, 2012)

III. RESULT AND DISCUSSION

A. Result

1. Agricultural Economic Valuation of Forest Area Conversion as Agricultural Land

Agriculture activities provide economic benefits for farmers so that they are considered economically feasible. The calculation of farm income can be seen in Table 2. Farm income is calculated by calculating the difference between total farm income per year in one hectare and the farming costs incurred per hectare in one year. Commodities developed by each farm include potatoes, carrots, cabbage, broccoli, leeks, and chilies. Potatoes have a harvest season of 3 times per year, carrots 2 times per year, leeks 4 times per year, cabbage 3 times per year, and chili 12 times per year. Chili peppers and leeks were chosen to be inter-crops planted between the main crops.

It can be seen in Table 2 that within one year and one hectare area, farming costs amounted to IDR 155,930,842.00. From the costs incurred, labor and seed costs are the largest cost components that need to be optimized to improve efficiency and profitability. The total revenue obtained from the sale of crops amounted to IDR 259,230,545.00. The profit from farming amounted to IDR 103,299,704.00

Table 1. SWOT analysis matrix

Internal External	Strength	Weaknesses
	Combining strengths and opportunities	Turning weaknesses into strengths
Opportunities	Combining strengths and opportunities	Turning weaknesses into strengths
Threats	Using strengths to turn threats into opportunities	Eliminating both aspects of weaknesses and threats

per year per hectare or, with a profit margin of 39.84%, this farming business is quite profitable. These results show that farming or activities carried out provide economic benefits for farmers. However, environmentally there are many impacts that arise both in the short and long term.

Table 2. Costs, revenue, and income of farming businesses

Cost	Cost per year per hectare
Seeds	IDR 63,991,136
Fertilizer	IDR 18,7448,33
Pesticides	IDR 10,418,706
Labor	IDR 51,152,574
Tools	IDR 11,623,592
Amount	IDR 155,930,842
<i>Revenue</i>	Revenue and income per year per ha
Sales income	IDR 259,230,545
Farm income	IDR 103,299,704

2. Estimation of Economic Losses Due to Landslides in the Utilized Area

The economic losses prediction due to landslides at observation location can be seen in Table 3. Table 3 presents estimates of losses (per hectare) due to landslides during each period at each observation locations. Table 3 shows that the largest losses occurred in observation locations 1, 2, and 6 amounting to IDR 219,180,000.00, IDR 125,128,571.00, and IDR 72,000,000, respectively.

Observation location 1 is located near Telaga Merdada, the occurrence of landslides will certainly cause greater losses if it damages the surrounding land and disrupts activities in the lake. Observation location 2 is in the vicinity of community agricultural land, landslides that occur can harm other community-owned agricultural land which of course will cause greater economic losses. Observation location 6 is located around the Steam Power Plant (PLTU) area, not a few community agricultural lands are located adjacent to the pipeline and PLTU area. If a landslide occurs, of course the losses incurred are very large, especially if

Table 3. Economic loss prediction due to landslides at observation locations

Obeservation location	Planting period (per ha)	Growing period (per ha)	Harvesting period (per ha)
1	IDR 219,180,000	IDR 352,900,000	IDR 1,192,377,381
2	IDR 125,128,571	IDR 234,954,762	IDR 1,192,377,381
3	IDR 17,312,500	IDR 65,680,556	IDR 131,454,167
4	IDR 15,800,000	IDR 20,200,000	IDR 51,400,000
5	IDR 21,992,000	IDR 30,397,333	IDR 74,188,000
6	IDR 72,000,000	IDR 131,450,000	IDR 355,893,333
7	IDR 61,708,333	IDR 118,425,000	IDR 290,425,000
8	IDR 30,416,456	IDR 58,026,697	IDR 160,154,955
9	IDR 56,500,000	IDR 94,000,000	IDR 254,000,000

the landslide damages the pipes belonging to the PLTU. In addition to economic losses, the danger that will occur as a result of damaged pipes will threaten the community. The losses that occur above are economic losses that occur during the planting period. The more the period increases, the greater the losses will be. The losses incurred at observation locations 3, 7, and 8 amounted to IDR 17,312,500.00 - IDR 61,708,333.00. Observation locations 7 and

8 are located in tourist areas where landslides will disrupt tourist activities. While observation location 3 is located around agricultural land with a very steep slope. If a landslide occurs at that location, it will have an effect on the livelihood of the community. Based on the results in Table 3, the average estimated economic loss for all agricultural land in the study area (per hectare) was calculated, as shown in Table 4.

Table 4. Estimation of economic losses due to landslides on agricultural land

Period	Component	Economic losses (per ha)
Planting period	Seeds	IDR 49,950,336
	Fertilizer	IDR 6,248,278
	Labor	IDR 3,920,243
Total		IDR 60,118,857
Growing period	Fertilizer	IDR 6,248,278
	Pesticides	IDR 3,472,902
	Labor	IDR 43,432,311
	Tools	IDR 11,623,592
	Number of planting period	IDR 60,118,857
Total		IDR 124,895,940
Harvesting period	Labor	IDR 3,800,021
	Harvest results	IDR 260,056,111
	Number of growing period	IDR 124,895,940
Total		IDR 388,752,071

Table 5. Estimation of economic losses due to landslides in 2019-2024

Year	Planting period (per ha)	Growing period (per ha)	Harvesting period (per ha)
2019	IDR 69,834,635	IDR 152,988,214	IDR 830,912,064
2020	IDR 73,850,127	IDR 161,785,036	IDR 878,689,507
2021	IDR 78,096,509	IDR 171,087,676	IDR 929,214,154
2022	IDR 82,587,058	IDR 180,925,217	IDR 982,643,968
2023	IDR 87,335,814	IDR 191,328,417	IDR 1,039,145,996
2024	IDR 92,357,624	IDR 202,329,801	IDR 1,098,896,891

Estimating economic losses at each time of the event gave different results. During the planting period the components needed are seeds, fertilizers, and labor. During the growing period, the calculation includes fertilizers, pesticides, labor, tools, and planting period total losses. Losses from the planting period are carried over and counted as part of the growing period losses. During the harvest period, the calculated components are labor, the harvest itself, and the total loss during the growing period. Of the three times of the incident, risk of landest loss occurred during the harvest period, which amounted to IDR 388,752,071.00. The loss during the harvest period was the largest because it was an accumulation of losses in the previous period. During the growing period, the loss amounted to IDR 124,895,940.00. While in the planting period the least loss was IDR 60,118,857.00. Losses during this period are small because the costs incurred or components calculated are still small. Economic losses due to landslides are calculated based on units per season per hectare. More details of the estimation of

economic losses incurred when landslides occur at the observed sample locations are shown in Table 4.

Estimation of economic losses due to landslides needs to be done for the next few years so that it can be a consideration for forest area managers and local governments in determining more appropriate policies and regulations. Table 5 shows the calculation of economic loss estimation in the year of the study, which is 2019. The estimation of economic losses in the following 6 years is calculated using the concept of time preference due to time differences that affect the value of money. The estimation of economic loss due to landslide in 2019-2024 can be seen in Table 5 below.

3. Environmental Management Strategy for Potential Landslide Disaster in Dieng Plateau Forest Area

The utilization of forest areas into agricultural land further triggers the potential for landslides. For this reason, an appropriate environmental management strategy is needed

Table 6. Matrix of environmental management strategies in Dieng Plateau

	Internal	Strength	Weakness
		- Soil fertility - High land productivity - Superior quality of agricultural products	- Lack of availability of agricultural land - Continuous tillage system - Disaster prone areas
External	Opportunity	- Cultivation of superior commodities - Utilization of certain types of trees to support agroforestry based tourism or landscape based tourism - Implementing mixed cropping systems on agricultural land	- Planting plants that can improve soil quality - Training and socialization to optimize the potential of nature tourism as employment for local communities - Intensive monitoring of land and resource utilization
	Threats	- Rehabilitation of damaged land - Educate farmers on better tillage	- Establishment of a disaster response team - Monitoring of agricultural activities around forest areas

to deal with these problems. The environmental management strategy is determined through SWOT analysis. The results of the SWOT analysis can be seen in Table 6.

B. Discussion

1. Agricultural Economic Valuation of Forest Area Conversion as Agricultural Land

Agricultural valuation analysis aims to determine the income of the community from the results of farming carried out in forest areas (Artani et al., 2019). Based on the Central Java Statistics Agency's report, this crop contributes 58% to the total potato production in Central Java. Agricultural activities have caused severe environmental degradation, leading to declining crop productivity in both quality and quantity over time. Additionally, intensive agricultural activities can lead to a decrease in the availability of nutrients for plants, such as nitrogen, phosphorus, and potassium, which are necessary for growth. Consequently, this can result in declining crop yields over time. Furthermore, land use changes from agriculture to non-agriculture can also reduce the available agricultural land area, thereby affecting agricultural productivity. We identified land hunger and land grabbing of forest conversion as a key threat. For example (Curtis et al., 2019), highlight how deforestation due to population pressures increases landslide activity and the role of land use changes, such as plantation development, in amplifying landslide risks in forested regions. In addition to the decline in land productivity, the threat of landslides that would cause economic losses for farmers should also be a concern. This is due to the loss of business capital due to crop failure (Arrogante-Funes et al., 2021; Kasno, 2020; Mandal et al., 2023; Woniala & Nyombi, 2014; Zhang et al., 2021; Zhang et al., 2021).

Variables that can be seen for the success of agricultural production include fertilizers, pesticides, and also labor. Fertilizers are used during the land preparation period, during land preparation the fertilizer used is organic fertilizer, while during the planting period

the fertilizer used is inorganic fertilizer. The fertilizer needs of each farmer are different. Pesticides used by farmers in the dry and rainy seasons are different. In the rainy season farmers need a lot of pesticides because of the increase in pests during the season, while in the dry season, farmers only use half of the pesticides needed in the rainy season. Pesticides are mixed with water and sprayed for 5 days a week using a suction device connected to a pipe to collect water from water sources or ponds. The tools used in agricultural activities are hoes, sickles, and water suction equipment from the lake. The total cost incurred by farmers for the provision of tools averaged IDR 3,000,000.00, the provision of tools is done at the beginning of land clearing or assumed to be the beginning of the planting season, at the beginning of the year. The labor required in one hectare varies in number according to what is needed by the landowner.

Similar research conducted on agricultural land in Bandung showed that the most costs were incurred in the cost of seeds, where potato seeds are a commodity that requires large capital. In addition, labor costs are also mostly incurred in land processing, planting, fertilizing, maintenance, watering, and harvesting activities. This is because the labor used is outside the family and requires wages (Rahmah & Wulandari, 2021). Economically, agricultural activities are feasible because they provide economic benefits for farmers. Income from farming plays a role in increasing the country's foreign exchange, is able to play a role in the absorption of labor for a growing population, and at the same time encourages regional development and regional economic growth and the national economy (Mangatas, 2021). On the one hand, agriculture in the Dieng Plateau is able to raise the dignity of farmers economically, but on the other hand it also creates a real socio-economic gap. Wealthy farmers who have large capital are able to become potato masters by planting the commodity on a very large area, while small farmers are increasingly alienated (Turasih, 2019).

2. Estimation of Economic Losses Due to Landslides in the Utilized Area

Areas utilized for activities are protected forest areas that have important functions in maintaining the balance of ecosystems and the environment (Saidah et al., 2021). The loss of protected areas causes an increase in erosion, landslides, and increases the volume of nutrients discharged into the lake due to high fertilizer use in agriculture (Noywuli, 2023; Soeprbowati et al., 2021). For this reason, an estimation of economic losses borne by farmers if landslides occur in the area is carried out. In estimating the amount of losses incurred due to landslides, the assumption of landslide occurrence time is used, namely during the planting period, growing period, and harvest period.

This research shows that as the year increases, the economic loss due to landslide on agricultural land increases, this is due to the increasing time of money. Landslides are one of the factors that cause economic losses in agricultural land, including direct losses such as partial or complete destruction of agricultural production and loss of land and/or reduction in land value (Bhandari et al., 2021; Perera et al., 2018). This event shows that the economic costs incurred due to landslides are increasing over time, particularly due to the conversion of agricultural land into less land and the greater losses experienced as a result of landslides (Shakya et al., 2023; Zumpano et al., 2018).

Disaster-related losses are estimated both retrospectively and through projections of potential future impact. (Zumpano et al., 2018). Estimation of economic losses due to landslides using the concept of time value of money. Time Value of money means that money has a time value. The value of money changes over time; hence, its future value differs from its present value. The method of valuing money in the future is the calculation of money owned today and invested with the determination of interest so that it undergoes a process of interest (compounding) so that the value will change in the future (Oktavia et

al., 2023). Table 5 shows that the losses Due to Landslides in the Utilized Area incurred would be different based on the time of landslide. The prediction of losses due to landslides is done for 6 years. The difference in time dimension will certainly lead to differences in the calculated value of money so that interest rates are used to predict the value of money according to the estimated period.

The Dieng Plateau has a height and slope that can potentially cause erosion and runoff. The phenomenon of erosion can also trigger various forms of threats to living things, ranging from property and infrastructure losses (Soeprbowati et al., 2021; Soeprbowati et al., 2021). The occurrence of erosion on a large area scale can cause landslides. According to previous studies, the erosion rate on the Dieng Plateau is generally very high, exceeding 480 tons/ha/year and is exacerbated by high intensity rainfall in the rainy season (Sari et al., 2021). High erosion rates result in significant economic losses, particularly in agricultural areas, where soil fertility declines and crop yields are reduced (Shakya et al., 2023). Landslides are one form of advanced erosion that is often overlooked by the community in Dieng, who generally lack resilience to land degradation processes, thus endangering livelihood sustainability (Rudiarto et al., 2020). This disaster has negative impacts, including decreased land productivity due to environmental imbalance and have led to slope instability (Advenia & Rahayu, 2023; Perera et al., 2018).

The inability to manage land degradation exacerbates the economic burden, as agricultural productivity continues to decline, leading to further livelihood insecurity for the community (Nguyen et al., 2023; Tadesse & Hailu, 2024). The most common erosion is furrow erosion which occurs up to 50%. While the average incidence of landslides in the rainy season is 38%. Besides affecting agricultural areas, landslides also have the potential to hit residential areas (Shabbir et al., 2023). Based on historical data, the Dieng area has at least three potential natural disasters, namely earthquakes,

landslides, and toxic gas disasters (Sumotarto et al., 2023; Wardoyo et al., 2021). These potential disasters have been proven to have a detrimental impact on the community including material losses, disruption of people's daily activities and even loss of life (Indrayati, 2013; Maesaroh & Suwarno, 2022; Zumpano et al., 2018).

A study conducted in Cibanteng Village, Cianjur showed that indirect economic losses due to landslides on agricultural land reached IDR 352,811,700 and IDR 1,205,152,300 for indirect losses in 2.5 years (Abidin et al., 2019). Other research with other types of natural disasters such as flooding showed that economic losses resulted in a reduction in crop yields of IDR 1,639,666.00/ha/year (Hanifah & Putri, 2022). Predicted losses of farmers due to landslides experienced by residents of Hargotirto Village, Kulonprogo Regency reached the highest value of IDR 220,460,000, - due to the relatively large agricultural land so that it can produce relatively many agricultural products. For the lowest value reached a value of IDR 60,900,000, - because the agricultural land is not so extensive so that the agricultural production produced is relatively small (Retnowati, 2104). The larger the farm, the greater the loss. This study shows that the longer the duration of the landslide, the higher the losses incurred. Losses during the planting season are lower than during the harvest season due to capital accumulation.

Moreover, maintaining the ecological integrity of forests has been identified as a cost-effective strategy for preventing soil erosion and reducing the economic risks associated with landslides (Soeprbowati et al., 2021; Suprpto et al., 2022). Sustainable forest management and reforestation efforts, especially in areas prone to landslides like Dieng Plateau, are crucial for safeguarding both the environment and local economies (Sari et al., 2021; Soeprbowati et al., 2021).

The prediction of economic loss due to landslides can be used as a consideration for farmers not to conduct activities in forest areas because it damages the function of the

forest as a protected area. If the forest area is maintained, the protection function and prevention of landslides can continue so that large economic losses to farmers due to landslides can be avoided (Pathak et al., 2025; Tarolli & Straffelini, 2020).

3. Environmental Management Strategy for Potential Landslide Disaster in Dieng Plateau Forest Area

Good environmental management is needed to manage forest areas that have been converted into agricultural land (Cahyani, 2020). The purpose of environmental management is to control and prevent greater impacts. Currently, landslides have often occurred on the Dieng Plateau. This suggests a decline in the area's environmental quality. The strategies that can be formulated based on the analysis that has been carried out are as follows:

SO (Strength & Opportunity) Strategy

The SO (Strength & Opportunity) strategy was created to maximize the strengths and opportunities. The high soil fertility in the area can be utilized to plant species that have many advantages. Planting superior commodities can increase farmers' income because the price offered is high according to the quality (Dabutar & Husein, 2022). The Dieng Plateau has high land productivity so that superior commodity cultivation has high potential to be developed in the area. The cultivation of superior commodities such as potatoes and vegetables in highland areas has been proven to increase farmers' income due to higher selling prices that correspond to product quality. Studies in the highlands of Himachal Pradesh, India, have shown that the use of improved potato varieties increases productivity and harvest quality, resulting in a significant increase in farmers' income (Roy et al., 2021).

Moreover, research in the Andes highlands of Peru reports that the development of local vegetable varieties resistant to cold climates has enhanced both the economic value and welfare of farmers (Aguilar-Luis et al., 2024). These superior commodities

not only provide economic benefits but also support the sustainability of agricultural systems in environmentally vulnerable areas. These superior commodities not only provide economic benefits but also support the sustainability of agricultural systems in these environmentally vulnerable areas. However, it is important to consider that potato plants require a substantial amount of water and are typically cultivated using a contour-cutting planting system (Abebe & Temam, 2024; Arifin et al., 2021). For this reason, the development of other superior commodity cultivation is recommended.

In addition to planting superior commodities, improvement of the mixed planting system is also recommended, in addition to providing additional benefits for farmers, trees planted around agricultural land have a positive impact on the environment, the smallest impact is to provide coolness which is now starting to be felt less (Yu et al., 2025). One type of plant that can be considered to prevent landslide and improve soil quality are *Schima wallichii* and *Ficus* spp. *Schima wallichii* is a high-altitude tree species whose roots and litter reduce surface erosion and enrich the soil, improving its structure and fertility (Fardhani, 2021). *Ficus* spp. offer effective solutions to restore soil fertility and ecosystem functions (Hendrayana, 2025).

The Dieng Plateau is also known as a beautiful natural tourist attraction, the utilization of certain types of vegetation to support natural tourism around is highly recommended. The creation of lodging that offers a natural atmosphere surrounded by trees is currently in great demand, this is a potential to increase the income of the government and local communities. Tree planting in the Dieng Plateau area certainly has a positive impact on the biotic, abiotic and cultural environment.

WO (Weakness & Opportunity) Strategy

This strategy is made to provide solutions to weaknesses so that they become strengths through existing opportunities. As we know that tillage on agricultural land is carried out

massively, by cultivating the soil continuously from the preparation period to post-harvest (Liu et al., 2022). This activity has a negative impact on soil quality, due to the reduction of aggregates, loss of organic matter, and increased sedimentation of the chemicals used (Bonifacio et al., 2024; Lal, 2016). Improving soil quality is essential to prevent land degradation through planting crops that can improve soil quality.

Training and socialization are also important to provide knowledge to the community about the tourism potential that exists and can be utilized as community employment (Noviyanti & Nuruddin, 2020). The natural beauty of the Dieng Plateau has a lot of potential to be developed as a natural tourist attraction to enjoy the scenery and coolness. The opening of new jobs in the tourism sector will reduce the possibility of opening new land for agriculture so that deforestation can be suppressed. Optimization of existing tourism objects also needs to be done, to increase visitor interest and regional income from the tourism sector.

Abundant natural resources attract many investors and communities to exploit them. This is very threatening to the environment on the Dieng Plateau, so it needs intensive monitoring by responsible parties so that the utilization of existing resources and land remains in accordance with applicable regulations.

ST (Strength & Threats) Strategy

Frequent landslides in the Dieng Plateau area have long been complained about by the community. This shows that the environmental quality in the area has declined. Frequent landslides not only cause material losses but also disrupt people's daily activities. Rehabilitation of degraded land is very important to do before greater impacts occur (UNDP, 2019). Some sites have experienced land degradation due to the lack of rehabilitation, such as Nepal, which has similar conditions where forest conversion to agricultural land has caused decreased soil fertility and increased erosion (Thapa & Paudel, 2002). According to farmers' testimonies, some unproductive lands have been abandoned, and

these lands need to be rehabilitated to improve the quality of the land, especially to strengthen soil aggregates so that they are not prone to landslides when it rains. Improving the quality of the environment in terms of biotic and abiotic will also affect the quality of the cultural environment on the Dieng Plateau.

WT (Weakness & Threats) Strategy

The threat of landslides that occur frequently and are difficult to predict is very troubling to the community. For this reason, a possible strategy is the establishment of a local disaster response team. We recommend that the team have a clearer institutional framework with strong multi-stakeholder engagement. The team still will operate under the local disaster management agency (BPBD), with coordination involving forestry, agriculture, and community stakeholders. Authorization will align with Indonesia's national disaster management regulations (e.g., *Peraturan Pemerintah* No. 21/2008). This structure is supported by practices outlined in Geo-environmental Disasters for multi-stakeholder disaster response coordination. The funding source we proposed was from local government budgets, national disaster management funds (e.g., through Indonesia's BNPB), and partnerships with NGOs or international programs focused on disaster risk reduction. Community-based crowdfunding will also be explored to enhance local ownership, as suggested by Perera et al. (2018) in their study on community-level disaster recovery in Sri Lanka. This aims to provide ease of evacuation to the community if a landslide occurs. Establishing a community-based team can enhance local awareness and understanding of landslide risks. The formation of a team from the community is easier because of the bonds of care and communication that have been established. The formation of evacuation teams also provides employment for people who do not have jobs or agricultural land as the main livelihood on the Dieng Plateau. The existence of a disaster evacuation team is also able to attract tourists to visit because there is

a sense of security when traveling to the Dieng Plateau.

Given the high risk of landslides, effective oversight by local authorities is essential to prevent illegal forest clearing for agriculture. Clear regulation is needed, especially to improve land use systems and align spatial plans for effective landslide risk management. We need alignment between national spatial planning (RTRW Nasional) and regional spatial planning (RTRW Daerah) policies to ensure cohesive land use management in landslide-prone areas. This aligns with findings from Varkkey et al. (2018), who emphasize the role of policy coherence in mitigating environmental degradation in forested regions. Specific recommendations for stricter zoning regulations, incorporation of landslide susceptibility maps, and capacity-building for local authorities to enhance compliance. These measures are supported by Bottaro et al. (2022), who highlight the importance of spatial planning in mitigating hydrogeological hazards in mountain forests. Law enforcement and strict sanctions on perpetrators of illegal encroachment of forest areas must also be enforced. Supervision aims to maintain the forest ecosystem so that the quality of the environment on the Dieng Plateau does not decline, because the decline in environmental quality can increase the potential for natural disasters due to human activities.

Conversion of forest areas into agricultural land in the Highlands has significant impacts on environmental degradation, particularly through increased landslide risks, declining land productivity, and soil degradation. Intensive agricultural practices, such as excessive use of fertilizers and pesticides as well as contour-cutting planting patterns, exacerbate erosion levels and threaten the sustainability of the agricultural system in this region. Economic loss estimations indicate that the highest financial impact occurs when landslides take place during the harvest period. The apparent increase in loss values over time does not reflect an escalation in landslide frequency or magnitude, but is solely the result of the time value of money, in

which future losses are valued higher under the applied economic projection model. Therefore, the increasing trend should be interpreted as an economic effect rather than a physical increase in landslide risk. Therefore, appropriate and sustainable environmental management strategies are necessary to minimize these risks.

IV. CONCLUSION

Agricultural activities in the Dieng Plateau Forest Area provide profits or income from farming of IDR 103,299,704.00 per year per hectare. The negative impact of these activities is the risk of landslides on agricultural land which causes different losses during the planting, growing, and harvesting periods. Of the three times of occurrence, the highest loss occurred during the harvest period which amounted to IDR 388,752,071.00. Losses during the growing period amounted to IDR 124,895,940.00. While during the planting period the least loss was IDR 60,118,857.00. The frequency of landslides is directly correlated with increased economic losses. Based on the SWOT analysis, several strategies can be implemented to support sustainable community development. Planting superior and mixed crops can increase farmers' income while improving soil quality. Community training and socialization play an important role in raising awareness of tourism potential and creating local jobs. Land rehabilitation efforts are needed to prevent further degradation, supported by community-based teams that strengthen awareness and preparedness for landslide risks. Finally, clear and consistent regulations are essential to optimize land use and ensure effective landslide risk management.

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REFERENCES

- Abebe, N., & Temam, M. (2024). Water requirement and irrigation scheduling of potato (*Solanum tuberosum* L.) by using CROPWAT 8.0 at Welmera District, Central Highland of Ethiopia. *American Journal of Water Science and Engineering*, 10(3), 54–63. <https://doi.org/10.11648/j.ajwse.20241003.12>
- Abidin, F. G., Kusratmoko, E., & Susiloningtyas, D. (2019). Assessing of economic losses in landslide affected areas in Cibanteng Village, Cianjur District, West Java. *IOP Conference Series: Earth and Environmental Science*, 311(1). <https://doi.org/10.1088/1755-1315/311/1/012047>
- Advenia, L., & Rahayu, D. (2023). Analysis of economic and social vulnerability to disaster risk in Tawangmangu and Kejajar Districts. *E3S Web of Conferences*, 02003(467), 1–7.
- Aguilar-Luis, M. A., Sanchez, J. M., Mercado, W., & Orihuela, J. C. A. (2024). Sustainable agriculture in Peru based on agrobiodiversity and climate-smart agriculture – Evaluation of a case study with small farmers in an Andean Basin. *Journal of Ecological Engineering*, 25(4), 278–293. <https://doi.org/10.12911/22998993/185221>
- Akmalia, H. A. (2022). The impact of climate change on agriculture in Indonesia and its strategies: A systematic review. *Agritepa: Jurnal Ilmu Dan Teknologi Pertanian*, 9(1), 145–160. <https://doi.org/10.37676/agritepa.v9i1.1691>
- Arifin, Z., Hermanto, C., & Dewi, I. R. (2021). Farming land management on potato cultivation in sloping upland. *IOP Conference Series: Earth and Environmental Science*, 648(1). <https://doi.org/10.1088/1755-1315/648/1/012056>
- Arrogante-Funes, P., Bruzón, A. G., Arrogante-Funes, F., Ramos-Bernal, R. N., & Vázquez-Jiménez, R. (2021). Integration of vulnerability and hazard factors for landslide risk assessment. *International Journal of Environmental Research and Public Health*, 18(22), 11987. <https://doi.org/10.3390/ijerph182211987>
- Artani, N. K. S., Estiyanti, N. M., & Dharma, E. M. (2019). Valuation analysis of digital startup companies (Case study on Kostpedia.id). *Journal of Applied Management and Accounting Science (JAMAS)*, 01(1), 24–37.
- Badan Pusat Statistik Jawa Tengah. (2021). *Provinsi Jawa Tengah dalam Angka*. Semarang: Badan Pusat Statistik Jawa Tengah.

- Bhandari, D., Joshi, R., Regmi, R. R., & Awasthi, N. (2021). Assessment of soil erosion and its impact on agricultural productivity by using the RMMF model and local perception: A case study of Rangun Watershed of Mid-Hills, Nepal. *Applied and Environmental Soil Science*, 2021. <https://doi.org/10.1155/2021/5747138>
- Bonifacio, E., Said-Pullicino, D., Stanchi, S., Potenza, M., Belmonte, S. A., & Celi, L. (2024). Soil and management effects on aggregation and organic matter dynamics in vineyards. *Soil and Tillage Research*, 240(March), 106077. <https://doi.org/10.1016/j.still.2024.106077>
- Bottaro, G., Gatto, P., & Pettenella, D. (2022). Assessing the economic impacts of climate change on mountain forests: A literature review. In R. Tognetti, M. Smith, & P. Panzacchi (Eds.), *Climate-Smart Forestry in Mountain Regions* (Vol. 40, pp. 453–459). Springer.
- Cahyani, F. A. (2020). Upaya peningkatan daya dukung lingkungan melalui penerapan prinsip sustainable development berdasarkan Undang-Undang Nomor 32 Tahun 2009 tentang Perlindungan dan Pengelolaan Lingkungan Hidup. *Indonesian State Law Review (ISLRev)*, 2(2), 168–179. <https://doi.org/10.15294/islrev.v2i2.38472>
- Candan Demirkol, E. (2022). Impacts of modern agriculture on environment and sustainable agriculture. *Journal of Life Economics*, 9(3), 171–182. <https://doi.org/10.15637/jlecon.9.3.05>
- Choudhury, B. U., Nengzouzam, G., Ansari, M. A., & Islam, A. (2022). Causes and consequences of soil erosion in northeastern Himalaya, India. *Current Science*, 122(7), 772–789. <https://doi.org/10.18520/cs/v122/i7/772-789>
- Dabutar, M., & Husein, R. (2022). Pengaruh produksi, harga dan luas lahan terhadap pendapatan petani cabai merah di Indonesia. *Jurnal Ekonomi Pertanian Unimal*, 5(2), 42–52. <https://doi.org/10.29103/jepu.v5i2.8721>
- Dewangga, T. A. (2018). *Analysis of the Potential Economic Losses in the Agricultural Sector Due to Landslide Disasters in Girimulyo District, Kulon Progo Regency, Special Region of Yogyakarta* [Thesis]. Gadjah Mada University.
- Elkhrachy, I., Ranjan Yadav, R., Nouh Mabdeh, A., Nguyen Thanh, P., Spalevic, V., & Dudic, B. (2023). Landslide susceptibility mapping and management in Western Serbia: an analysis of ANFIS- and SVM-based hybrid models. *Frontiers in Environmental Science*, 11. <https://doi.org/10.3389/fenvs.2023.1218954>
- Galindo, V., Giraldo, C., Lavelle, P., Armbrecht, I., & Fonte, S. J. (2022). Land use conversion to agriculture impacts biodiversity, erosion control, and key soil properties in an Andean watershed. *Ecosphere*, 13(3), 1–19. <https://doi.org/10.1002/ecs2.3979>
- Garcia-Chevesich, P., Wei, X., Ticona, J., Martínez, G., Zea, J., García, V., Alejo, F., Zhang, Y., Flamme, H., Graber, A., Santi, P., McCray, J., Gonzáles, E., & Krahenbuhl, R. (2021). The impact of agricultural irrigation on landslide triggering: A review from chinese, english, and Spanish literature. *Water (Switzerland)*, 13(1), 1–17. <https://doi.org/10.3390/w13010010>
- Hanifah, M., & Putri, N. E. (2022). Impact of flood on rice business income in Ibul Besar I Village Pemulutan District Ogan Ilir Regency. *Prosiding Seminar Nasional Lahan Suboptimal Ke-10 Tahun 2022*, 562–571.
- Haty, I. P., Yudiantoro, D. F., Choiriah, S. U., Putri, A., & Magdalena, E. (2021). *Geologi dan Potensi Panas BUMi di Kompleks Vulkanik Dieng*. Yogyakarta: UPN Veteran Yogyakarta.
- Hossain, T., Tushar, M. A. N., Murshed, S., Basak, U., & Islam, Md. A. (2024). Landslide studies in the context of disaster management in Bangladesh—A systematic literature review. *Earth*, 5(4), 784–811. <https://doi.org/10.3390/earth5040041>
- Indrayati, A. (2013). Peningkatan ketahanan terhadap risiko bencana melalui pendidikan konservasi lahan berbasis masyarakat di Dataran Tinggi Dieng. *Jurnal Geografi*, 10(2), 154–166.
- Istiqomah, & Andriyanto, I. (2017). Analisis SWOT dalam pengembangan bisnis (Studi pada sentra jenang di Desa Wisata Kaliputu Kudus). *Jurnal Bisnis Dan Manajemen Islam*, 5(2), 363–382.
- Jarwinto, D. A., Darsono, & Mei Tri Sundari, S. (2015). Analisis produktivitas lahan dan pendapatan usaha tani padi di Kawasan Pesisir Kabupaten Purworejo. *Jurnal Ilmiah Mahasiswa Agribisnis UNS*, 3(2), 1–12.
- Kasno, A. (2020). Perbaikan tanah untuk meningkatkan efektivitas dan efisiensi pemupukan berimbang dan produktivitas lahan kering masam. *Jurnal Sumberdaya Lahan*, 13(1), 27. <https://doi.org/10.21082/jsdl.v13n1.2019.27-40>
- Kimura, T., Sato, G., Ozaki, T., Van Thang, N., & Wakai, A. (2023). Land cover trajectories and their impacts on rainfall-triggered landslide occurrence in a cultivated mountainous region of Western Japan. *Water (Switzerland)*, 15(24). <https://doi.org/10.3390/w15244211>

- Krisnandi, R., Trianda, O., Rizqi, A., Febby, L., & Hanafi, M. (2021). Identifikasi kawasan rawan bencana longsor metode skoring daerah Mojotengah dan sekitarnya, Kecamatan Reban, Kabupaten Batang, Provinsi Jawa Tengah. *Prosiding Nasional Rekayasa Teknologi Industri Dan Informasi XVI Tahun 2019 (ReTII)*, 2021(November), 501–508.
- Kumalawati, R. (2005). *Valuasi ekonomi risiko bencana alam gerakan massa dan erosi terhadap lahan pertanian di DAS Tinalah Kulonprogo*. Universitas Gadjah Mada.
- Lal, R. (2016). Soil health and carbon management. *Food and Energy Security*, 5(4), 212–222. <https://doi.org/10.1002/fes3.96>
- Lawrence, D., & Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. *Nature Climate Change*, 5(1), 27–36. <https://doi.org/10.1038/nclimate2430>
- Liu, L., Cui, S., Qin, M., Chen, L., Yin, D., Guo, X., Li, H., & Zheng, G. (2022). Effects of continuous ridge tillage at two fertilizer depths on microbial community structure and rice yield. *Agriculture (Switzerland)*, 12(7). <https://doi.org/10.3390/agriculture12070923>
- Maesaroh, M., & Suwarno, S. (2022). Community empowerment and disaster management of Dieng Plateau Tourism Area. *Proceedings Series on Social Sciences & Humanities*, 6, 92–98. <https://doi.org/10.30595/pssh.v6i.447>
- Mandal, D., Patra, S., Sharma, N. K., Alam, N. M., Jana, C., & Lal, R. (2023). Impacts of soil erosion on soil quality and agricultural sustainability in the North-Western Himalayan Region of India. *Sustainability*, 15(6), 5430. <https://doi.org/10.3390/su15065430>
- Mangatas, R. (2021). Kajian alih fungsi lahan hutan serta peranannya dalam penyerapan tenaga kerja, pertumbuhan ekonomi dan peningkatan indeks pembangunan manusia di Kabupaten Perbatasan Kalimantan Barat. *Prosiding Seminar Nasional SATIESP 2021 Universitas Tanjungpura*. Pp 140–155.
- Marín-Rodríguez, N. J., Vega, J., Zanabria, O. B., González-Ruiz, J. D., & Botero, S. (2024). Towards an understanding of landslide risk assessment and its economic losses: a scientometric analysis. *Landslides*, 21(8), 1865–1881. <https://doi.org/10.1007/s10346-024-02272-2>
- Maya, V. I. E. (2022). Perencanaan penerapan angkutan wisata sebagai pengembangan Kawasan Wisata Dieng yang berkelanjutan. *Jurnal Syntax Admiration*, 3(8), 1072–1071. <https://doi.org/10.46799/jsa.v3i8.469>
- Mutia, R., Suharyadi, & Mardiatno, D. (2018). *Assessment of Damage and Losses in the Housing and Agricultural Sectors Due to Landslide Disasters in Clapar Village, Madukara, Banjarnegara, Central Java* [Thesis]. Gadjah Mada University.
- Nguyen, T. T., Grote, U., Neubacher, F., Rahut, D. B., Do, M. H., & Paudel, G. P. (2023). Security risks from climate change and environmental degradation: implications for sustainable land use transformation in the Global South. *Current Opinion in Environmental Sustainability*, 63(June), 101322. <https://doi.org/10.1016/j.cosust.2023.101322>
- Noviyanti, U. D. E., & Nuruddin2. (2020). Socialization and tourism awareness training around Arosbaya Cretaceous Tourism Object, Madura. *Darmabakti Cendekia: Journal of Community Service and Engagements*, 02 (2020): 20-25. <https://doi.org/10.20473/dc.v2i1.2020.20-25>
- Noywuli, N. (2023). Pendekatan konservasi dalam pengelolaan lahan perbukitan untuk usaha pertanian. *Jurnal Pertanian Unggul*, 2 (1), 16–27.
- Oktavia, L. S., Aldina, L., Nurdianto, Fahrati, M., & Yulaeli, T. (2023). Faktor-faktor yang mempengaruhi nilai waktu uang: Future value, present value, dan annuity. *Jurnal Publikasi Ilmu Manajemen (JUPIMAN)*, 2(3), 153–168. <https://doi.org/10.55606/jupiman.v2i2.2061>
- Pathak, L., Baral, B., Joshi, K., & Basnet, D. R. (2025). Landslides in the Himalayas : The role of conditioning factors and their resolution in susceptibility mapping. *Geosciences* 2025, 15(4), 131; <https://doi.org/10.3390/geosciences15040131>
- Perera, E. N. C., Jayawardana, D. T., Jayasinghe, P., Bandara, R. M. S., & Alahakoon, N. (2018). Direct impacts of landslides on socio-economic systems: a case study from Aranayake, Sri Lanka. *Geoenvironmental Disasters*, 5(1), 11. <https://doi.org/10.1186/s40677-018-0104-6>
- Pujiwinarko, A., Soeprbowati, T. R., & Kismartini. (2024). Land management and factors influencing agroforestry adoption on potato farmlands in the Dieng Plateau, Indonesia. *Biodiversitas*, 25(6), 2623–2641. <https://doi.org/10.13057/biodiv/d250633>
- Rahayuningsih, M., & Wati, Y. H. (2023). Strategi pengembangan pariwisata Kawasan Dieng Kejajar Wonosobo. *Jurnal Geosains West Science*, 1(01), 17–22.
- Rahmah, S. A., & Wulandari, E. (2021). Analysis of potato farmers revenue and factors related To revenue of potato in Pangalengan Sub

- District, Bandung District. *Jurnal Ekonomi Dan Agribisnis (JEPA)*, 5, 1–15.
- Retnowati, E. (2014). *Mapping of Landslide Disaster Risks and Prediction of Farmer Losses* [Thesis]. Badan Pertahanan Nasional Republik Indonesia.
- Retnowati, E. (2014). *Pemetaan Risiko Bencana Tanah Longsor dan Prediksi Kerugian Petani (Studi di Desa Hargotirto Kecamatan Kokap Kabupaten Kulon Progo)*. Sekolah Tinggi Pertanian Nasional.
- Rey-Romero, D. C., Domínguez, I., & Oviedo-Ocaña, E. R. (2022). Effect of agricultural activities on surface water quality from páramo ecosystems. *Environmental Science and Pollution Research*, 29(55), 83169–83190. <https://doi.org/10.1007/s11356-022-21709-6>
- Roy, P., Hansra, B. S., Burman, R. R., Roy, T. N., Bhattacharyya, S., & Kumar, P. (2021). Impact of improved varieties on farmers income: Insight from lower Shivalik hills. *Indian Journal of Agricultural Sciences*, 91(11), 1612–1616. <https://doi.org/10.56093/ijas.v91i11.118542>
- Rudiarto, I., Rahmawati, I., & Sejati, A. W. (2020). Land degradation and community resilience in rural mountain area of java, indonesia. *Advances in Science, Technology and Innovation*, 449–460. https://doi.org/10.1007/978-3-030-23243-6_30
- Sahara, D., Wulanjari, M. E., & Triastono, J. (2023). Optimasi penggunaan input produksi pada usahatani kentang di Dataran Tinggi Dieng, Jawa Tengah. *Jurnal Ilmu Pertanian Indonesia (JIPI)*, 28(4), 612–619. <https://doi.org/10.18343/jipi.28.4.612>
- Saidah, H., Hariyanto, B., Supriyadi, A., & Jaya Negara, I. D. G. (2021). Evaluasi penentuan kawasan lindung Kota Mataram dalam perannya sebagai kawasan peresapan air. *SADE : Jurnal Arsitektur, Planologi Dan Teknik Sipil*, 1(1), 1–5. <https://doi.org/10.29303/sade.v1i1.2>
- Santosa, F. J. (2022). Efforts to revitalize the Dieng Critical Slope through community empowerment : Case tambu coffee. *Indonesia Journal of Social Responsibility Review*, 1(3), 163–170. <https://doi.org/10.55381/ijssr.v1i3.68>
- Sari, K., Soeprbowati, T. R., Jumari, J., Hariyati, R., & Miller, J. R. (2021). Trace metals and diatom stratigraphy along the sill between lakes Telaga Warna and Telaga Pengilon, Dieng, Central Java, Indonesia. *Sustainability*, 13(7), 3821. <https://doi.org/10.3390/su13073821>
- Sarsby, A. (2012). *A Useful Guide to SWOT Analysis*. Pansophic Online.
- Shabbir, W., Omer, T., & Pilz, J. (2023). The impact of environmental change on landslides, fatal landslides, and their triggers in Pakistan (2003 – 2019). *Environmental Science and Pollution Research*, 33819–33832. <https://doi.org/10.1007/s11356-022-24291-z>
- Shakya, A., Sigdel, P., & Pokhrel, S. (2023). Socio-economic impacts of landslides and applied mitigation techniques: A case study in Bagnaskali. *Original Article Journal of Sustainability and Environmental Management*, 2(3), 170–178. <https://www.nepjol.info/index.php/josem>
- Shano, L., Raghuvanshi, T. K., & Meten, M. (2020). Landslide susceptibility evaluation and hazard zonation techniques – a review. *Geoenvironmental Disasters*, 7(1), 18. <https://doi.org/10.1186/s40677-020-00152-0>
- Soeprbowati, T., Purnaweni, H., Jumari, J., & Sari, K. (2021). The relationship of water quality to epipellic diatom assemblages in Cebong Lake, Dieng Indonesia. *Polish Journal of Environmental Studies*, 31(1), 281–295. <https://doi.org/10.15244/pjoes/137084>
- Soeprbowati, T. R., Addadiyah, N. L., Hariyati, R., & Jumari, J. (2021). Physico-chemical and biological water quality of Warna and Pengilon Lakes, Dieng, Central Java. *Journal of Water and Land Development*, 51 (X-XII), 38–49. <https://doi.org/10.24425/jwld.2021.139013>
- Sumotarto, U., Hendrasto, F., & Meirawaty, M. (2023). Gas hazards in Dieng geothermal field, Central Java. *AIP Conference Proceedings*, 2598(1), 30004. <https://doi.org/10.1063/5.0134337>
- Suprpto, F. A., Juanda, B., Rustiadi, E., & Munibah, K. (2022). Study of disaster susceptibility and economic vulnerability to strengthen disaster risk reduction instruments in Batu City, Indonesia. *Land*, 11(2041). <https://doi.org/doi.org/10.3390/land11112041>
- Swarnawati, A. (2018). Participatory communications in the strengthening community-based forest and watershed management program (SCBFWM) on Dieng Plateau. *Malaysian Journal of Social Sciences and Humanities (MJSSH)*, 3(1), 36. www.msosocialsciences.com
- Tadesse, A., & Hailu, W. (2024). Causes and consequences of land degradation in Ethiopia: A review. *International Journal of Science and Qualitative Analysis*, 10(1), 10–21. <https://doi.org/10.11648/j.ijjsqa.20241001.12>
- Tarolli, P., & Straffellini, E. (2020). Agriculture in hilly and mountainous landscapes: Threats,

- monitoring and sustainable management. *Geography and Sustainability*, 1(1), 70–76. <https://doi.org/10.1016/j.geosus.2020.03.003>
- Thapa, G., & Paudel, G. (2002). Farmland degradation in the mountains of Nepal: A study of watersheds “with” and “without” external intervention. *Land Degradation & Development*, 13, 479–493. <https://doi.org/10.1002/ldr.536>
- Tolimir, M., Kresović, B., Životić, L., Dragović, S., Dragović, R., Sredojević, Z., & Gajić, B. (2020). The conversion of forestland into agricultural land without appropriate measures to conserve SOM leads to the degradation of physical and rheological soil properties. *Scientific Reports*, 10(1), 1–12. <https://doi.org/10.1038/s41598-020-70464-6>
- Truong, N. C. Q., Khoi, D. N., Nguyen, H. Q., & Kondoh, A. (2022). Impact of forest conversion to agriculture on hydrologic regime in the large basin in Vietnam. *Water (Switzerland)*, 14(6), 1–15. <https://doi.org/10.3390/w14060854>
- Turasih, T. (2019). Transformasi sosial petani kentang di Dataran Tinggi Dieng. *Empower: Jurnal Pengembangan Masyarakat Islam*, 4(2), 279. <https://doi.org/10.24235/empower.v4i2.5462>
- UNDP. (2019). *Combating Securing Land a Sustainable*. United Nations Development Programme. p 166.
- Varkkey, H., Tyson, A., & Choiruzzad, S. A. B. (2018). Palm oil intensification and expansion in Indonesia and Malaysia: Environmental and socio-political factors influencing policy. *Forest Policy and Economics*, 92, 148–159. <https://doi.org/10.1016/j.forpol.2018.05.002>
- Wahono, F., & Puspitawati, T. (2021). Be kind with nature: A case of terrace farming in Dieng Plateau, Wonosobo, Central Java, Indonesia. *Vegeta*, 21(1), 303–317. <https://doi.org/10.51349/veg.2021.1.12>
- Wahyuni, H., & Suranto, S. (2021). Dampak deforestasi hutan skala besar terhadap pemanasan global di Indonesia. *JlIP: Jurnal Ilmiah Ilmu Pemerintahan*, 6(1), 148–162. <https://doi.org/10.14710/jiip.v6i1.10083>
- Waithaka, S. (2023). Effects of Agriculture on the Environment. *International Journal of Agriculture*, 8(1), 10–20. <https://doi.org/10.47604/ija.1933>
- Wardoyo, M. A. I., Prayuda, R., Susena, Y., Bardi, F. A. W., Ashari, A., & Imamah, L. F. (2021). Geomorphological hazard at some area of the Outer Dieng Volcanic Complex post explosive eruption era. *IOP Conference Series: Earth and Environmental Science*. <https://doi.org/10.1088/1755-1315/884/1/012007>
- Wijaya, M. G. K., Destiyani, I., & Rahayu, R. (2024). Identifikasi dampak perubahan suhu pada Dataran Tinggi Dieng, Jawa Tengah. *Jurnal Ekologi, Masyarakat Dan Sains*, 5(1), 31–38. <https://doi.org/10.55448/ems>
- Wolka, K., Biazin, B., Martinsen, V., & Mulder, J. (2021). Soil and water conservation management on hill slopes in Southwest Ethiopia. I. Effects of soil bunds on surface runoff, erosion and loss of nutrients. *Science of the Total Environment*, 757, 142877. <https://doi.org/10.1016/j.scitotenv.2020.142877>
- Woniala, J., Nyombi, K. (2014). Soil fertility management by smallholder farmers and the impact on soil chemical properties in Sironko District, Uganda. *Research Journal of Agriculture and Forestry Sciences*, 2(1), 5–10.
- Yu, R. P., Dresbøll, D. B., Finckh, M. R., Justes, E., van der Werf, W., Fletcher, A., Carlsson, G., & Li, L. (2025). Intercropping: ecosystem functioning and sustainable agriculture. *Plant and Soil*, 506(1), 1–6. <https://doi.org/10.1007/s11104-024-07111-w>
- Zhang, J., Lu, M., Zhang, L., & Xue, Y. (2021). Assessing indirect economic losses of landslides along highways. *Natural Hazards*, 106(3), 2775–2796. <https://doi.org/10.1007/s11069-021-04566-3>
- Zhang, K., Wang, S., Bao, H., & Zhao, X. (2019). Characteristics and influencing factors of rainfall-induced landslide and debris flow hazards in Shaanxi Province, China. *Natural Hazards and Earth System Sciences*, 19(1), 93–105. <https://doi.org/10.5194/nhess-19-93-2019>
- Zhang, L., Huang, Y., Rong, L., Duan, X., Zhang, R., Li, Y., & Guan, J. (2021). Effect of soil erosion depth on crop yield based on topsoil removal method: a meta-analysis. *Agronomy for Sustainable Development*, 41(5), 1–13. <https://doi.org/10.1007/s13593-021-00718-8>
- Zhao, X., Zhao, Z., Huang, F., Huang, J., Yang, Z., Chen, Q., Zhou, D., Fang, L., Ye, X., & Chao, J. (2023). Application of environmental variables in statistically-based landslide susceptibility mapping: A review. *Frontiers in Earth Science*, 11. <https://doi.org/10.3389/feart.2023.1147427>
- Zumpano, V., Pisano, L., Malek, Ž., Micu, M., Aucelli, P. P. C., Roskopf, C. M., Balteanu, D., & Parise, M. (2018). Economic losses for rural land value due to landslides. *Frontiers in Earth Science*, 6. <https://doi.org/10.3389/feart.2018.00097>

STAKEHOLDER ANALYSIS IN PRODUCTION FOREST MANAGEMENT AREAS OF FMU DAMPELAS TINOMBO, CENTRAL SULAWESI

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STAKEHOLDER ANALYSIS IN PRODUCTION FOREST MANAGEMENT AREAS OF FMU DAMPELAS TINOMBO, CENTRAL SULAWESI. The forest management unit (FMU) of Dampelas Tinombo was the initial formation of the FMU organization based on the typology of the local area in Central Sulawesi. The organization's growth cycle gradually encourages this FMU model as a strategy for a gradual approach to institutional formation across stakeholders. This research aimed to identify and describe patterns of power and connectivity between stakeholder actors in the management of production forest areas at FMU Dampelas Tinombo (Unit IV). This research used a qualitative approach with a case study method to understand the interests and influence of various stakeholders in managing production forests at the research site. The technique used was a stakeholder analysis matrix involving the categories of Good Relations, Protect, Monitor, and Low Priority, and "3R" (Rights, Responsibilities, and Revenues) analysis. This research revealed an imbalance between rights, responsibilities, and benefits in forest management. Stakeholders with high rights and duties have not received balanced benefits, indicating the problem of unequal distribution of profits. Weak law enforcement and a low public understanding of sustainable forest management were significant obstacles. The policy implications of this research are the need to increase law enforcement, empower communities through education and training regarding sustainable forest management, and review the distribution of rights, responsibilities, and benefits to make them more fair and effective. The findings also provide implications for future research by highlighting the need for comparative and longitudinal studies across different Forest Management Units (FMUs) to evaluate the long-term effectiveness of stakeholder collaboration, institutional governance, and social forestry policies in achieving sustainable forest management.

Keywords: FMU Dampelas Tinombo, stakeholder analysis, sustainable forests, benefit distribution

ANALISIS PEMANGKU KEPENTINGAN DI KAWASAN HUTAN PRODUKSI KPH DAMPELAS TINOMBO, SULAWESI TENGAH. Kesatuan Pengelolaan Hutan (KPH) Dampelas Tinombo merupakan awal terbentuknya organisasi KPH berdasarkan tipologi wilayah lokal di Sulawesi Tengah. Siklus pertumbuhan organisasi secara bertahap mendorong model KPH ini sebagai strategi pendekatan pembentukan kelembagaan secara bertahap di seluruh pemangku kepentingan. Penelitian ini bertujuan untuk mengidentifikasi dan mendeskripsikan pola kekuasaan dan konektivitas antaraktor pemangku kepentingan dalam pengelolaan kawasan hutan produksi di wilayah KPH Dampelas Tinombo, Sulawesi Tengah. Penelitian ini menggunakan pendekatan kualitatif dengan metode studi kasus untuk memahami kepentingan dan pengaruh berbagai pemangku kepentingan dalam pengelolaan hutan produksi. Teknik yang digunakan adalah matriks analisis pemangku kepentingan dengan kategori Hubungan Baik, Melindungi, Memantau, dan Prioritas Rendah serta analisis "3R" (Hak, Tanggung Jawab, dan Pendapatan). Penelitian ini mengungkap adanya ketidakseimbangan antara hak, tanggung jawab, dan manfaat dalam pengelolaan hutan di wilayah pengelolaan hutan. Stakeholder yang mempunyai hak dan kewajiban yang tinggi belum memperoleh manfaat yang seimbang. Hal ini menunjukkan adanya permasalahan ketimpangan distribusi manfaat. Lemahnya penegakan hukum dan rendahnya pemahaman masyarakat terhadap pengelolaan hutan lestari menjadi kendala yang signifikan. Implikasi kebijakan dari penelitian ini adalah perlunya peningkatan penegakan hukum, pemberdayaan masyarakat melalui pendidikan dan pelatihan mengenai pengelolaan hutan lestari, serta peninjauan

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kembali pembagian hak, tanggung jawab, dan manfaat agar lebih adil dan efektif. Temuan ini juga memberikan implikasi bagi penelitian di masa mendatang dengan menekankan perlunya studi komparatif dan longitudinal pada berbagai Kesatuan Pengelolaan Hutan (KPH) untuk mengevaluasi efektivitas jangka panjang kolaborasi pemangku kepentingan, tata kelola kelembagaan, dan kebijakan perhutanan sosial dalam mewujudkan pengelolaan hutan yang berkelanjutan.

Kata kunci: KPH Dampelas Tinombo, analisis stakeholder, hutan berkelanjutan, distribusi manfaat.

I. INTRODUCTION

A Forest Management Unit (FMU) is a crucial component of the national forest management system and plays a significant role in efficient and sustainable forest management. The division of the entire forest area into FMUs, each with its primary function and designation, underscores the importance of FMUs in preserving the public function of forests and serving as the foundation for sustainable forest management (Kim et al., 2016; McGlone et al., 2020).

Based on their primary functions, FMUs are classified into Forest Management Unit for conservation (FMU-Conservation), Forest Management Unit for protection (FMU-Protection), and Forest Management Unit for production (FMU-Production). Institutionally, FMU-conservation and FMU-production fall under the authority of provincial governments and are implemented through Regional Technical Implementation Units (UPTD). According to Decree of the Minister of Forestry Number: 79/2010, Central Sulawesi Province has 21 FMU units, consisting of 5 FMU-conservation and 16 FMU-Production, including FMU Dampelas Tinombo (Unit IV).

However, the formal establishment of FMUs does not automatically guarantee their effective operation at the site level. In practice, many forest areas remain characterized by de facto open access conditions, weak law enforcement, overlapping claims, and limited institutional capacity. These challenges indicate that the existence of FMUs as administrative entities still needs to be strengthened through institutional consolidation, capacity building, and multi-stakeholder engagement (Fisher et al., 2017; Hutabalian, 2023; Kim et al., 2016; McGlone et al., 2020).

This condition has encouraged stronger commitment among stakeholders to operationalize and strengthen forest management institutions at the site level through the effective implementation of FMUs. In other words, the current challenge is no longer the establishment of FMUs per se, but rather ensuring that these institutions function effectively in managing forest resources in a sustainable, inclusive, and equitable manner.

FMU Dampelas Tinombo is a model FMU established in Central Sulawesi Province. The development of this FMU model was an initial form of FMU institution based on the typology of the local area, which was gradually encouraged to develop by the organization's growth cycle. Thus, the FMU Model is a strategy for a gradual approach to the formation of FMU institutions towards the actual situation and conditions of FMUs at the site level, which is indicated, among other things, by an ability to absorb labor (including FMU organizational personnel), investment, producing forestry goods and services that are institutionalized in a sustainable and efficient forest management system. To manage forest resources optimally and fairly, FMU Dampelas Tinombo plays a role in empowering local communities through Village Forest (VF), Community Forest (CF), and Community Plantation Forest (CPF) schemes (Fisher et al., 2018; Kusmana & Sukwika, 2018; McGlone et al., 2020; Sukwika et al., 2016; Sukwika & Fransisca, 2021).

The development of forest potential in the FMU Dampelas Tinombo production forest area (Unit IV) encounters quite serious consequences and challenges due to this situation. The challenges identified include domination by certain actors, the interests of various actors, difficulties in accessing resources,

and uncertainty in obtaining added economic value from the area's development. Those challenges can be resolved if forest management is done with the support of all stakeholders in a mutually beneficial partnership framework. As key stakeholders, the community around the forest plays a crucial role in this process. It is in line with the principle of forestry partnerships that collaboration between stakeholders is essential for the success of sustainable forest management (Attanasio et al., 2022; Boutilier, 2017; Hariram et al., 2023; Mato-Santiso et al., 2021; McComb et al., 2017; Sukwika, 2018; Zubayr et al., 2014).

The implementation of cooperation/partnership schemes for forest utilization and assistance to forest farmer groups carried out by FMU in Central Sulawesi is expected to minimize social conflicts related to forest resources, achieving the goal of sustainable forests and a prosperous society.

The research was designed to identify and describe patterns of strength and connection between stakeholder actors in the Production FMU Unit IV area managed by FMU Dampelas

Tinombo. The research results will be beneficial for determining the appropriate institutional model related to the coordination pattern and involvement of stakeholders in developing the potential of FMU-Production Unit IV in a participatory and sustainable manner.

II. MATERIAL AND METHOD

A. Research Location

The research was conducted in the area managed by FMU Dampelas Tinombo, Central Sulawesi. This location was selected due to its relevance as a model production forest management unit with complex stakeholder dynamics, making it suitable for analyzing stakeholder importance and influence in site-level forest governance. The collection of data was conducted from October 2023 to December 2023.

Based on its administrative boundaries, the working area of FMU Dampelas Tinombo (Unit IV) is located in two regencies, namely Donggala and Parigi Moutong, and is distributed across six sub-districts. These include three

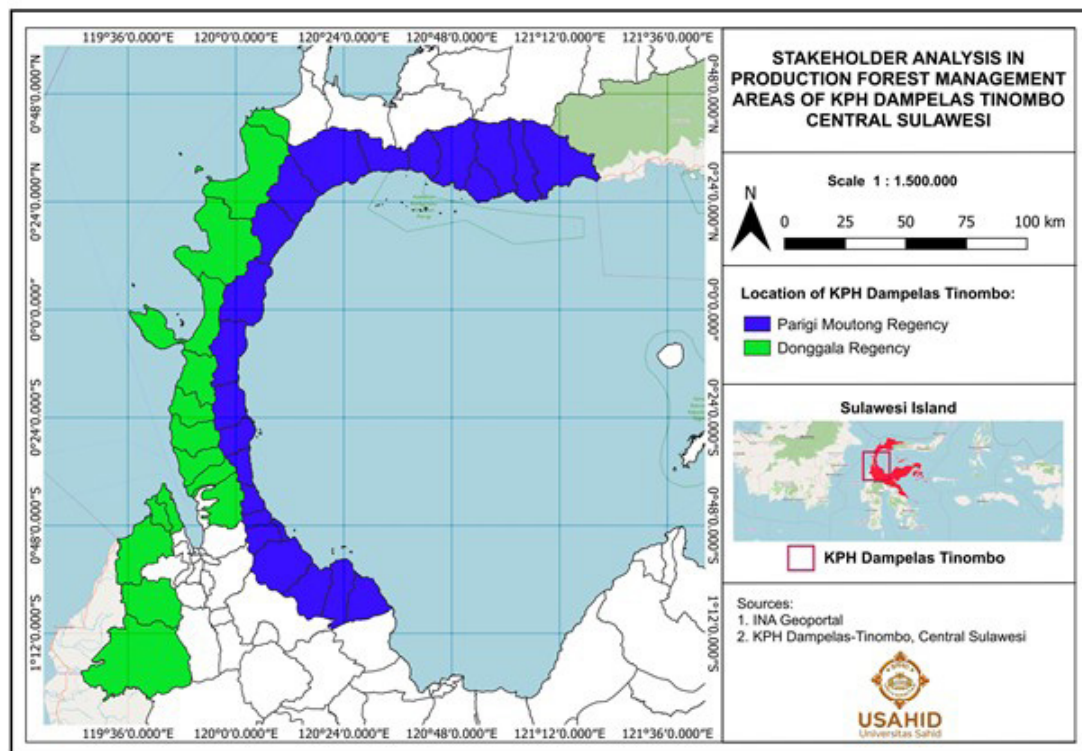


Figure 1. Research location in the Dieng Plateau Protection Forest area

sub-districts in Donggala Regency—Balaesang, Damsol, and Sojol—and three sub-districts in Parigi Moutong Regency—Kasimbar, Tinombo Selatan, and Tinombo.

Geographically, FMU Dampelas Tinombo is located at 119° 35' 54" E to 120° 04' 45" E and 0° 01' 50" N to 0° 43' 57" N. The Forest Management Unit for Production (FMU-Production) Model Dampelas Tinombo has a total forest area of 100,912 hectares. The map of FMU Dampelas Tinombo is presented in Figure 1.

B. Methods

The selection of informants was based on a purposive sampling technique, namely, a research method that ensures that illustrations are quoted using a method that determines a unique identity with a research objective to respond to a research case. This method can also be called a non-random sampling method

(Creswell & Creswell, 2017; Sugiyono, 2017). Several informants, including representatives from the Central Government, Provincial Government, Regency Regional Government, Educational Institutions, and Community Organizations, played a crucial role in this study. Their insights and perspectives, detailed in Table 1, were instrumental in understanding the stakeholder interests and influence in production forest management.

The research method in this study involved several systematic steps: (1) Research Approach: This research used a qualitative approach with a case study method to understand the interests and influence of various stakeholders in production forest management. (2) Data Collection: Data collection included primary and secondary data. Primary data were collected through in-depth interviews with various stakeholders, including the government, local communities, NGOs, forestry companies, and

Table 1. Data on stakeholders involved in the action area at FMU Dampelas Tinombo (Unit IV)

Code	Stakeholder	Code	Stakeholder
1.	Central Government (CG)	PDK8	Regional and Local Police
PPU1	Ministry of Environment and Forestry	PDK9	Regional and Local Indonesian National Armed Forces
PPU2	UPT BPSKL Sulawesi Region		
PPU3	UPT BPKH Wil XVI Palu	4.	Educational Institutions (EI)
PPU4	UPT BPHP XII Palu	LPG1	Higher Education
PPU5	UPT BPDASHL Palu Poso	LPG2	Formal education around FMU
PPU6	UPT BKSDA Central Sulawesi		
PPU7	UPT Balai Gakkum Sulawesi	5.	Mass Organizations and Society (MOS)
2.	Provincial Regional Government (PRG)	ODM1	Community Proposing Social Forestry
PDP1	Governor of Central Sulawesi	ODM2	Seroja Women's Group
PDP2	BAPPEDA Central Sulawesi	ODM3	NTFP taker community
PDP3	Forestry Service of Central Sulawesi	ODM4	Rattan brokers
PDP4	Environmental of Central Sulawesi	ODM5	Rattan buying industry
PDP5	Service FMU Dampelas	ODM6	Illegal logging perpetrators
3.	Regency Regional Government (RRG)	ODM7	Illegal timber buyers
PDK1	Regent of Donggala District	ODM8	Industry uses illegal wood from forests
PDK2	Regent of Parigi Moutong District	ODM9	Planters encroach on forest areas
PDK3	District Env. Service Donggala	ODM10	Mosque Community Figures
PDK4	District Env. Service Parigi Moutong	ODM11	Church Community Figures
PDK5	Head of District in Kab. Donggala	ODM12	Traditional Figure: Tajio, Kaili, Pendau, Lauje
PDK6	Head of District in Kab. Parigi Moutong	ODM13	Indigenous Cmty or Remote Tribes
PDK7	Village and Hamlet Heads around FMU Dampelas	ODM14	Tajio and Kaili Tribe Cmty
		ODM15	Communities outside forest activities

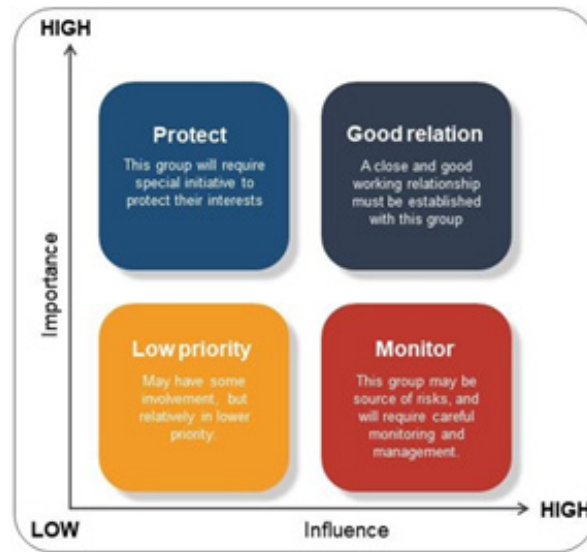


Figure 2 The stakeholder analysis matrix with criteria of protection, good relations, monitoring, and low priority

Table 2. Classification of Stakeholder Influence and Importance Levels Based on Likert Scale

Score Range	Mean Interval	Category	Description
1	1.00 – 1.80	Very Low	No influence/no support in the FMU-Production Unit IV area
2	1.81 – 2.60	Low	Limited influence/limited support in the FMU-Production Unit IV area
3	2.61 – 3.40	Moderate	Sufficient influence/ adequate support in the FMU-Production Unit IV area
4	3.41 – 4.20	High	Strong influence/high level of support in the FMU-Production Unit IV area
5	4.21 – 5.00	Very High	Very strong influence/ very high level of support in the FMU-Production Unit IV area

academics who were selected using a purposive sampling technique to ensure representation from various stakeholder groups that influence production forest management. This interview explored their views, interests, and influence on production forest management. The secondary data were collected through document studies, such as annual reports, government policies, statistical data, and relevant publications. (3) Informants Data Analysis: The data collected were then analyzed using a Stakeholder and Content Analysis approach. Stakeholder analysis aimed to identify and map the interests

and influence of each stakeholder using an interest-influence matrix. Subsequently, the content analysis techniques were used to code and categorize information obtained from interviews and documents. The data were then analyzed to find main themes related to stakeholder interests and influence. The analysis data were presented using a matrix with Protect Good Relations, Monitor, and Low Priority (Figure 2). (4) Data Validity: Data triangulation was carried out by comparing information from various sources to increase the validity of research results. The data analysis technique

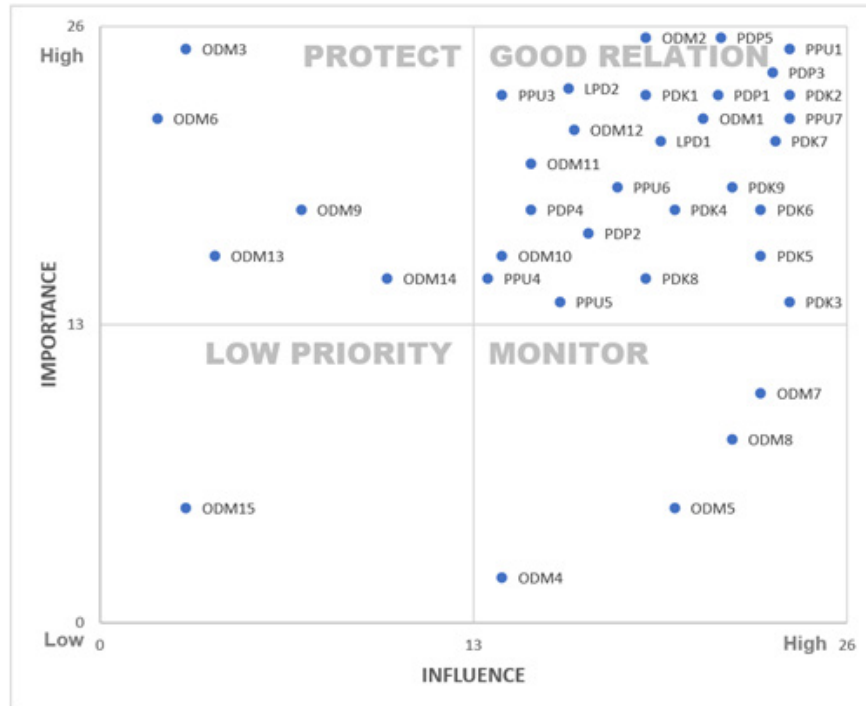


Figure 3. Mapping matrix of stakeholder importance and influence in FMU Dampelas Tinombo

for this research used the Miles and Huberman model, consisting of data collection, data presentation, data reduction, and conclusion (Sugiyono, 2017; Yin, 2018). (5) Reporting Results: Research results were presented as a report that included identification and analysis of stakeholder interests and influences, with strategic recommendations for sustainable and inclusive production forest management.

The level of stakeholder influence and importance was measured using a five-point Likert scale (1 = very low to 5 = very high). The average scores obtained from interviews were then classified into five categories using interval ranges as presented in Table 2, using Eden and Ackerman's stakeholder mapping concept approach (Colvin et al., 2020; Freeman, 2023).

III. RESULT AND DISCUSSION

A. Identify Stakeholder Mapping

According to the Eden and Ackerman concept, stakeholder groups were classified into four categories based on the influence and importance matrix results (Colvin et al., 2020; Freeman, 2023). Influence relates to the

power possessed by stakeholders to control the process and results of a decision using power variables, namely compensation power, individual power, condition power, feasibility power, and organizational power (Colvin et al., 2020; Freeman, 2023; Freeman et al., 2018; Mahajan et al., 2023).

Results of the interviews and secondary data analysis found the roles and positions of stakeholders in the FMU-Production Unit IV area, FMU Dampelas Tinombo, as depicted in Figure 2. There are 36 stakeholders with an interest and influence in the area, spread across four quadrant groups. There are 28 stakeholders in Quadrant I, Good Relationships; five stakeholders in Quadrant II, Protecting; one stakeholder in Quadrant III; and four stakeholders in Quadrant IV.

Based on the level of influence and level of importance, stakeholders can be grouped into four quadrant categories, namely:

- (1) Stakeholders who hold significant influence and have a high level of importance are crucial to the success of the program or project. Their total involvement at all stages is essential to instill confidence that their

support is key to the project's success. This group is not just a group, but a cornerstone that must be approached with respect to establish good cooperation (Good Relations: Quadrant I).

- (2) Stakeholders with little influence but a high level of importance are essential to the project. They require special efforts and unique strategies to ensure they understand that their needs align with the project's goals and that their involvement is significant. This group is not just a group; it needs to be nurtured and protected to foster their ongoing interest in the project (Protect: Quadrant II).
- (3) Stakeholders with little or no influence and importance must also be involved in the program or project but do not need a particular participation or involvement strategy (Low Priority: Quadrant III).
- (4) High-influence stakeholders but with low importance but have high influence are also important. While they may not be the main targets of programs or projects, they will likely be opponents or at least always intervene. Treating their existence as important, providing them with the necessary information, and acknowledging their views are crucial. This needs to be done to prevent trouble and open conflict from arising. This group requires careful supervision and management, acknowledging their potential impact (Monitor: Quadrant IV).

Based on the stakeholder position map in Figure 3, 36 stakeholders are spread across four quadrants. Several stakeholders were found to be key stakeholders, namely: a) In quadrant II, Good Relations, those are: (1) The Central Government, is represented by the Ministry of Environment and Forestry, (2) The provincial government consists of the governor of Central Sulawesi Province, the Forestry Service of Central Sulawesi Province, and FMU Dampelas, (3) The Regency Government is represented by the Regent of Donggala District, the Regent

of Parigi Moutong District, the village head (along with his officials), and the head of the hamlet around FMU Dampelas and (4) Mass organizations and communities i.e. community groups that propose social forestry, for example, the lotus (women) group proposed HPHD in Bondoyong Village, the group proposing CF in Sintuwu Raya Village, and other villages). b) In Quadrant I, Protect, the key stakeholders are: Mass organizations and community groups that take Non-timber forest products (NTFPs) such as rattan, palm sugar and other NTFPs, industries that use illegal wood from the forest, and remote communities or remote indigenous communities of the Pendau and Lauje tribes in the hamlet V Lambani in Silutung Village in the forest area. c) In Quadrant III, Low Priority, the key stakeholders are: the Tajio and Kaili Tribe Communities, who are communities outside of forestry activities. d) In Quadrant IV, Protect, the key stakeholders are: Mass organizations and communities, namely traders, collectors, or dealers who buy rattan from group members; barons or dealers who buy illegal wood from the forest; industrial users of illegal wood from the forest; residents or communities who encroach on or use the forest area for agriculture or plantations. Table 3 presents key stakeholders at the FMU Dampelas Tinombo (Unit IV).

Stakeholders in Quadrant I, who have high importance but relatively low influence, often depend heavily on forest resources for their livelihoods. However, structural imbalances in rights, responsibilities, and benefit distribution, combined with the dominance of top-down decision-making, limit their access to equitable opportunities. This condition may increase their reliance on unsustainable or destructive forest practices. Therefore, reducing dependence on destructive forest resources requires not only livelihood diversification but also strengthening stakeholder inclusion, improving access to rights, and integrating local knowledge into forest management planning to enhance legitimacy and reduce resistance. The role of NGOs and academics cannot influence the solid national interests supported by high authorities. The

Table 3. Results of identification of key stakeholders at FMU Dampelas Tinombo

Code	Stakeholders	Position/Quadrant
Central government		
PPU1	Ministry of Environment and Forestry	Good Relation/II
Provincial Government		
PDP1	Governor of Central Sulawesi Province	Good Relation/II
PDP3	Central Sulawesi Provincial Forestry Service	Good Relation/II
PDP5	FMU Dampelas Tinombo	Good Relation/II
Regent of Donggala Regency		
PDK1	Regent of Donggala Regency	Good Relation/II
PDK2	Regent of Parigi Moutong Regency	Good Relation/II
PDK7	Village Heads and Hamlet Heads around FMU Dampelas Tinombo	Good Relation/II
Mass Organizations and Society		
ODM2	Seroja women's group	Good Relation/II
ODM3	Community groups taking NTFPs	Protect/I
ODM4	Rattan collectors or dealers	Monitor/IV
ODM7	Dealer who buys illegal wood from the forest	Monitor/IV
ODM8	Farming communities encroach on forest areas	Monitor/IV
ODM9	Industry uses illegal wood from forests	Protect/I
ODM13	Remote Indigenous Communities of the Pendau and Lauje Tribes	Protect/I

inequality of responsibilities, rights, and income experienced by forest management stakeholders when they start implementing the policy becomes more of a burden (Kartodihardjo, 2013). Incorporating stakeholder knowledge into land use analysis provides credibility and relevance and can create critical support that can help reduce distrust and resistance during plan implementation (Attanasio et al., 2022; Hariram et al., 2023; Sukwika, 2018).

Apart from providing basic awareness, targeted capacity-building is also needed to improve community livelihoods and economic standards (Boutilier, 2017; Fisher et al., 2017; Hutabalian, 2023). In this context, providing understanding refers to enhancing community knowledge on sustainable harvesting of non-timber forest products (NTFPs), improved cultivation techniques, value-added processing, and relevant regulatory frameworks such as social forestry schemes. For example, at FMU Dampelas Tinombo (Unit IV), the Forest Investment Program II (FIP-2) has supported the processing of patchouli oil in Sibualong and Malonas Villages, as well as palm sugar processing in Oncone Raya Village.

NTFPs such as patchouli, rattan, and sugar palm need to be further developed through improved planting, cultivation, and processing techniques. Strengthening extension services and targeted training programs is therefore essential to increase product value and promote sustainable forest-based livelihoods (Daher et al., 2019; Fisher et al., 2018; McGlone et al., 2020; Sukwika et al., 2016). The regional government and FMU Dampelas Tinombo (Unit IV) must develop similar programs in other areas, especially areas that are prone to encroachment and illegal timber harvesting. Changing professions or livelihoods from illegal logging and forest encroachment to other livelihoods that do not damage forest resources may reduce pressure on the forests (Boiral & Heras-Saizarbitoria, 2017; Fisher et al., 2017; Hariram et al., 2023; Mato-Santiso et al., 2021).

The livelihoods of the community in the Dampelas Tinombo FMU area (Unit IV), apart from collecting NTFPs, are coconut or copra farming and cattle breeding. Cocoa farming, which was the previous primary livelihood source for the communities around the FMU, has been abandoned by many due

to widespread pest and disease attacks. To alleviate community pressure on forests, promoting alternative livelihood options, such as livestock development, especially beef cattle, is crucial. Another viable community activity is silvopastoral, a combination of forestry activities with cattle breeding. It involves planting grass underground or on damaged forest land and keeping cows in pens. Currently, the cattle rearing system involves releasing them to graze, which can contribute to forest pressure.

B. Analysis of Stakeholder Roles

This analysis used the "3R" concept, namely Rights, Responsibilities, and Revenues. This tool helps review, negotiate, and rebuild the roles of stakeholders according to the demands of their needs (Meyer et al., 2014). Furthermore, this tool has the necessary work steps to internalize and strengthen the role of stakeholders by dissecting the 'role' of the components of 'stakeholder rights', 'responsibilities', and 'income', and then exploring and identifying 'relationships' between stakeholders. This analysis is considered a complement to stakeholder power analysis because it has the following characteristics: Exploring relative power between stakeholders, exploring mutual relationships between stakeholders, and providing a basis for negotiating roles

by building dialogue and agreement between stakeholders (Freeman, 2023; Freeman et al., 2018; Kazadi et al., 2016; Meyer et al., 2014; Reed et al., 2018; Sukwika, 2018; Zubayr et al., 2014).

There are three levels of stakeholder influence, namely the macro level (where broader environmental and policy contexts influence stakeholders), the meso level (which reflects interactions between the FMU institution as the focal management entity and other stakeholders, and the micro level (which captures interactions among stakeholders within the same network) (Boutilier, 2017; Colvin et al., 2020; Fares, 2023; Freeman, 2023; Freeman et al., 2018; Mahajan et al., 2023; Mato-Santiso et al., 2021). This analysis consists of two parts: (a) a study of the balance between rights, responsibilities, and revenues, both inter and intra-stakeholder, and (b) a study of the status of relationships between stakeholders. The "3R" analysis identifies who has significant responsibility through joint assessments carried out by community groups with certain weights, who control access (management rights holders), and who receives the benefits or users and custodians of access to FMU forest resources. For greater clarity, the following Table 4 presents the roles of stakeholders in detail from the "3R" analysis assessment results.

Table 4. Rights, responsibilities, and revenues of stakeholders in FMU Dampelas Tinombo

Stakeholder	Right	Score	Responsibility	Score	Revenue	Score
Ministry of Environment and Forestry/UPT	Policy regulations	4	Monitor the implementation of policy regulations	4	Forest Resource Provision (PSDH) Admissions	2
Governor/Forest Service	Supervision, policy	4	Central budgeting	4	Regional original income (PAD) revenue	1
FMU Dampelas Tinombo (Unit IV)	Management of the entire area	5	Management cost budgeting	5	Receive salary/wages as a manager	2

Stakeholder	Right	Score	Responsibility	Score	Revenue	Score
Village Head/Hamlet Head	Access to all resources	3	Controlling management, security	2	Revenue sharing from HTR, rubber, palm sugar, patchouli, etc.	1
Community groups proposing Social Forestry (For example, the Seroja women's group, the group proposing HPHD in Bondoyong Village, the CF Proposing Group in Sintuwu Raya Village, and other villages)	Access to resources and land	4	Maintain and supervise the area	2	Fees, wages	5
Community groups that take NTFPs from rattan, palm sugar, and other NTFPs	Access to Rattan NTFPs	4	Issue permits for planning business work	1	Selling, consuming farming/ planting products	5
Rattan collectors/ dealers who buy rattan from group members	None	0	Planting rattan seeds	3	Selling rattan products	3
Rattan buyer/recipient industry	None	0		0	Receive rattan from local communities	3
Residents/Communities who commit illegal logging (taking wood in the forest)	Access to forest resources (timber)	4	Manage permits, pay PSDH	1	Receive rattan from traders/ middlemen (broker)	5
Dealer who buys illegal wood from the forest	There is none	0	There is none	0	Selling timber forest products	5
Industry uses illegal wood from forests	None	0	Planting tree seedlings, managing permits (in the form of Social Forestry groups)	0	Receive wood from woodcutters	5
Residents/Communities are encroachers/users of forest areas for agriculture/plantations	Access to land resources	4	None	1	Receive wood from wood buyers	5

Stakeholder	Right	Score	Responsibility	Score	Revenue	Score
Remote Communities / Remote Indigenous Communities within Kaw. Pendau and Lauje tribes in V Lambani Hamlet in Silutung Village (11.7 km) in the forest	Access to forest resources	4	None	1	Selling and consuming agricultural/ plantation products	5

Description: 1= very poor, 2= poor, 3= fair/medium, 4= high, 5= very high (maximum)

Table 5. Comparison between stakeholders in terms of rights, responsibilities, and benefits

Highest stakeholder: Rights	Highest stakeholder: Responsibilities	Highest stakeholder: Benefits
1. FMU Dampelas Tinombo 2. Ministry of Environment and Forestry or UPT 3. Governor or Forest Service. 4. Community groups proposing Social Forestry. 5. Community groups that take NTFPs, such as rattan, palm sugar, and other NTFPs 6. Residents or communities carrying out illegal logging (taking wood in the forest) 7. Residents or communities encroaching on or using forest areas for agriculture or plantations 8. Remote Communities or Remote Indigenous Communities in the Area	1. FMU Dampelas Tinombo 2. Ministry of Environment and Forestry or UPT 3. Governor or Forest Service	1. Community groups proposing Social Forestry 2. Community groups that take NTFPs from rattan, palm sugar, and other NTFPs 3. Residents or communities carrying out illegal logging (taking wood in the forest). 4. Dealer who buys illegal wood from the forest 5. Industrial users of illegal wood from forests 6. Residents or communities that are encroachers or users of forest areas for agriculture or plantations. 7. Remote Communities or Remote Indigenous Communities in the Area

Table 5 compares stakeholders regarding different aspects of rights, responsibilities, and benefits. There are eight groups or stakeholders with the highest rights in managing and utilizing forest resources in FMU. The FMU Dampelas management, as a stakeholder, holds the highest rights and has significant authority over management. Five stakeholders have the highest responsibility, namely the FMU Dampelas Manager, the Ministry of Environment and Forestry, and the Governor or Forest Service. Meanwhile, there are seven stakeholders and beneficiaries.

The current condition is that there is still an imbalance between rights, responsibilities, and benefits in forest management in the

FMU Dampelas area. Stakeholders with high rights and duties have not received high benefits. Meanwhile, stakeholders with low or almost no rights and obligations have received high benefits. This shows the importance of enforcement mechanisms or sanctions for violations of applicable regulations. Moreover, understanding of the FMU management program at the community level is still low. Therefore, continuous socialization, followed by accelerated programs that accommodate community rights, are needed so that they do not conflict with applicable regulations. This can be done, for example, by accelerating social forestry permits, both in the form of Village Forest Management and Community Forest.

Table 6. Summary of relationships between stakeholders in FMU Dampelas Tinombo

Stakeholder	Ministry of EF/UPT	Governor/EF Service	FMU Dampelas Tinombo	Head of the village	Seroja women's group	N'TFP takers	Rattan buyers	Rattan buyers	Rattan buyers	Rattan buyers	Rattan buyers	Rattan buyers	Rattan buyers
Ministry of EF/UPT		*****	*****	****	****	*	*	*	*	*	***	*	*
Governor/EF Service			*****	****	****	****	***	***	*	*	***	***	***
FMU Dampelas Tinombo				*****	*****	*****	*****	*	***	*	*	***	****
Head of the village					*****	*****	*****	*	*****	*****	*	*****	*****
Seroja women's group						*****	*****	*	*****	*****	*	*****	*****
N'TFP takers							*****	*	*****	*	*	*****	*
Rattan buyers								*****	*	*	*	*	*
Rattan industry									*	*	*	*	*
Wood Picker										*****	*	*****	*
Lumber baron											*****	*	*
Wood industry												*	*
Encroachers/Cultivators													*
Indigenous Community													

Information:

Relationship quality: Good (*****), Average (****), Poor (***), Poor (**), No interaction (*).

***** : There is personal or institutional interaction and sustainable synergy with a minimum of 3 contacts per 3 months.

**** : There is interaction, synergistic, not sustainable, maximum of three contacts per 3 months.

*** : There is interaction, lack of synergy, polemics, and one contact, and it needs to be more sustainable.

** : There is interaction, which is not synergistic or conflictual.

* : No interaction at all

Table 6 shows the relationship pattern between stakeholders in the management of FMU Dampelas Tinombo (Unit IV). Based on these relationships, two stakeholders have good relationships with almost all parties, namely the Village Head (including hamlet-level leadership) and the Social Forestry Proposing Group. The Proposing Groups include, for example, the Seroja women's group as the proponent of village forest management in Bondoyong Village, the CF proposing group in Sintuwu Raya Village, and other village-based proposing groups. These two stakeholders might function as facilitators in improving relations between

groups (Brouwer et al., 2013; Fares, 2023; Fisher et al., 2017; Hariram et al., 2023; Kartodihardjo et al., 2013; Mato-Santiso et al., 2021; Sahraoui et al., 2021; Tian et al., 2020).

Regarding the fair distribution of benefits to the parties, this study still found inequality among beneficiaries around FMU Dampelas Tinombo (Unit IV). Some parties have high rights and responsibilities in the FMU Dampelas Tinombo (Unit IV) management program but have yet to receive maximum benefits, for example, the manager of FMU Dampelas Tinombo (Unit IV) himself. At the same time, some parties obtain high benefits but have yet to

carry out their rights and responsibilities as they should. For example, illegal wood-takers from the forest, illegal timber brokers (middlemen in illegal timber trade networks), and encroachers on forest land for agriculture or planting. This condition shows that there is a lack of consensus regarding a structural approach to stakeholder influence that considers stakeholder relationship patterns as a determining factor of influence (Colvin et al., 2020; Fares, 2023; Hariram et al., 2023; Kazadi et al., 2016; Reed et al., 2018; Sukwika, 2018; Sukwika et al., 2018; Sukwika & Fransisca, 2021).

Stakeholders with negative roles will influence the sustainability of the unhealthy management of FMU Dampelas Tinombo (Unit IV). For example, illegal loggers and brokers buying wood will drain wood resources from the forest without having a balance of obligations or responsibilities in carrying out replanting, as well as not paying Forest Resources Provision (PSDH) commitments or fees for obtaining forest products. Encroachers who convert forest land into agricultural areas often obtain significant economic benefits from farming activities but do not fulfill formal obligations, such as securing permits through social forestry schemes. The persistence of encroachment and illegal logging, despite routine patrols conducted by FMU Dampelas Tinombo (Unit IV), can be attributed to multiple factors. These include limited law enforcement capacity due to constraints in personnel and resources, high economic dependence of local communities on forest land, unequal distribution of rights and benefits among stakeholders, and limited access to formal forest management schemes. These conditions are consistent with previous studies highlighting that weak enforcement, livelihood pressures, and institutional constraints contribute to ongoing forest encroachment and illegal resource use (Fisher et al., 2017; Fisher et al., 2018; Hariram et al., 2023; Kartodihardjo, 2013; McGlone et al., 2020).

The frequency of communication between officials in different forestry institutions will be higher among those who participate in

stakeholder engagement activities. However, there needs to be more evidence to show that participation in stakeholder engagement activities can increase the frequency of communication between forestry stakeholders. There is also insufficient evidence to conclude that people in forestry institutions will have a higher frequency of communication with stakeholders due to higher levels of concern about future deforestation in the Region (Boiral & Heras-Saizarbitoria, 2017; Colvin et al., 2020; Daher et al., 2019; Fares, 2023; McGlone et al., 2020; Zubayr et al., 2014). Often, what is ideal from a planning perspective fails to meet decision-makers' needs, such as regional forest management area authorities. Although the principles of sustainable forest management have strong appeal in theory, they often fail to be implemented because of the disconnection between what is desired on a large scale and the willingness of individuals to make decisions on a small scale to achieve those outcomes (Attanasio et al., 2022; Boutilier, 2017; Brouwer et al., 2013; Daher et al., 2019; Fisher et al., 2018; Kartodihardjo et al., 2013).

Therefore, FMU Dampelas Tinombo (Unit IV) must also inform the community well about preserving forests. Apart from that, the community should be provided with several facilitation efforts, including: approach the introduction of sustainable livelihood options such as non-timber forest products (NTFPs), agroforestry, and silvopastoral systems; offering technical training on sustainable harvesting, cultivation, and post-harvest processing to increase product value; and facilitating access to social forestry schemes to ensure legal and secure resource use. In addition, technical support for market access, value chain development, and continuous extension services are essential to improve community livelihoods. A persuasive and participatory approach is also needed to encourage encroaching groups to transition toward sustainable economic activities. Collaboration among FMU, local government, NGOs, and communities is crucial to support sustainable forest management and balance

economic and environmental interests (Attanasio et al., 2022; Hariram et al., 2023; Kartodihardjo et al., 2013; Mato-Santiso et al., 2021; McGlone et al., 2020; Zubayr et al., 2014).

So far, FMU Dampelas Tinombo (Unit IV) has made efforts to reach out to illegal logging perpetrators through facilitation assistance through the participation of village heads or hamlet heads. Furthermore, FMU Dampelas Tinombo (Unit IV) also collaborates with social forestry groups to obtain precise information about their activities. The data needed are who the perpetrators are, where they come from, how many people, and how much area is being converted into agricultural land or gardens. In this way, FMU Dampelas Tinombo (Unit IV) can evaluate different livelihood options that may be offered to them and do not conflict with applicable regulations and the objectives of the management of FMU Dampelas Tinombo (Unit IV). For example, continuing to use forest products but not wood, such as switching to palm sugar and planting patchouli. Currently, the culture of raising cattle is entirely developed around FMU Dampelas Tinombo, especially the development of other forest-based businesses such as silvopastoral, namely the development of stable cattle livestock by planting grass under forest stands.

Implementation of the cooperation and partnership scheme for forest utilization by FMU Dampelas Tinombo (Unit IV) includes cooperation in the utilization of environmental services through natural tourism activities and collaboration in the utilization of Non-Timber Forest Products (NTFPs) such as rattan, honey, pine resin, other resins, and more NTFPs. Besides utilizing forests through cooperation schemes, FMU Dampelas Tinombo (Unit IV) has also guided the productive businesses of Forest Farmer Groups (FFG) in the FMU buffer area. Some of the FFG products that have been developed by FMU Dampelas Tinombo (Unit IV) include moringa leaf tea, kahumama leaf tea, granulated palm sugar, coffee, patchouli leaf oil, eucalyptus leaf oil, genitri fruit crafts, as well as several other products. In general, the FMU

Dampelas Tinombo Area (unit IV) has quite a lot of potential for sugar palm stands spread throughout the Donggala Regency and Parigi Moutong Regency. In the Donggala Regency area, there are 2 FFGs, namely FFG Mentai in Malonas Village and FFG Alam Lestari in Siweli Village, that have submitted a proposal for developing a sugar palm processing business through the FIP II program. Meanwhile, in the Parigi Moutong Regency area, FFG Seroja in Bondoyong Village and FFG Puncak Hijau in Sigega Bersehati Village have implemented palm sugar processing businesses, which are supported by funding through the FIP II program. By facilitating palm sugar through FIP II, our KTHs can contribute to increasing the income of villages around the forest in the production business sector.

IV. CONCLUSION

Based on the analysis carried out using the Stakeholder Analysis Matrix and the "3R" method (Rights, Responsibilities, Revenues), this study found several vital findings: (1) There is a significant imbalance between rights, responsibilities, and benefits in production forest management. Stakeholders with high rights and responsibilities, such as the government and forestry companies, have yet to receive comparable benefits. (2) Weak law enforcement is one of the main factors hampering the effectiveness of production forest management. The lack of supervision and firm action against violations leads to illegal practices and forest exploitation that harm all parties. (3) Public understanding of sustainable forest management still needs to be improved. Local communities, which should be one of the essential pillars of forest conservation, still need to gain sufficient knowledge and skills to manage forests sustainably. Their participation in forest management needs to be optimized.

The policy implication of these findings is the need for increased law enforcement and supervision of forest management practices. The government must strengthen regulations

and ensure all parties comply with the rules. In addition, empowering local communities through education and training regarding sustainable forest management is very important. Programs that increase community awareness and capacity to protect and utilize forests responsibly must be implemented. Furthermore, reviewing the distribution of rights, responsibilities, and benefits in forest management is a must. The government and FMU Dampelas Tinombo are eager to develop fair and more inclusive policies to ensure all stakeholders receive balanced benefits according to their roles and contributions. With this, production forest management can run more effectively, fairly, and sustainably, providing maximum environmental and community welfare benefits. Finally, as research partners, stakeholders have a role in evaluating the validity of models, especially for research projecting future changes in forest areas where empirical data is often limited. This study also provides important implications for future research. Further studies should examine the long-term effectiveness of stakeholder collaboration models and policy interventions in improving the balance of rights, responsibilities, and benefits among stakeholders in production forest management. Comparative studies involving different Forest Management Units (FMUs) across regions are recommended to assess whether similar stakeholder dynamics and institutional challenges occur under different socio-ecological contexts. In addition, future research could adopt mixed-method or longitudinal approaches to evaluate changes in stakeholder relationships, community participation, and governance performance following the implementation of social forestry programs, law enforcement improvements, and community empowerment initiatives. Such studies would contribute to the development of more adaptive, inclusive, and evidence-based forest governance strategies for sustainable forest management.

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REFERENCES

- Attanasio, G., Preghenella, N., De Toni, A. F., & Battistella, C. (2022). Stakeholder engagement in business models for sustainability: The stakeholder value flow model for sustainable development. *Business Strategy and the Environment*, 31(3), 860-874. <http://dx.doi.org/10.1002/bse.2922>
- Boiral, O., & Heras-Saizarbitoria, I. (2017). Managing biodiversity through stakeholder involvement: Why, who, and for what initiatives? *Journal of Business Ethics*, 140(3), 403-421. <http://dx.doi.org/10.1007/s10551-015-2668-3>
- Boutillier, R. (2017). *Stakeholder politics: Social capital, sustainable development, and the corporation*. New York: Routledge.
- Brouwer, H., Hiemstra, W., van Vugt, S., & Walters, H. (2013). Analysing stakeholder power dynamics in multi-stakeholder processes: insights of practice from Africa and Asia. *Knowledge Management for Development Journal*, 9(3), 11-31.
- Colvin, R., Witt, G. B., & Lacey, J. (2020). Power, perspective, and privilege: The challenge of translating stakeholder theory from business management to environmental and natural resource management. *Journal of Environmental Management*, 271, 110974. <http://dx.doi.org/10.1016/j.jenvman.2020.110974>
- Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Thousand Oaks, California: Sage Publications.
- Daher, B., Hannibal, B., Portney, K. E., & Mohtar, R. H. (2019). Toward creating an environment of cooperation between water, energy, and food stakeholders in San

- Antonio. *Science of The Total Environment*, 651, 2913-2926. <http://dx.doi.org/10.1016/j.scitotenv.2018.09.395>
- Fares, J. (2023). A multi-level typology for stakeholder influence: A systematic literature review using the structural approach. *European Management Journal*, 24. <http://dx.doi.org/10.1016/j.emj.2023.08.004>
- Fisher, Kim, Y.-S., Latifah, S., & Mukarom, M. (2017). Managing forest conflicts: perspectives of Indonesia's forest management unit directors. *Forest and Society*, 1(1), 8-26. <http://dx.doi.org/10.24259/fs.v1i1.772>
- Fisher, Moeliono, M., Mulyana, A., Yuliani, L., Adriadi, A., Kamaluddin, . . . Sahide, M. A. K. (2018). Assessing the new social forestry project in Indonesia: recognition, livelihood and conservation? *International Forestry Review*, 20(3), 346-361. <http://dx.doi.org/10.1505/146554818824063014>
- Freeman, R. E. (2023). The politics of stakeholder theory: Some future directions. R. *Edward Freeman's selected works on stakeholder theory and business ethics* (pp. 119-132). Springer. https://doi.org/10.1007/978-3-031-04564-6_5
- Freeman, R. E., Harrison, J. S., & Zyglidopoulos, S. (2018). *Stakeholder theory: Concepts and strategies*. Cambridge University Press.
- Hariram, N., Mekha, K., Suganthan, V., & Sudhakar, K. (2023). Sustainalism: An integrated socio-economic-environmental model to address sustainable development and sustainability. *Sustainability*, 15(13), 10682. <http://dx.doi.org/10.3390/su151310682>
- Hutabalian, R. (2023). The part of the production forest management unit to the realizing sustainable forest management at the Sarmi Regency Province of Papua. *Bengkoelen Justice: Jurnal Ilmu Hukum*, 13(2), 155-171. <http://dx.doi.org/10.33369/jbengkoelenjust.v13i2.30877>
- Kartodihardjo, H., Jaya, I., & Nugroho, B. (2013). Stakeholders analysis of policy-making process: The case of timber legality policy on private forest. *Journal of Tropical Forest Management/Jurnal Manajemen Hutan Tropika*, 19(2). <http://dx.doi.org/10.7226/jtfm.19.2.156>
- Kazadi, K., Lievens, A., & Mahr, D. (2016). Stakeholder co-creation during the innovation process: Identifying capabilities for knowledge creation among multiple stakeholders. *Journal of Business Research*, 69(2), 525-540. <http://dx.doi.org/10.1016/j.jbusres.2015.05.009>
- Kim, Y.-S., Bae, J. S., Fisher, L. A., Latifah, S., Affi, M., Lee, S. M., & Kim, I.-A. (2016). Indonesia's forest management units: effective intermediaries in REDD+ implementation? *Forest Policy and Economics*, 62, 69-77. <http://dx.doi.org/10.1016/j.forpol.2015.09.004>
- Kusmana, C., & Sukwika, T. (2018). Coastal community preference on the utilization of mangrove ecosystem and channelbar in Indramayu, Indonesia. *AACL Bioflux*, 11(3), 905-918. <http://www.bioflux.com.ro/home/volume-11-3-2018/>
- Mahajan, R., Lim, W. M., Sareen, M., Kumar, S., & Panwar, R. (2023). Stakeholder theory. *Journal of Business Research*, 166, 114104. <http://dx.doi.org/10.1016/j.jbusres.2023.114104>
- Mato-Santiso, V., Rey-García, M., & Sanzo-Pérez, M. J. (2021). Managing multi-stakeholder relationships in nonprofit organizations through multiple channels: A systematic review and research agenda for enhancing stakeholder relationship marketing. *Public Relations Review*, 47(4), 102074. <http://dx.doi.org/10.1016/j.pubrev.2021.102074>
- McComb, E. J., Boyd, S., & Boluk, K. (2017). Stakeholder collaboration: A means to the success of rural tourism destinations? A critical evaluation of the existence of stakeholder collaboration within the Mourne, Northern Ireland. *Tourism and Hospitality Research*, 17(3), 286-297. <http://dx.doi.org/10.1177/1467358415583738>
- McGlone, M. S., McNutt, K., Richardson, S. J., Bellingham, P. J., & Wright, E. F. (2020). Biodiversity monitoring, ecological integrity, and the design of the New Zealand Biodiversity Assessment Framework. *New Zealand Journal of Ecology*, 44(2), 1-12.
- Meyer, S. R., Johnson, M. L., Lilieholm, R. J., & Cronan, C. S. (2014). Development of a stakeholder-driven spatial modeling framework for strategic landscape planning using Bayesian networks across two urban-

- rural gradients in Maine, USA. *Ecological Modelling*, 291, 42-57. <http://dx.doi.org/10.1016/j.ecolmodel.2014.06.023>
- Reed, M. S., Vella, S., Challies, E., De Vente, J., Frewer, L., Hohenwallner-Ries, D., . . . Sidoli del Ceno, J. (2018). A theory of participation: what makes stakeholder and public engagement in environmental management work? *Restoration Ecology*, 26, S7-S17. <http://dx.doi.org/10.1111/rec.12541>
- Sahraoui, Y., Leski, C. D. G., Benot, M.-L., Revers, F., Salles, D., van Halder, I., . . . Carassou, L. (2021). Integrating ecological networks modelling in a participatory approach for assessing impacts of planning scenarios on landscape connectivity. *Landscape and Urban Planning*, 209, 104039. <http://dx.doi.org/10.1016/j.landurbplan.2021.104039>
- Sugiyono. (2017). *Quantitative, qualitative and R&D research methods*. Bandung Alfabeta.
- Sukwika, T. (2018). Actor analysis in formulating institutional models for community-forest development in Bogor Regency. *Journal of Regional and Rural Development Planning*, 2(2), 133-150. <http://dx.doi.org/10.29244/jp2wd.2018.2.2.133-150>
- Sukwika, T., Darusman, D., Kusmana, C., & Nurrochmat, D. R. (2016). Evaluating the level of sustainability of privately managed forest in Bogor, Indonesia. *Biodiversitas, Journal of Biological Diversity*, 17(1), 241-248. <http://dx.doi.org/10.13057/biodiv/d170135>
- Sukwika, T., Darusman, D., Kusmana, C., & Nurrochmat, D. R. (2018). Policy scenarios for managing of sustainability private-forests in Bogor Regency. *Journal of Natural Resources and Environmental Management*, 8(2), 207-215. <http://dx.doi.org/10.29244/jpsl.8.2.207-215>
- Sukwika, T., & Fransisca, L. (2021). The policy model for sustainable community forest: A factor analysis. *Indonesian Journal of Forestry Research*, 8(2), 135-157. <http://dx.doi.org/10.20886/ijfr.2021.8.2.135-157>
- Tian, F., Li, M., Han, X., Liu, H., & Mo, B. (2020). A production–living–ecological space model for land-use optimisation: A case study of the core Tumen River region in China. *Ecological Modelling*, 437, 109310. <http://dx.doi.org/10.1016/j.ecolmodel.2020.109310>
- Yin, R. K. (2018). *Case study research and applications: Design and Methods (6th ed.)* CA: Sage Thousand Oaks.
- Zubayr, M., Darusman, D., Nugroho, B., & Nurrochmat, D. R. (2014). The roles of stakeholders in policy implementation of the use of forest area for mining activity. *Jurnal Analisis Kebijakan Kehutanan*, 11(3), 239-259. <http://dx.doi.org/10.20886/jakk.2014.11.3.239-259>

EXPANSION OF OIL PALM PLANTATIONS IN THE ASIAN AROWANA (*Scleropages formosus*) GOLDEN RED CONSERVATION AREA IN RIAU PROVINCE, INDONESIA AND ITS EFFECTS ON SOIL EROSION AND WATER QUALITY

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EXPANSION OF OIL PALM PLANTATIONS IN THE ASIAN AROWANA (*Scleropages formosus*) GOLDEN RED CONSERVATION AREA IN RIAU PROVINCE, INDONESIA AND ITS EFFECTS ON SOIL EROSION AND WATER QUALITY. The study was conducted due to rapid land use change driven by oil palm expansion in the Arowana Golden Red Conservation Area (AgrCA) in Riau Province, Indonesia. The study assessed the expansion of oil palm plantations and their influence on the environment of AgrCA. Using satellite imagery in 2017 and 2021, we found that oil palm plantations expanded from 2,234 ha (60.4% of the total area of AgrCA) in 2017 to 2,752 ha (74.4%) in 2021 by the conversion of swamps and swamp forests. The soil erosion rate estimated by a USLE method ranged from 5.26 to 186.34 t ha⁻¹ yr⁻¹ in the AgrCA. The soil erosion rates of oil palm plantations were the same as those under other agricultural land uses such as other plantations, mixed farms, and horticulture. Cleared land (land clearing or replanting area) that had not yet been planted exhibited the highest soil erosion rates. To mitigate the risk of soil erosion, it is crucial to replant oil palm trees on the cleared land as soon as possible. Water bodies adjacent to old oil palm plantations and the cleared land exhibited low levels of dissolved oxygen and were considered very trophic regarding phosphate concentrations. The low water quality was probably caused by the residual effects of fertilization in the old oil palm plantations.

Keywords: Land use change, soil erosion, endangered species, habitat.

PERLUASAN PERKEBUNAN KELAPA SAWIT DI KAWASAN KONSERVASI AROWANA GOLDEN RED (*Scleropages formosus*) DI PROVINSI RIAU, INDONESIA DAN PENGARUHNYA TERHADAP EROSI TANAH DAN KUALITAS AIR. Penelitian ini dilakukan karena perubahan penggunaan lahan yang cepat akibat perluasan perkebunan kelapa sawit di Kawasan Konservasi Arowana Golden Red (AgrCA) di Provinsi Riau, Indonesia. Penelitian ini mengevaluasi perluasan perkebunan kelapa sawit dan pengaruhnya terhadap lingkungan AgrCA. Dengan menggunakan citra satelit pada tahun 2017 dan 2021, kami menemukan bahwa perkebunan kelapa sawit meluas dari 2.234 ha (60,4% dari total luas AgrCA) pada tahun 2017 menjadi 2.752 ha (74,4% dari total luas AgrCA) pada tahun 2021 melalui konversi rawa dan hutan rawa. Laju erosi tanah yang diperkirakan dengan metode USLE berkisar antara 5,26 hingga 186,34 t ha⁻¹ thn⁻¹ di AgrCA. Laju erosi tanah pada perkebunan kelapa sawit sama dengan laju erosi tanah pada penggunaan lahan pertanian lainnya seperti perkebunan lainnya, pertanian campuran, dan hortikultura. Lahan yang dibuka (lahan yang sedang dibersihkan atau lahan sedang peremajaan) dan belum ditanami menunjukkan tingkat erosi tanah tertinggi. Untuk mengurangi risiko erosi tanah, sangat penting untuk menanam kembali pohon kelapa sawit di lahan yang telah dibuka sesegera mungkin. Badan air yang berdekatan dengan perkebunan kelapa sawit tua dan lahan yang telah dibuka menunjukkan tingkat oksigen terlarut yang rendah dan konsentrasi fosfat yang sangat tinggi. Rendahnya kualitas air kemungkinan disebabkan oleh efek residu dari pemupukan di perkebunan kelapa sawit tua.

Kata kunci: Perubahan penggunaan lahan, erosi tanah, spesies terancam punah, habitat

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I. INTRODUCTION

Indonesia is one of the leading countries in global palm oil production. In 2019, Indonesia's palm oil production reached 42.86 million tons, accounting for 57% of the world's total palm oil production, which was 74.58 million tons (FAO, 2022). Only 35% of Indonesia's palm oil is consumed domestically, while the remaining 65% is exported worldwide. In 2010–2020, Indonesia's palm oil exports were distributed across various regions, including Asia (64.72%), the EU (16.29%), Africa (13.59%), America (5.30%), and Oceania (0.07%) (Bogheiry, Thaha, & Rahmah, 2023).

The prominent position of Indonesia in palm oil production is attributed to the extensive expansion of oil palm plantations in the country. This expansion has been remarkable, surging from 0.13 million ha in 1970 to 15.38 million ha in 2022 (Directorate General of Estate, 2022). The conversion of numerous forests, peatlands, coastal areas, and other natural landscapes into oil palm plantations, has contributed to increased palm oil production. While this conversion has led to environmental impacts, Indonesia has concurrently experienced significant economic benefits from this thriving agricultural sector (Ayompe, Schaafsma, & Egoh, 2021; Meijaard et al., 2020; Monitor, 2023; Srisawasdi, Tsusaka, & Cortes, 2023).

Indonesia has witnessed the conversion of natural forests into oil palm plantations in pursuit of increased economic gains. However, conversion of natural areas is widely believed to be the primary threat to nature, leading to global declines in species abundance, diversity, and ecosystem health. Despite extensive research into the drivers of these global changes, there remains a need for the effective preservation of biodiversity across various species and habitats (Davison, Rahbek, & Morueta-Holme, 2021). The United Nations introduced the 2030 Agenda for Sustainable Development, encompassing the Sustainable Development Goals (SDGs), calling upon nations to balance between economic, social, and environmental

aspects to promote sustainable development (United Nations Development Group, 2017).

The transition of natural areas to oil palm plantations in Indonesia has had detrimental effects on biodiversity. Sumatran orangutans (*Pongo abelii*) and Bornean orangutans (*Pongo pygmaeus*) are on the brink of extinction due to the expansion of oil palm plantations (Nellemann, 2007; Swarna & Tisdell, 2009; Tan, Lee, Mohamed, & Bhatia, 2009). Furthermore, Sumatran elephants (*Elephas maximus sumatrensis*), Sumatran tigers (*Panthera tigris sumatrae*), and Sumatran rhinoceros (*Dicerorhinus sumatrensis*) face critical threats due to these developments (Danielsen et al., 2009; Sheil et al., 2009). Indonesia is a nation renowned for its mega-biodiversity and high national biodiversity index (NBI). The country's actions and policies are crucial for preserving this biodiversity (Keong, 2015; Von Rintelen, Arida, & Häuser, 2017).

Freshwater biodiversity has been the overriding international conservation priority since 2005. Given the critical importance of freshwater ecosystems, efforts to study and safeguard them are ongoing to ensure their sustainability (Albert et al., 2021; Birk et al., 2020; Darwall et al., 2018; Dudgeon et al., 2006; Flitcroft, Cooperman, Harrison, Juffe-Bignoli, & Boon, 2019; Maasri et al., 2022; Reid et al., 2019; Strayer & Dudgeon, 2010; Su et al., 2021). One of the freshwater fish species in Indonesia is the Asian arowana (*Scleropages formosus*) variety golden red. This fish was found initially in Rokan Hulu Regency of Riau Province, Indonesia.

The Asian arowana golden red is highly sought after and is considered valuable due to its exotic and precious nature. Unfortunately, over the past 30 years, its popularity has led to significant overexploitation of its natural habitat (Fernando et al., 1997). As a result of its declining numbers, the Asian arowana golden red has been categorized as an endangered species on the International Union for Conservation of Nature and Natural Resources (IUCN) Red List since 2006 (Dawes, 2006; Yue, Chang, Yuzer, & Suwanto, 2020). Furthermore,

the Asian arowana golden red has been on Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) since 1975. It has also been recognized as a protected species in Indonesia as declared by the Government of The Republic of Indonesia in 1999.

Initially, the Rokan Hulu Regency was covered by a natural forest. However, over the last five decades, the area has been cleared and converted into oil palm plantations. The Central Statistics Agency of Riau Province reported an increase in the oil palm plantation area in Rokan Hulu from 208,47 ha in 2012 to 267,84 ha in 2021 (Central Statistics Agency of Riau Province, 2022). This transition has boosted the community's economic income but has exerted significant pressure on the habitat of the Asian arowana golden red. In response to these challenges, the Regent of Rokan Hulu designated the Arowana Golden Red Conservation Area (AgrCA), spanning approximately 3,700 ha, in 2009. However, as the designation of this area as a protected zone to preserve the habitat of the Asian arowana golden red progressed, the outcomes have not been promising. Despite the conservation efforts in the AgrCA, the expansion of oil palm plantations has continued. The swamps and swamp forests within the AgrCA, which serve as the natural habitat of the Asian arowana golden red, have been drained and converted into oil palm plantations.

A previous study conducted in the AgrCA (Purnama & Masunaga, 2023) on aquatic organisms identified 47 species with a total of 424 individuals: 7 genera of benthos, 11 species of planktonic algae, and 29 species of fish. The diversity index was in the range of 0.46–2.45 in 2020, which was comparable to or higher than that in other areas in Kalimantan, Aceh province, and Malaysia. However, swamp forests, which are the habitat of the Asian arowana golden red, only covered 7.0% of the area (264 ha) in 2017, and only 31 Asian arowana golden red individuals were found in the AgrCA in 2020.

These land use changes, accompanied by the drying and clearing of the land, may increase soil erosion. The eroded materials entering water bodies have the potential to alter the condition of aquatic environments and biodiversity (Issaka & Ashraf, 2017). Purwanto et al. (2019) and Agustina and Dewi (2020) measured soil erosion rates in oil palm plantations located in Palangkaraya, Central Kalimantan, and Muara Enim, South Sumatra, respectively. However, no studies, including the aforementioned ones, have examined the effects of oil palm plantations on soil erosion and the surrounding environment.

Considering the importance of the AgrCA to protect aquatic biodiversity, including the Asian arowana golden red, it is crucial to understand and mitigate the impacts of land use changes on water quality. In the present research, we investigated the influence of land use changes in the AgrCA from 2017 to 2021, estimated soil erosion rates, and analyzed the effects of land use changes on water quality. This study provides the first integrated assessment linking multi-temporal land-use change (2017–2021), soil erosion modeling, and water quality dynamics within a designated AgrCA in Riau, Indonesia.

II. MATERIAL AND METHOD

A. Study Site

The present study was conducted in the AgrCA (Figure 1). For the water quality analysis, water sampling sites were established where the Asian arowana golden red still existed and the original vegetation (i.e., swamp forest) still dominated. Starting in 2020, we set up three types of water sampling sites in Middle Mahato. They were waterbodies adjacent to 1) oil palm plantations of varying ages (OP1: aged 1–7 years, OP2: aged 8–15 years, and OP3: aged 16–20 years), 2) cleared land, and 3) swamp forests. The term “cleared land” refers to the cleared land that was previously old oil palm plantations and was being replanted with oil palms. Oil palm farmers have cleared the old

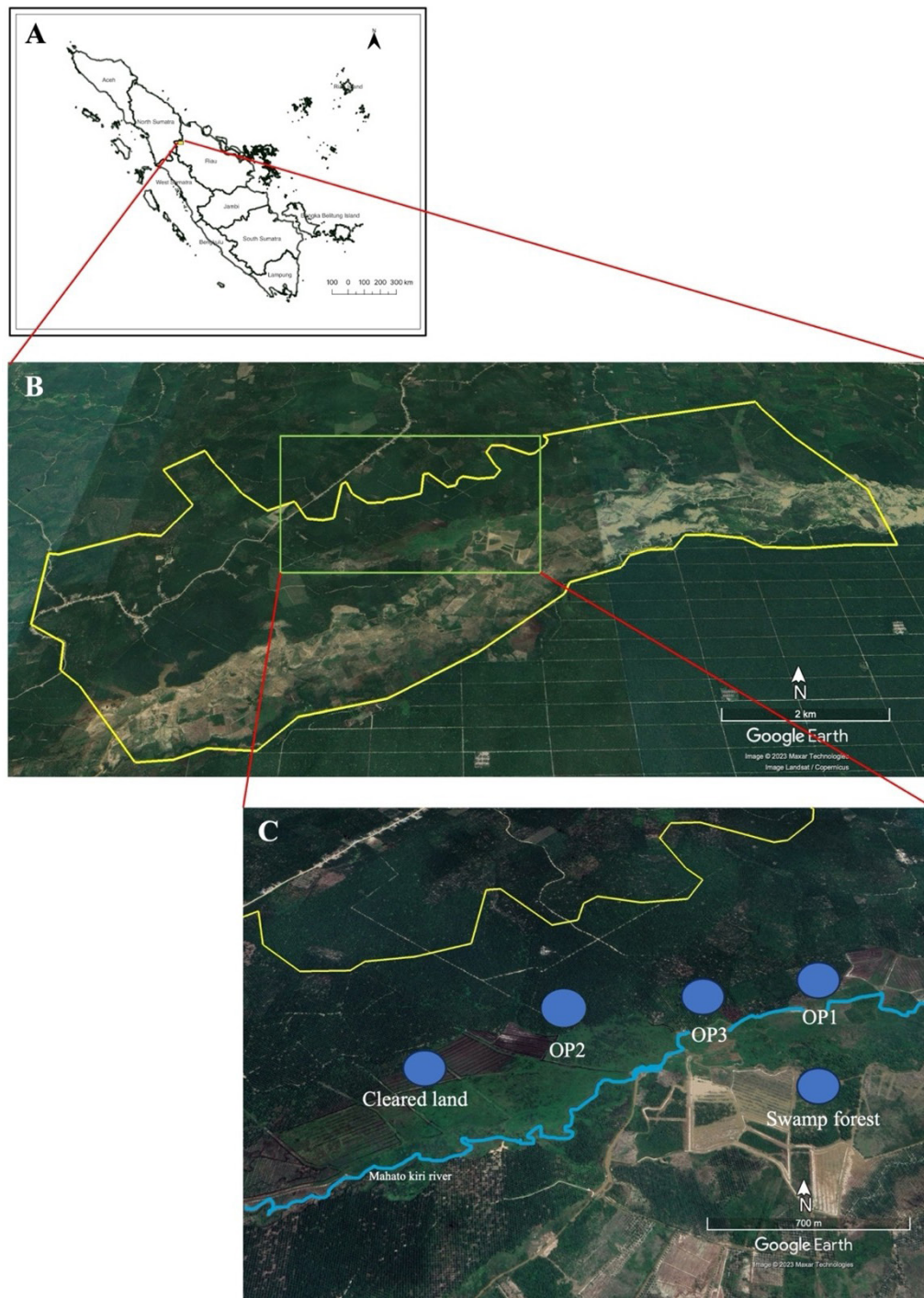


Figure 1. Map of AgrCA and research sampling site

oil palm fields with the age more than 20 years by cutting and chopping the old palms using machines. The chopped stems were then spread across the land and left to decompose. On the cleared lands, few grasses were observed even after 2 years of the land clearance (Figure 2).

On the land use types of “settlement” and “industrial area”, the house and industrial area properties (courtyard) were utilized for a traditional home garden (so-called Pekarangan, i.e. home garden consisting with orchard trees, small crop field and/or grasses (Figure 3).



Figure 2. Cleared land more than 2 years after clearance (foreground)



Figure 3. A farmer's house with home garden, so-called Pekarangan in Indonesia, in settlement area

B. Data Collection

1. Key Resource Assessment of Perum Perhutani's Cajuput Oil Business

The land-use change mapping was performed using QGIS 3.20.2 (García-Álvarez, Camacho Olmedo, Paegelow, & Mas, 2022). The polygon boundary of the Asian Arowana

Golden Red Conservation Area (AgrCA), covering approximately 3,700 ha, was obtained from Regent of Rokan Hulu Decree No. 169 of 2009 (Regent of Rokan Hulu, 2009). The boundary was georeferenced and overlaid with the Indonesian geospatial reference map (Indonesian Geospatial, 2022). Land-use

data for 2017 and 2021 were derived from Google Earth Pro Digital Terrain Model data and processed into digital elevation model (DEM) layers. The DEM layers were clipped to the AgrCA boundary and overlaid with the conservation-area polygon, after which land-use classes were digitized and their respective areas calculated. The resulting spatial data were exported as shapefiles (.shp), and area calculations were tabulated using Microsoft Excel. Land-use classification followed the categories established by the Ministry of Agrarian Affairs of the Republic of Indonesia (2009), with modifications to reflect the specific conditions of oil palm plantations and swamp areas (Table 3). Field surveys were conducted to validate the mapped land-use classes, and geographic coordinates were recorded using a Garmin GPSMAP 64.

The Universal Soil Loss Equation (USLE) has been widely utilized by researchers to estimate soil erosion across various environments. To assess the applicability of the USLE in the present study, we referenced the work of Agustina and Dewi (2020), who validated the method within oil palm plantations through comparison with actual measurements in Muara Enim Regency, Indonesia. Their findings demonstrated that erosion rates

predicted by the USLE closely corresponded with those measured in field plots (4 m × 20 m) established on slopes of 5°, 10°, and 15°, under rainfall conditions of less than 43.5 mm day⁻¹. Notably, the average daily rainfall in the present study area from 2012 to 2021 remained within this range. Furthermore, we found that the results obtained using the USLE in the present study were comparable to the values reported in previous studies Anasiru (2015), Purwanto et al. (2019), and Agustina and Dewi (2020), which conducted field measurements of soil erosion, as detailed in the Results section. Therefore, we determined that the USLE was applicable for the present study. The calculation of USLE is.

$$A = R \times K \times L \times S \times C \times P \dots\dots\dots(1)$$

where: A is the average annual soil loss per area unit (t ha⁻¹ yr⁻¹), R is the average rainfall erosivity factor (MJ mm ha⁻¹ h⁻¹ yr⁻¹) in 10 years, K is the soil erodibility factor (t ha h MJ⁻¹ mm⁻¹), L is the slope length factor, S is the slope steepness factor, C is the land use factor, and P is the support and conservation practices factor. R was analyzed using the Lenvain equation (Asdak, 1995, DHV Consulting Engineers, 1989):

$$R = 2.21 \text{ Precip}^{1.36} \dots\dots\dots(2)$$

Table 1. Monthly rainfall in Arowana golden red Conservation Area (2012 – 2021)

Years	Months											
	January	February	March	April	May	June	July	August	September	October	November	December
2021	290.3	180.8	253.3	482.3	365.5	224.1	147.8	187.1	179.1	334.6	405.3	307.3
2020	153.1	108.2	129.6	233.9	177.1	160.9	255.6	219.3	148.1	270.5	304.7	138.3
2019	274.3	93	67.1	203.1	226.2	311.1	23.9	68	23	284.8	273.6	242.3
2018	80.7	18.6	227.5	55.6	303.1	202.4	128.2	75.6	107.6	442.8	493.4	274.1
2017	338.2	354.4	370.2	386.2	401.5	296.9	119	148.3	28	73.5	255.2	388.8
2016	258.1	192.8	177.9	332.4	220.7	105.1	272.7	43.7	274	159.1	511.4	168.8
2015	139.9	11.1	333.5	129.3	140.3	98	13.5	300.1	61	64.7	380.9	317.1
2014	255.9	18.6	181.5	348.3	225.9	140.2	175.5	105	141.6	362.9	328.2	297.6
2013	120.9	325	339	176.9	126.9	53.5	140.3	183.7	146.6	469.7	453.4	541.5
2012	102.5	211.8	329	202.4	190.1	165.5	235.6	97	185.8	228.9	443.4	241.1

Source: Indonesian Meteorology, Climatology and Geophysical Agency (Indonesian Agency for Meteorological, Climatological and Geophysics, 2022)

where: Precip is the monthly rainfall over 10 years (mm/month). Rainfall data were collected from the Indonesian Meteorology, Climatology and Geophysical Agency (Indonesian Agency for Meteorological, Climatological and Geophysics, 2022) (Table 1). Soil type classification was sourced from the Food and Agriculture Organization (FAO) (Food and Agricultural Organization of the United Nations, 2022). A field soil sampling was conducted to confirm soil type. We collected soil samples at OP1, OP2, OP3, and cleared land using a random method, for a total of 4 soil samples. All the soil samples were analyzed at the Soil Laboratory, Agricultural Modernization Testing and Application Installation (IP2MP) - West Sumatra.

The LS factor accounts for the influence of topography on soil erosion. The slope length factor (L) represents the effect of slope length on erosion, while the slope steepness factor (S) reflects the impact of slope gradient. In

this study, the LS factor was estimated using a digital elevation model (DEM) from the data of Indonesian Agency for Geospatial Information (2021). The calculation of the LS factor requires both flow accumulation and slope steepness. Flow accumulation was derived from the DEM using watershed delineation techniques, while slope steepness was calculated directly from the DEM by the Desmat and Grover (1996) method in QGIS. The slope gradient (%) and slope length (m) can be accurately determined and combined with the incline of the DEM to form a LS factor. The equation used to compute this parameter was recommended by Morgan (2009).

$$LS = (x/22.13)^n (0.065 + 0.045 + 0.0065s^2) \dots\dots(3)$$

where: x is the slope length (m), n is the index value percentage slope categories (<1%: 0.2; 1 - 3 %: 0.3; 3 - 5 %: 0.4; 5 - 20 %: 0.5; >20%: 7.10), and s is the slope gradient (%). Based on

Table 2. C and P-factor values

Land use type	C value	P value	Author/Source
Oil palm plantation	0.2	1	Asdak (1995), Regulation of the Minister of Forestry of The Republic of Indonesia (2009)
Swamp	0	0	-
Swamp forest	0	0	-
Cleared land	0.9	1	Regulation of the Minister of Forestry of The Republic of Indonesia (2009)
Other-plantations	0.2	1	Asdak (1995), Regulation of the Minister of Forestry of The Republic of Indonesia (2009)
Shrubland	0.4	1	Asdak (1995), Regulation of the Minister of Forestry of The Republic of Indonesia (2009)
Mixed farm	0.4	1	Asdak (1995), Regulation of the Minister of Forestry of The Republic of Indonesia (2009)
Settlement	0.3	1	Regulation of the Minister of Forestry of The Republic of Indonesia (2009)
Industrial area	0.3	1	Regulation of the Minister of Forestry of The Republic of Indonesia (2009)
Horticultural land	0.2	1	Asdak (1995), Regulation of the Minister of Forestry of The Republic of Indonesia (2009)

the Regulation of the Minister of Forestry of The Republic of Indonesia (2009), the LS value can be converted into the following categories: Flat (0-0.25), slope (>0.25-1.20), rather slope (>1.20-4.25), steep (>4.25 - 9.50), very steep (>9.25). Soil erodibility (K), which measures the influence of physical and organic properties on the soil's susceptibility to erosion.

The soil type in the AgrCA is classified as *Plinthic Acrisols*. Based on finding Alim & Anggraini (2021), the K value in Rokan Hulu ranges from 0 to 0.39; we referred to and identified K value in AgrCA as 0.29. The C and P value was decided based on Indonesian Centre for Irrigation Research and Development (Asdak, 1995) and the Regulation of the Minister of Forestry of The Republic of Indonesia (2009), considering land surface conditions. We adopted the C value of land category “Bareland (bare soil + no-till)” of the Regulation, where this category is similar to clear land in our study

that is not being cultivated. Cleared land has a C value of 0.9; settlement and industrial area have a C value of 0.3; shrubland and mixed farm have a C value of 0.4; and oil palm plantation, other plantation, and horticultural land have a C value of 0.2 (Table 2).

The lowest C value was in oil palm plantations, other plantations, and horticultural land and the highest C value was in cleared land, settlements, and industrial areas. A C value of 1 indicates the absence of ground cover, while a C value close to 0 indicates well-protected soil cover and management (Pham, Degener, & Kappas, 2018). The P value for all land uses was 1, which implies poor conservation practices. P values range from 0 for good conservation practices to 1 for bad conservation practices (Ganasri & Ramesh, 2016).

Quantum GIS (QGIS) software was used to generate erosion maps. The analysis of the soil erosion estimation model from QGIS

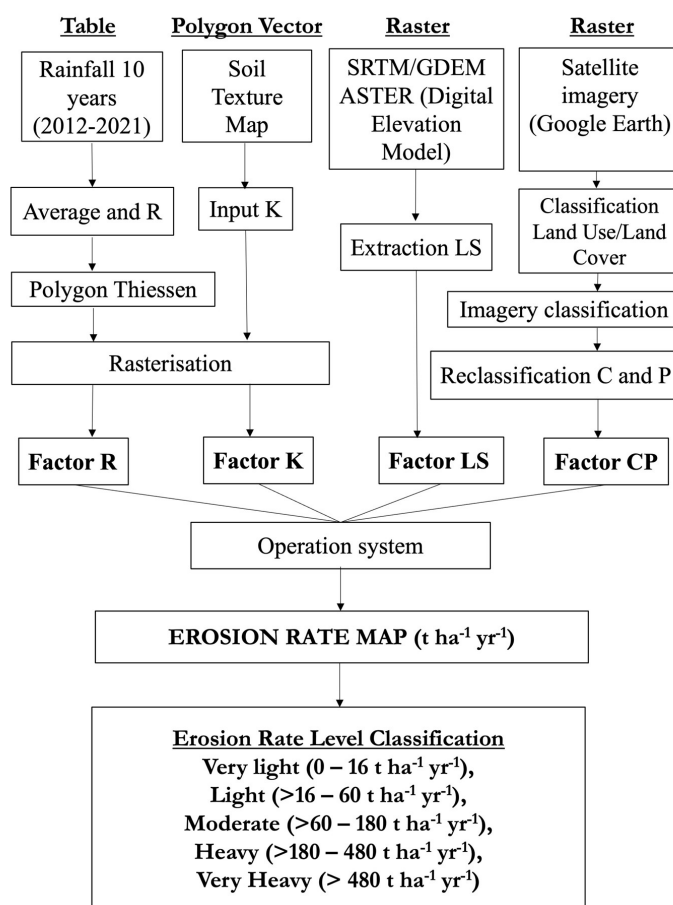


Figure 4. Soil erosion estimation model through Quantum GIS (QGIS)

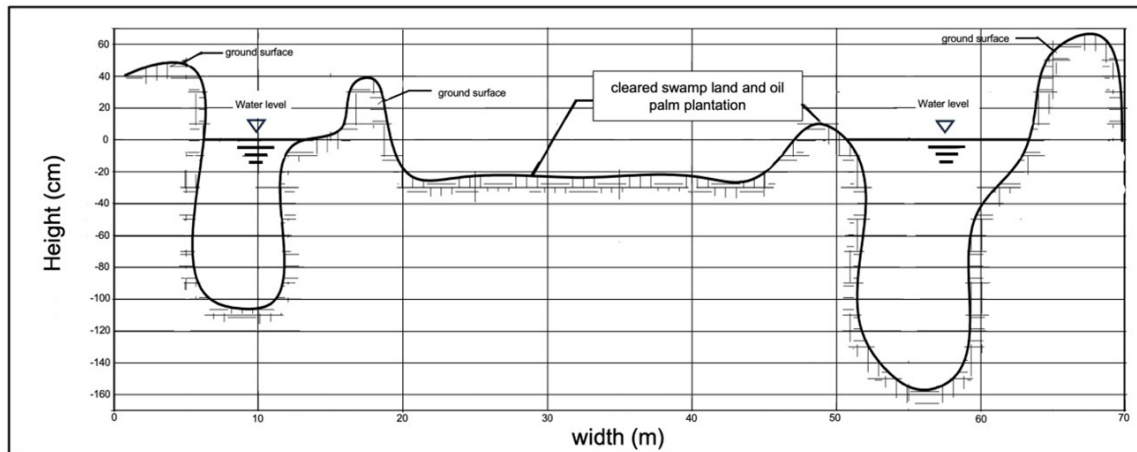


Figure 5. Cross-section in formed swamp and swamp forests, and new oil palm plantation in AgrCA

is shown in Figure 4. The integration of the USLE method with GIS efficiently predicts the intensity of soil erosion and its spatial distribution (Nyesheja et al., 2019; Amellah & el Morabiti, 2021; Vijith, 2012; Saswattecha, Hein, Kroeze, & Jawit, 2016; Sestras et al., 2023). Erosion rates were classified into five classes: level I (very light: $0-16 \text{ t ha}^{-1} \text{ yr}^{-1}$), level II (light: $>16-60 \text{ t ha}^{-1} \text{ yr}^{-1}$), level III (moderate: $>60-180 \text{ t ha}^{-1} \text{ yr}^{-1}$), level IV (Heavy: $>180-480 \text{ t ha}^{-1} \text{ yr}^{-1}$), and level V (very heavy: $>480 \text{ t ha}^{-1} \text{ yr}^{-1}$) (Minister of Forestry, 2009).

Soil erosion was not estimated for swamps, swamp forests, or cleared swamp land, or for oil palm plantations developed in swamps, swamp forests, or cleared swamp land. This was because the USLE is not applicable to the concave areas between canals (Figure 5), where the land was submerged by overflowed canal water during heavy rainfall events.

2. Water Sampling and Analysis

We collected and analyzed surface water samples at OP1, OP2, OP3, and cleared land, approximately 1 m from the riverbanks to assess water quality. At the sites, we measured water temperature and depth. Simultaneously, we collected 2 L of river water using a sample bottle, which was then transported to the laboratory for analysis.

Water samples were analyzed for pH, total suspended solids (TSS), dissolved oxygen (DO), turbidity, ammonia ($\text{NH}_3\text{-N}$), total nitrogen (TN), phosphate (PO_4), potassium (K), and sediment total organic carbon. All water-quality analyses followed the standard procedures of the American Public Health Association (APHA, 2005).

Sampling was conducted from 2020 to 2023 at three-month intervals, with two sampling events during the dry season (January–June) and two during the rainy season (July–December) each year. Five replicates were collected for each sampling event. Sampling locations represented three land-use categories: oil palm plantations (OP1, OP2, and OP3), cleared land, and swamp forest. Measured water-quality parameters were compared with the water-quality criteria for Asian arowana golden red habitat specified in Regulation of the Minister of Marine Affairs and Fisheries of the Republic of Indonesia No. 12/PERMEN-KP/2015. Water pollution status and trophic conditions were further assessed according to the Indonesian national water-quality standards for river environments established under Government Regulation of the Republic of Indonesia No. 22/PP/2021.

Water quality standards from the Water Analysis Manual, Tropical Aquatic Biology Program, Biotrop, Southeast Asian Regional

Centre for Tropical Biology (Wardoyo, 1982) were used. One-way analysis of variance (ANOVA) and Duncan's multiple range test (DMRT) were used to analyze the differences between sampling sites for PO_4 parameters.

III. RESULT AND DISCUSSION

A. Result

1. Expansion of Oil Palm Plantations in The AgrCA in 2017–2021

In 2017, oil palm plantations covered an area of 2,234 ha. Between 2017 and 2021, there was a notable increase in the area dedicated to oil palm plantations, resulting in an expansion of 518 ha, bringing the total to 2,752 ha. All conversions took place on land formerly covered by swamps and swamp forests. Consequently, the swamp area decreased by 664 ha (from 921 ha to 257 ha), and the swamp forest area decreased by 116 ha (from 264 ha to 148 ha). By 2021, oil palm plantations had the highest coverage at approximately 74%, while swamp

forests covered approximately 4%. The land use change from swamps and swamp forests to cleared swamp land accounted for 258 ha.

Other land use categories, such as other plantations, shrublands, mixed farms, settlements, cleared land, industrial areas, and horticultural land, remained relatively stable in their coverage, with a combined total area of less than 90 ha. Detailed information regarding land use and the corresponding areas is provided in Table 3, and a visual representation is presented in Figure 6.

2. Estimated Soil Erosion Rates in Respective Land Uses in 2021

As all land conversions into oil palm plantation or cleared swamp land took place on land formerly covered by swamps and swamp forests where the USLE was not applicable, we estimated soil erosion rates only in 2021. The rainfall erosivity value (R) in the AgrCA was $1,903.62 \text{ MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$. The LS value ranges from 0 to 1.56 (Figure 7).

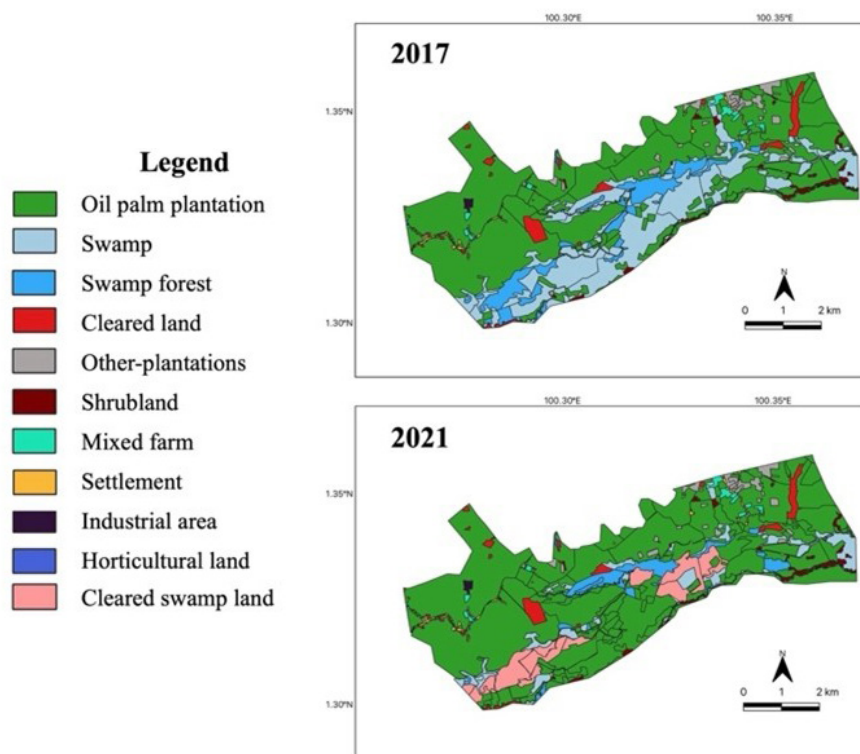


Figure 6. Land use change during 2017 to 2021 in AgrCA

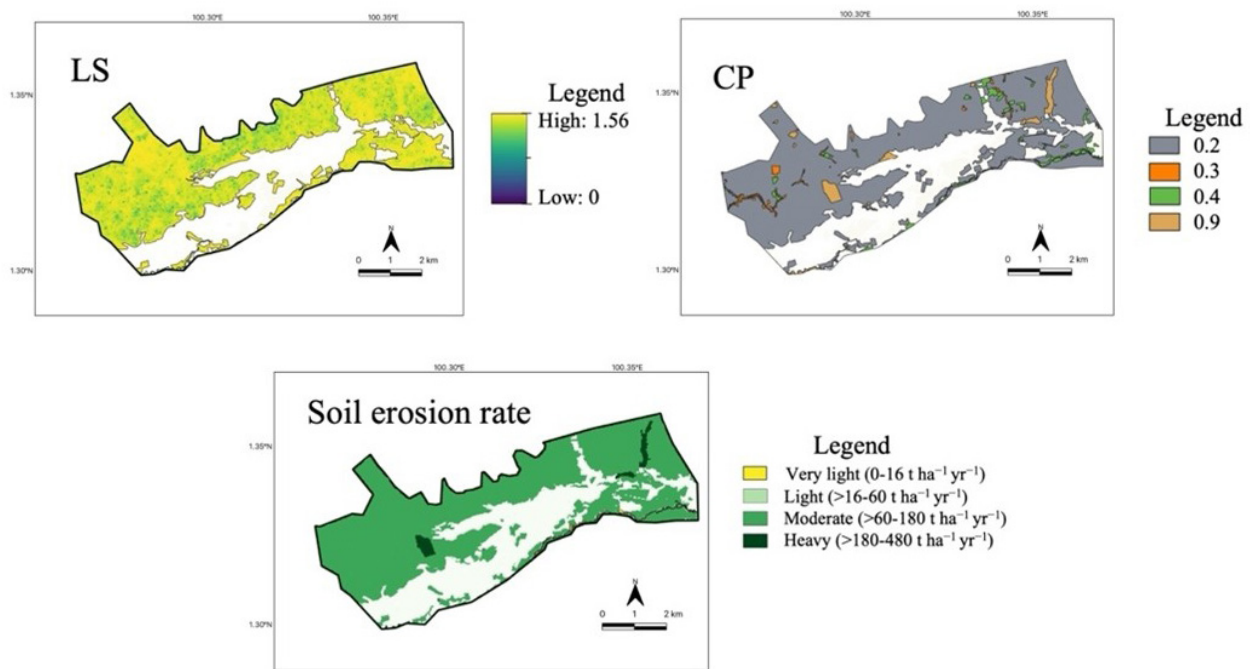


Figure 7. MAP of LS, CP, and soil erosion rate in AgrCA

Table 3. Land use cover changed in AgrCA

Land use type	Area (ha)		Covering (%)	
	2017	2021	2017	2021
Oil palm plantation	2234	2752	60.4	74.4
Swamp	921	257	24.9	6.9
Swamp forest	264	148	7.1	4.0
Cleared land	85	85	2.3	2.3
Other-plantations	76	76	2.1	2.1
Shrubland	47	52	1.3	1.4
Mixed farm	36	36	1.0	1.0
Settlement	29	29	0.8	0.8
Industrial area	6	6	0.2	0.2
Horticultural land	2	2	0.1	0.1
Cleared swamp land	0	258	0.0	7.0
Total	3700	3700	100.00	100

The soil erosion rate ranged from 5.26 to 186.34 t ha⁻¹ yr⁻¹ (Table 5). In general, land coverage (C) influenced the soil erosion rate in the AgrCA. Relatively high soil erosion rates were observed in the area of cleared land, where 142.11 – 186.34 t h⁻¹ yr⁻¹. Settlements and industrial areas exhibited similar soil erosion

rates ranging from 61.22 to 101.12 t ha⁻¹ yr⁻¹, and 66.08 to 109.34 t ha⁻¹ yr⁻¹, respectively. Agricultural areas, including oil palm plantations (60.16–158.29 t ha⁻¹ yr⁻¹), other plantations (60.17–128.20 t ha⁻¹ yr⁻¹), mixed farms (60.16–118.34 t ha⁻¹ yr⁻¹), and horticultural land (60.66–115.18 t ha⁻¹ yr⁻¹), displayed similarly

high erosion rates. In contrast, shrubland exhibited relatively low erosion values, ranging from 5.26 to 61.16 t ha⁻¹ yr⁻¹.

3. Water Quality

Table 4 shows the average values of water quality parameters of selected sampling sites at swamp forest, oil palm plantation, and cleared land. In general, the water parameters were classified as “not polluted,” except phosphate (PO₄) and dissolved oxygen (DO), according to the water quality standard for the

environment of the Southeast Asian Regional Centre for Tropical Biology. Dissolved oxygen was classified as “lightly polluted” for all sites, and the phosphate level was classified as “very trophic” in OP3 and cleared land. Water quality measurements were compared among the sites, and only the PO₄ concentration showed significant differences, with the concentration in OP3 and cleared land being significantly higher ($P < 0.05$) than that in other sites. However, the water quality was habitable for arowana.

Table 4. Average of water quality parameters in AgrCA during 2020 - 2023 (Mean $\pm$ standard deviation)

Parameters	Unit	Standard for environment	Standard for arowana***	Swamp forest	Oil palm plantation			
					OP 1 (aged 1-7 years)	OP 2 (aged 8-15 years)	OP 3 (aged 16-20 years)	Cleared land
Temperature	°C	25 - 33*	20 - 30	28.00 $\pm$ 2.17	29.25 $\pm$ 0.96	29.50 $\pm$ 0.58	28.5 $\pm$ 1.00	28.40 $\pm$ 2.19
pH	-	6 - 9*	5.5 - 7.5	5.38 $\pm$ 0.44	5.26 $\pm$ 0.47	5.43 $\pm$ 0.33	5.28 $\pm$ 0.33	5.37 $\pm$ 0.25
Total Suspended Solid	mg L ⁻¹	Not polluted (≤ 50)*	≤ 50	0.06 $\pm$ 0.04	0.08 $\pm$ 0.03	0.09 $\pm$ 0.05	0.34 $\pm$ 0.52	0.06 $\pm$ 0.05
Depth	cm	-	100 - 200	178.00 $\pm$ 65.03	106.25 $\pm$ 25.79	109.75 $\pm$ 31.32	194 $\pm$ 24.25	119.60 $\pm$ 22.26
Dissolved Oxygen (DO)	mg L ⁻¹	"Lightly polluted" (4.5 <, ≤ 6.4)**	≥ 4	5.87 $\pm$ 1.60	5.98 $\pm$ 0.36	5.22 $\pm$ 2.29	6.32 $\pm$ 1.12	6.27 $\pm$ 1.10
Turbidity	NTU	-	-	160.50 $\pm$ 27.03	97.01 $\pm$ 59.17	77.90 $\pm$ 37.00	117.48 $\pm$ 60.77	111.67 $\pm$ 172.78
Ammonia (NH ₃ N)	mg L ⁻¹	Not polluted (≤ 0.50)*	≤ 1	0.20 $\pm$ 0.13	0.23 $\pm$ 0.02	0.22 $\pm$ 0.09	0.16 $\pm$ 0.10	0.11 $\pm$ 0.03
Total Nitrogen	mg L ⁻¹	Not polluted (≤ 15)*	≤ 20	4.94 $\pm$ 1.02	3.92 $\pm$ 1.23	3.97 $\pm$ 1.29	4.37 $\pm$ 1.40	4.52 $\pm$ 2.61
Phosphate (PO ₄)	mg L ⁻¹	"trophic" (0.05 <, ≤ 0.10)** "very trophic" (0.10 <, ≤ 0.20)**	≤ 1	0.09 $\pm$ 0.06	0.07 $\pm$ 0.05	0.06 $\pm$ 0.03	0.13 $\pm$ 0.45	0.16 $\pm$ 0.10

Parameters	Unit	Standard for environment	Standard for arowana***	Swamp forest	Oil palm plantation			Cleared land
					OP 1 (aged 1-7 years)	OP 2 (aged 8-15 years)	OP 3 (aged 16-20 years)	
Potassium (K)	mg L ⁻¹	-	-	0.05 ± 0.02	0.05 ± 0.02	0.05 ± 0.02	0.06 ± 0.02	0.03 ± 0.01
Sediment Total Organic Carbon	%	-	-	0.17 ± 0.04	0.12 ± 0.05	0.10 ± 0.03	0.02 ± 0.01	0.04 ± 0.02

Notes: *Indonesian national water quality standards for the river environment in Regulation of Republic of Indonesia Number 22/PP/2021; **Water quality standards for environment in Water Analysis Manual Tropical Aquatic Biology Program, Biotrop, Southeast Asian Regional Centre for Tropical Biology (Wardoyo, 1982); ***Water quality standards for Arowana habitat in Regulation Minister of Marine and Fishery the Republic of Indonesia Number 12/PERMEN-KP/2015.

Table 5. Estimated soil erosion rates of respective land uses in 2021

Land use type	t ha ⁻¹ yr ⁻¹
Oil palm plantation	61.19 - 158.29
Swamp	Not estimated
Swamp forest	Not estimated
Cleared land	142.11 - 186.34
Other-plantations	60.17 - 128.20
Shrubland	5.26 - 61.16
Mixed farm	60.16 - 118.34
Settlement	61.22 - 101.12
Industrial area	66.08 - 109.34
Horticultural land	60.66 - 115.18
Cleared swamp land	Not estimated

B. Discussion

1. Effects of Oil Palm Plantation Expansion on Environmental Quality in The AgrCA

In the AgrCA, 60.4% of the land had already been converted to oil palm plantations in 2017. Swamps and swamp forests were intensively converted to oil palm plantations, and thus their area decreased from 32.0% in 2017 to 10.9% in 2021 (Table 3). The expansion of oil palm plantations has led to the reduction of swamps and swamp forests that are the habitat

of the Asian arowana golden red in the AgrCA. Although the influence of the expansion on soil erosion was not discussed in the present study since the USLE was not applicable, it resulted in the reduction of the arowana habitat area by drying the swamp land.

The expansion of oil palm plantations possibly increased soil erosion rates through the land-clearing process, i.e., the status of cleared land, before oil palm planting (Flores et al., 2020; Sahat, Yusop, Askari, & Ziegler, 2016;

Satriawan, Harahap, & Karim, 2015). Cleared land was susceptible to soil erosion due to no plant coverage and the soil erosion rates were estimated to range from 142.11 to 186.34 t ha⁻¹ year⁻¹ (Table 5). In general, oil palm plantations older than 20 years are cleared for re-plantation in this region, and the cleared land is left bare for 2–4 years. Areas with more oil palm plantations had more cleared land. This situation could increase soil erosion in the AgrCA in the future, although an increase in cleared land area was not observed in the study period.

The presence of ground cover is crucial for protecting soil from erosion. According to Sahat et al. (2016), the presence of trees and grasses in oil palm plantations can reduce soil erosion rates by up to 67%. We strongly advise farmers not to leave land cleared for a long time. Quickly re-planting trees could reduce the heavy soil erosion levels in the AgrCA.

2. Effects of Soil Erosion on Water Quality

Soil erosion in Agricultural areas in AgrCA 60.16–158.29 t ha⁻¹ yr⁻¹. Anasiru (2015) recorded a maximum soil loss of 316.9 t ha⁻¹ from a mixed plantation plot (2 m x 22 m) in Gorontalo, Sulawesi, during the rainy season from March to July 2012. The rainfall patterns and amounts in that study were generally comparable to those in AgrCA. The primary soil types in Gorontalo were Andosols and Podzols, which likely had comparable or lower K factors than those in AgrCA.

The estimated soil erosion rates in AgrCA were lower than the values reported by Anasiru

(2015). However, the estimated erosion rates for oil palm plantations in AgrCA, ranging from 60.16 to 158.29 t ha⁻¹ yr⁻¹, were higher than those measured by Purwanto et al. (2019) (15.03 to 16.70 t ha⁻¹ yr⁻¹) in Palangkaraya, Central Kalimantan, and by Agustina and Dewi (2020) (5 to 47 t ha⁻¹ yr⁻¹) in Muara Enim, South Sumatra. The higher soil erosion rates in AgrCA could be attributed to variations in the soil erodibility factor (K) and slope length (L). In Muara Enim and Palangkaraya, the soil types were Latosols, with K factors of 0.12 and 0.07, respectively (Asdak, 1995). In contrast, our study used a K value of 0.29 for Plinthic Acrisols, representing an approximately 2.5 to 4 times difference in K factors. Additionally, Purwanto et al. (2019) and Agustina and Dewi (2020) measured soil erosion rates in plots with slope lengths of 20 m and 25 m, whereas the oil palm plantations in AgrCA had slope lengths ranging from 100 m to 300 m. For the oil palm plantations in AgrCA with a slope length of 100 m, the estimated soil erosion rates ranged from 61.19 to 84.68 t ha⁻¹ yr⁻¹. Considering the higher K and L values, the soil erosion rates estimated in the present study were comparable to those reported by Purwanto et al. (2019) and Agustina and Dewi (2020).

Although the water quality was judged as habitable for Arowana, the expansion of oil palm plantations probably influenced the water quality. Erosion has transported soil organic matter into nearby water bodies, with the amount of erosion varying across different land uses, thereby affecting water quality differently.

Table 6. Areal sizes of soil erosion rates levels in AgrCA

Soil erosion rate *	Area (ha)	Area percentage (%)
I: Very light (0-16 t ha ⁻¹ yr ⁻¹)	16	0.43
II: Light (16-60 t ha ⁻¹ yr ⁻¹)	31	0.84
III: Moderate (60-180 t ha ⁻¹ yr ⁻¹)	2415	64.70
IV: Heavy (180-480 t ha ⁻¹ yr ⁻¹)	53	1.30

Notes: *Regulation of procedure for preparing a forest rehabilitation technique plan and land rehabilitation of watershed areas Number: P. 32/Menhut-II/2009 (The Minister of Forestry of the Republic Indonesia, 2009).

Phosphate concentrations differ between land uses, with water bodies adjacent to OP3 and cleared land exhibiting higher phosphate levels compared to OP1 and OP2. Based on phosphate concentrations, the water in the swamp forests, OP1, and OP2 was classified as trophic, and it was classified as very trophic in OP3 and cleared land, as shown in Table 4.

The estimated soil erosion rates of 1 ha (100 m x 100 m) areas adjacent (10 m) to the water sampling sites were 147.44, 147.29, 154.92 and 153.76 t ha⁻¹ yr⁻¹ for OP1, OP2, OP3, and cleared land, respectively. The erosion rate was observed mostly at a “moderate” level, accounting for 64.70% of the area (Table 6). The higher phosphate concentration in OP3 and cleared land was probably caused by the excessive fertilization in oil palm plantations. The high phosphate levels were observed during the July–September period in water bodies near to OP3 and cleared land (Figure 8). Our analysis indicated that this increase in phosphate concentration was primarily due to the runoff from nearby oil palm plantations. Farmers commonly apply phosphate-containing fertilizers to oil palm plantations from July to September, which is the rainy season, to boost crop yields. The crop yield increased from around 500 kg ha⁻¹ in OP1 to around 1000 kg ha⁻¹ in OP2 (personal communication), and the farmers doubled the amount of fertilizers from OP1 to OP2. In older oil palm plantations, namely OP3, which were 16–20 years, the fertilizer was applied twice in the rainy season

(Table 7), although the yield was similar to that of OP2. The composition and frequency of fertilizer applied are shown in Table 7. The farmers practiced this fertilization management following local community suggestions. Fertilizer not absorbed by the oil palm trees likely accumulated in the soil and was carried away by soil erosion into water bodies in OP3. This could explain the elevated phosphate levels in the water. The higher phosphate concentration in the cleared land than in OP1 and OP2 (Table 4, Figure 8) indicated that the fertilizer runoff continued in the cleared land. This observation was consistent with the results of Comte et al. (2015). It is likely that this land still contains residual fertilizer that was not absorbed by the oil palm trees. In the absence of oil palm trees, a higher soil erosion rate occurred (Table 5) and probably washed the residual fertilizer into water bodies, leading to increased phosphate levels in the water bodies besides the cleared land.

The DO in water in the AgrCA ranged from 5.22 to 6.32 mg L⁻¹ (Table 4), which resulted in the water being classified as lightly polluted. Low oxygen levels can hinder the production of zooplankton and zoobenthos (Dudgeon et al., 2006), which are important components of the Asian arowana golden red food chain (Yue et al., 2020). Therefore, it is imperative to manage land use change in the AgrCA to protect water quality and sustain the Asian arowana golden red ecosystem.

Table 7. Composition and frequency of fertilizer applied in oil palm plantations in AgrCA

Site	Age (years old)	Average combination fertilizer (kg ha ⁻¹)					Frequency of fertilization (time ⁻¹ year ⁻¹) ^b
		TSP (Triple Super Phosphate) (P ₂ O ₅ : 46%) ^a	Urea (N:46%) ^a	KCl (Potassium chloride) (K ₂ O: 60%) ^a	Dolomite (CaO: 30%, MgO: 18%) ^a	Borate (B ₂ O ₃ : 46%) ^a	
OP1	1-7	49	58.5	58.5	250	4	1
OP2	8-15	97.5	117	117	500	6.5	1
OP3	16-20	97.5	117	117	500	6.5	2

Notes: a: guaranteed composition, b: in rainy season, July to September

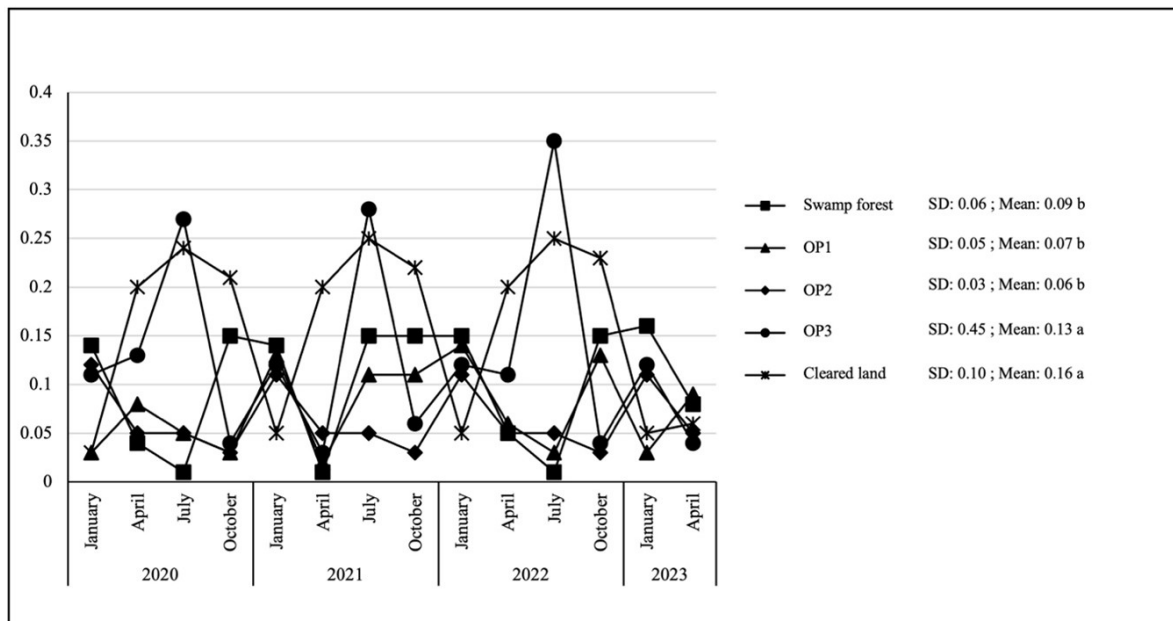


Figure 8. Phosphate concentration during 2020-2023 in different sites in AgrCA

IV. CONCLUSION

The expansion of oil palm plantations has led to the reduction of swamps and swamp forests that are the habitat of the Asian arowana golden red in the AgrCA. High soil erosion rates were observed in the area of cleared land. The present fertilizer management method used in the oil palm plantations caused water quality degradation. Water bodies adjacent to old oil palm plantations and the cleared land exhibited low levels of dissolved oxygen and were considered very trophic regarding phosphate concentrations. The water quality around the oil palm plantations was still at a habitable level for the Asian arowana golden red. However, further water quality degradation caused by the expansion of oil palm plantations could lead to biodiversity loss and negatively affect the balance of the aquatic ecosystems.

Future research should evaluate the long-term effects of oil palm expansion on the habitat quality, population status, and survival of the Arowana golden red. Particular attention should be given to the impacts of sedimentation, nutrient enrichment, and declining water quality on aquatic biodiversity. Studies are also needed to assess the effectiveness of

sustainable management practices, such as riparian buffer restoration, erosion control, and improved fertilizer management, in mitigating environmental degradation and maintaining suitable habitat conditions.

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REFERENCES

- Agustina, H., & Dewi, V. A. K. (2020). Analisa erosi metode USLE pada lahan sawit kabupaten muara enim (Erosion analysis of USLE method at palm oil plantation in Muara Enim Regency). *Jurnal Teknik Pertanian Lampung*, 9(3), 157-162. doi: //10.23960/jtep-l.v9.i3.157-162.
- Albert, J. S., Destouni, G., Duke-Sylvester, S. M., Magurran, A. E., Oberdorff, T., Reis, R. E.,

- Kirk, O. W., & Ripple, W. J. (2021). Scientists' warning to humanity on the freshwater biodiversity crisis. *Ambio*, 50(1), 85-94. doi://10.1007/s13280-020-01318-8.
- Alim, A. S., & Anggraini, R. S. (2021). Assessing land degradation as the impact of deforestation due to the expansion of oil palm plantation in Rokan Hulu, Riau. In *IOP Conference Series: Earth and Environmental Science* (Vol. 733, No. 1, p. 012146). IOP Publishing. doi://10.1088/1755-1315/733/1/012146
- Amellah, O. & el Morabiti, K. (2021). Assessment of soil erosion risk severity using GIS, remote sensing and RUSLE model in Oued Laou Basin (North Morocco). *Soil science annual*, 72(3), 1-11. doi://10.37501/soilsa/142530
- American Public Health Association (APHA). (2005). *Standard methods for the examination water and wastewater*. 20th ed, Washington DC: American Water Works Association.
- Anasiru, R. H. (2015). Perhitungan laju erosi metode USLE untuk pengukuran nilai ekonomi ekologi di Sub DAS Langge, Gorontalo. *Jurnal Pengkajian dan Pengembangan Teknologi Pertanian*, 18(3), 273-289.
- Asdak. (1995). *Hydrology and watershed management*, Gadjah Mada University Press. Yogyakarta, Indonesia.
- Ayompe, L. M., Schaafsma, M., & Egoh, B. N. (2021). Towards sustainable palm oil production: The positive and negative impacts on ecosystem services and human wellbeing. *Journal of cleaner production*, 278, 123914. doi:// 10.1016/j.jclepro.2020.123914.
- Birk, S., Chapman, D., Carvalho, L., Spears, B. M., Andersen, H. E., Argillier, C., ... & Hering, D. (2020). Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. *Nature Ecology & Evolution*, 4(8), 1060-1068.
- Bogheiry, A., Thaha, M., & Rahmah, L. (2023). Global dependence analysis on Indonesian palm oil production and its effect on environmental security using the Copenhagen school approach. *Journal of World Science*, 2(3), 466-482. doi://10.58344/jws.v2i3.243.
- Central Statistics Agency of Riau Province. (2022). Rokan Hulu in Numbers 2022. Central Statistics Agency of Riau province. Riau. Indonesia.
- Comte, I., Colin, F., Grünberger, O., Whalen, J. K., Harto Widodo, R., & Caliman, J. P. (2015). Watershed-scale assessment of oil palm cultivation impact on water quality and nutrient fluxes: a case study in Sumatra (Indonesia). *Environmental Science and Pollution Research*, 22, 7676-7695. doi: //10.1007/s11356-015-4359-0
- Danielsen, F., Beukema, H., Burgess, N. D., Parish, F., Brühl, C. A., Donald, P. F., ... & Fitzherbert, E. B. (2009). Biofuel plantations on forested lands: double jeopardy for biodiversity and climate. *Conservation Biology*, 23(2), 348-358. doi://10.1111/j.1523-1739.2008.01096.x.
- Darwall, W., Bremerich, V., De Wever, A., Dell, A. I., Freyhof, J., Gessner, M. O., ... & Weyl, O. (2018). The alliance for freshwater life: A global call to unite efforts for freshwater biodiversity science and conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 28(4), 1015-1022. doi://10.1002/aqc.2958.
- Davison, C. W., Rahbek, C., & Morueta-Holme, N. (2021). Land-use change and biodiversity: Challenges for assembling evidence on the greatest threat to nature. *Global Change Biology*, 27(21), 5414-5429. doi://10.1111/gcb.15846.
- Dawes, J. (2006). Update on the dragon fish trade. *Aquarama*, 7, 7-11.
- DHV Consulting Engineers. (1989). *Study on Catchment Preservation and Environmental Impact of the Water Supply Project of Bandung and Sukabumi*. Jakarta: Ministry of Public Works Directorate General Cipta Karya.
- Directorate General of Estate. (2022). *Statistical of National Leading Estate Crops Commodity*. Jakarta: Secretariate of Directory General of Estates, Ministry of Agriculture of the Republic of Indonesia.
- Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., ... & Sullivan, C. A. (2006). Freshwater biodiversity: importance, threats, status and conservation challenges. *Biological reviews*, 81(2), 163-182. doi://10.1017/S1464793105006950.
- Erencia, Z. (2000). *C-factor mapping using remote sensing and GIS: A case study of Lom Sak/Lom Kao, Thailand*. Geographisches Institut der Justus-Liebig-Universität Giessen. Netherland.
- Food and Agriculture Organization (FAO). (2022). *World Food and Agriculture – Statistical Yearbook 2022*. Rome: Food and Agriculture Organization of the United Nations.
- Food and Agriculture Organization (FAO). (2022). *Fao/Unesco Soil Map of The World*. Rome: Food and Agriculture Organization of the

- United Nations. <https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/faunesco-soil-map-of-the-world/en/>. Accessed On 4 February 2022.
- Fernando, A. A., Lim, L. C., Jeyaseelan, K., Teng, S. W., Liang, M. C., & Yeo, C. K. (1997). DNA fingerprinting: application to conservation of the CITES-listed dragon fish, *Scleropages formosus* (Osteoglossidae). *Aquarium Sciences and Conservation*, 1, 91–104.
- Flitcroft, R., Cooperman, M. S., Harrison, I. J., Juffe-Bignoli, D., & Boon, P. J. (2019). Theory and practice to conserve freshwater biodiversity in the Anthropocene. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 29(7), 1013–1021. doi://10.1002/aqc.3187.
- Flores, B. M., Staal, A., Jakovac, C. C., Hirota, M., Holmgren, M., & Oliveira, R. S. (2020). Soil erosion as a resilience drain in disturbed tropical forests. *Plant and Soil*, 450, 11–25. doi://10.1007/s11104-019-04097-8.
- Ganasri, B. P. & Ramesh, H. (2016). Assessment of soil erosion by RUSLE model using remote sensing and GIS - A case study of Nethravathi Basin. *Geoscience Frontiers*, 7(6): 953-961. doi://10.1016/j.gsf.2015.10.007.
- García-Álvarez, D., Camacho Olmedo, M. T., Paegelow, M., & Mas, J. F. (2022). *Land Use Cover Datasets and Validation Tools: Validation Practices with QGIS*. Switzerland: Springer.
- Government of The Republic of Indonesia. (1999). *Government Regulation of The Republic of Indonesia Number 7 of 1999 Concerning The Preservation of Plant And Animal Species*. Jakarta: Ministry of the State Secretary Republic of Indonesia. Indonesian Agency for Meteorological, Climatological and Geophysics. (2021). *Climate Data (Rainfall)*. <https://dataonline.bmkg.go.id/home>. Accessed on 2 February 2022.
- Indonesian Geospatial. (2022). DEM Rokan Hulu Regency. <https://tanahair.indonesia.go.id/portal-web>. Accessed on 5 February 2022.
- Issaka, S. & Ashraf, M. A. (2017). Impact of soil erosion and degradation on water quality: a review. *Geology, Ecology, and Landscapes*, 1(1), 1–11. doi://10.1080/24749508.2017.1301053.
- Keong, C. Y. (2015). Sustainable resource management and ecological conservation of mega-biodiversity: The Southeast Asian Big-3 Reality. *International Journal of Environmental Science and Development*, 6(11), 876–882. doi://10.7763/IJESD.2015.V6.715.
- Maasri, A., Jähnig, S. C., Adamescu, M. C., Adrian, R., Baigun, C., Baird, D. J., ... & Worischka, S. (2022). A global agenda for advancing freshwater biodiversity research. *Ecology Letters*, 25(2), 255-263. doi://10.1111/ele.13931.
- Meijaard, E., Brooks, T. M., Carlson, K. M., Slade, E. M., Garcia-Ulloa, J., Gaveau, D. L., ... & Sheil, D. (2020). The environmental impacts of palm oil in context. *Nature plants*, 6(12), 1418-1426.
- Minister of Marine and Fishery. (2015). *Regulation of the Minister of Marine and Fisheries of the Republic of Indonesia number 12/PERMEN-KP/2015 Concerning General Guidelines for Ornamental Fish Cultivation Arowana Super Red (Scleropages formosus)/Siluk*, Jakarta: Ministry of Marine and Fisheries Republic of Indonesia.
- Minister of Forestry. (2009). *Regulation of the Minister of Forestry of the Republic of Indonesia number: P. 32/Menbut-II/2009 Concerning Procedures for Preparing Forest Rehabilitation Technique Plans and River Flow Land*. Jakarta: Ministry Forestry of the Republic of Indonesia.
- Monitor, P. (2023). Advantages of oil palm plantations as carbon sink and emission-efficient oil production. *Journal Analysis of Palm Oil Strategic*, 4, 15.
- Morgan, R. P. C. (2009). *Soil erosion and conservation*. United Kingdom: John Wiley Sons.
- Nellemann, C., Miles, L., Kaltenborn, B. P., Virtue, M., & Ahlenius, H. (2007). *The last stand of the orangutan - State of emergency: Illegal logging, fire and palm oil in Indonesia's national parks*. GRID-Arendal, Norway: United Nations Environment Programme. (Eds. 2007).
- Nyesheja, E. M., Chen, X., El-Tantawi, A. M., Karamage, F., Mupenzi, C., & Nsengiyumva, J. B. (2019). Soil erosion assessment using RUSLE model in the Congo Nile Ridge region of Rwanda. *Physical Geography*, 40(4), 339-360. doi://10.1080/02723646.2018.1541706
- Pham Gia, T., Degener, J., & Kappas, M. (2018). Integrated universal soil loss equation (USLE) and Geographical Information System (GIS) for soil erosion estimation in A Sap basin: Central Vietnam. *International Soil and Water Conservation Research*, 6(2), 99-110. doi://10.1016/j.iswcr.2018.01.001.
- Purnama A.A., & Masunaga T. (2023). Present condition of the protected area of endangered Asian Arowana (*Scleropages formosus*) golden-red in east-central Sumatra,

- Indonesia. *Ekológia (Bratislava)*, 42(4), 371–380. doi://10.2478/eko-2023-0042.
- Purwanto, E., Jaya, A., Widiastuti, L., Birawa, B., Adji, F. F., & Anwar, M. (2019). Kajian erosi, aliran permukaan dan kehilangan hara pada tanaman kelapa sawit dengan umur yang berbeda. Study of Erosion, Runoff and Nutrient Losses from Oil Palm Plantation with Different Ages. *Jurnal AGRI PEAT*, 20(2).
- Ramadhan, S., Rusman, B., & Yasin, S. (2021). Erosion hazard index (EHI) on different land use in sub-watershed Kaos, Jambi. In *IOP Conference Series: Earth and Environmental Science* (Vol. 741, No. 1, p. 012035). IOP Publishing. doi:// 10.1088/1755-1315/741/1/012035.
- Regulation of the Republic of Indonesia. (2021). Implementation of protection and management environment number 22/PP/2021. Jakarta, Indonesia. https://jdih.setkab.go.id/PUUdoc/176367/PP_Nomor_22_Tahun_2021.pdf
- Regulation of the Minister of Marine and Fishery of the Republic of Indonesia. (2015). General guidelines for cultivation of Arowana (*Scleropages formosus*)/silur ornamental fish number 12/PERMEN-KP/2015. Jakarta: Ministry of Marine and Fishery the Republic of Indonesia. <https://www.regulasip.id/book/3634/read>
- Regulation of the Minister of Forestry of The Republic of Indonesia. (2009). Procedure for preparing a forest rehabilitation technique plan and land rehabilitation of watershed areas number P.32/Menhut-II/2009. Jakarta: Ministry of Forestry of The Republic of Indonesia, [https://jdih.menlhk.go.id/new/uploads/files/P.32%20\(9\).pdf](https://jdih.menlhk.go.id/new/uploads/files/P.32%20(9).pdf)
- Reid, A. J., Carlson, A. K., Creed, I. F., Eliason, E. J., Gell, P. A., Johnson, P. T., ... & Cooke, S. J. (2019). Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, 94(3), 849–873. doi://10.1111/brv.12480.
- Regent of Rokan Hulu. (2009). *Rokan Hulu Regent Decree Number 169 of 2009 Concerning the Designation of Mahato Kanan Limited Production Forest Area (Rawa Seribu) Covering an Area of ± 3,700 ha as a Conservation Area for Arowana Fish (Scleropages formosus)*. Regency office of Rokan Hulu Riau Province Indonesia. Riau, Indonesia.
- Sahat, S., Yusop, Z., Askari, M., & Ziegler, A. D. (2016). Estimation of soil erosion rates in oil palm plantation with different land cover. In *IOP Conference Series: Materials Science and Engineering* (Vol. 136, No. 1, p. 012086). IOP Publishing. doi://10.1088/1757-899X/136/1/012086
- Saswattecha, K., Hein, L., Kroeze, C., & Jawjit, W. (2016). Effects of oil palm expansion through direct and indirect land use change in Tapi river basin, Thailand. *International Journal of Biodiversity Science, Ecosystem Services and Management*, 12(4), 291–313. doi://10.1080/21513732.2016.1193560
- Satriawan, H., Harahap, E. M., & Karim, A (2015). Effectiveness of soil conservation to erosion control on several land use types. *Agriculture (Pol'nobospodarstvo)*, 61(2), 61–68. doi://10.1515/agri-2015-0011.
- Sestras, P., Mircea, S., Rosca, S., Bilasco, S., Salagean, T., Dragomir, L. O., ... & Kader, S. (2023). GIS based soil erosion assessment using the USLE model for efficient land management: a case study in an area with diverse pedo-geomorphological and bioclimatic characteristics. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, 51(3), 13263–13263. doi://10.15835/nbha51313263
- Sheil, D., Casson, A., Meijaard, E., Noordwijk, M. V., Gaskell, J., Sunderland-Groves, J., ... & Kanninen, M. (2009). *The Impacts and Opportunities of Oil Palm in Southeast Asia: What Do We Know and What Do We Need to Know*. Bogor, Indonesia: Center for International Forestry Research.
- Silva, R. M., Santos, C. A. G., & Montenegro, S. M. G. L. (2013). Identification of critical erosion prone areas and estimation of natural potential for erosion using GIS and Remote Sensing. *Brazilian Journal of Cartography*, 65(3), 125–136.
- Srisawasdi, W., Tsusaka, T. W., & Cortes, J. R. (2023). Palm oil trade and production toward achieving sustainable development goals: a global panel regression analysis. *ABAC Journal*, 43(3), 98–111. doi://10.59865/abacj.2023.31
- Strayer, D. L. & Dudgeon, D. (2010). Freshwater biodiversity conservation: Recent progress and future challenges. *Journal of the North American Benthological Society*, 29(1), 344–358.
- Su, G., Logez, M., Xu, J., Tao, S., Villéger, S., & Brosse, S. (2021). Human impacts on global freshwater fish biodiversity. *Science*, 371(6531), 835–838.
- Swarna, N. H. & Tisdell, C. (2009). The orangutan–oil palm conflict: economic constraints and

- opportunities for conservation. *Biodiversity and Conservation*, 18, 487-502. doi://10.1007/s10531-008-9512-3.
- Tan, K. T., Lee, K. T., Mohamed, A. R. & Bhatia, S. (2009). Palm oil: Addressing issues and towards sustainable development. *Renewable and Sustainable Energy Reviews*, 13(2), 420-427. doi://10.1016/j.rser.2007.10.001.
- United Nations Development Group. (2017). *Mainstreaming the 2030 Agenda for Sustainable Development Reference Guide to UN Country Teams*. New York: United Nations.
- Vijith, H., Suma, M., Rekha, V. B., Shiju, C., & Rejith, P. G. (2012). An assessment of soil erosion probability and erosion rate in a tropical mountainous watershed using remote sensing and GIS. *Arabian Journal of Geosciences*, 5, 797-805. doi://10.1007/s12517-010-0265-4
- Von Rintelen, K., Arida, E., & Häuser, C. (2017). A review of biodiversity-related issues and challenges in megadiverse Indonesia and other Southeast Asian countries. *Research Ideas and Outcomes*, 3, e20860. doi://10.3897/rio.3.e20860.
- Wardoyo, S. T. H. (1982). *Water Analysis Manual Tropical Aquatic Biology Program*. Bogor, Indonesia: SEAMEO Biotrop.
- Yue, G. H., Chang, A., Yuzer, A., & Suwanto, A. (2019). Current knowledge on the biology and aquaculture of the endangered Asian Arowana. *Reviews in Fisheries Science & Aquaculture*, 28(2), 193-210. doi://10.1080/23308249.2019.1697641.

LIFE CYCLE ASSESSMENT OF BLACK LOCUST AND POPLAR TIMBER PRODUCTION IN HUNGARY

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LIFE CYCLE ASSESSMENT OF BLACK LOCUST AND POPLAR TIMBER PRODUCTION IN HUNGARY. Forests play a vital role in carbon sequestration and storage through photosynthesis. However, in Hungary, only a few studies have elaborated on the potential carbon emissions that are released during forest operations. The objective of this study was to assess the potential environmental impacts (including the carbon footprint) of forest operation in timber production. Data collection and data analysis followed the life cycle assessment (LCA) procedure in ISO 14044. Furthermore, for calculating the result of the life cycle impact assessment, we used the Sphera LCA for Experts Education License version 9.2.1.68 Software. The findings showed that fuel consumption and agrochemicals applications (fertilizer and pesticides) drive key impact categories-acidification, resource depletion, and global warming potential- with harvesting identified as the largest contributor to the overall environmental impact. Harvesting activity has contributed more dominantly to abiotic depletion, acidification potential, global warming potential, human toxicity potential, ozone layer depletion potential, and terrestrial ecotoxicity potential than thinning and plantation establishment activities. Furthermore, based on the input sources, applications of fertilizer have contributed significantly to global warming potential, followed by fuels and lubricants, respectively. According to research findings, the application of fertilizer and fuel consumption should be reduced to minimize the lower environmental impacts.

Keywords: Life Cycle Assessment, Carbon footprint, Climate change mitigation, Environmental impacts, long-rotation management systems

PENILAIAN DAUR HIDUP PRODUKSI KAYU BLACK LOCUST DAN POPLAR DI HONGARIA. Hutan terbukti memiliki peran penting dalam penyerapan dan penyimpanan karbon melalui fotosintesis. Akan tetapi, di Hongaria, hanya sedikit penelitian yang menguraikan potensi emisi karbon yang dilepaskan selama kegiatan kehutanan. Tujuan dari penelitian ini adalah untuk menilai potensi dampak lingkungan (termasuk jejak karbon) dari kegiatan kehutanan dalam produksi kayu. Pengumpulan dan analisis data mengikuti prosedur penilaian daur hidup (life cycle assessment/LCA) dalam ISO 14044. Selanjutnya, untuk menghitung hasil penilaian dampak daur hidup, kami menggunakan perangkat lunak Sphera LCA for Experts Education License versi 9.2.1.68. Hasil yang diperoleh menunjukkan bahwa konsumsi bahan bakar dan aplikasi agrokimia (pupuk dan pestisida) dalam kegiatan kehutanan telah menghasilkan kategori dampak penting-pengasaman, penipisan sumber daya, dan potensi pemanasan global- dimana aktivitas pemanenan teridentifikasi sebagai penyumbang terbesar dari dampak tersebut. Aktivitas pemanenan telah memberikan kontribusi yang lebih dominan terhadap penipisan abiotik, potensi pengasaman, potensi pemanasan global, potensi toksisitas manusia, potensi penipisan lapisan ozon, potensi ekotoksitas terestrial daripada kegiatan penjarangan dan pembangunan hutan tanaman. Lebih jauh, berdasarkan sumber input, penggunaan pupuk memiliki kontribusi yang signifikan terhadap potensi pemanasan global, diikuti oleh bahan bakar dan pelumas. Berdasarkan hasil penelitian, penggunaan pupuk dan konsumsi bahan bakar harus dikurangi untuk meminimalkan dampak negatif terhadap lingkungan.

Kata kunci: Penilaian daur hidup, Jejak karbon, Mitigasi perubahan iklim, Dampak lingkungan, Sistem pengelolaan daur panjang

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I. INTRODUCTION

Forest-based production systems play a crucial role in supplying raw materials while also contributing to climate change mitigation. In Hungary, black locusts and poplars play a vital role in timber production, supplying the wood industry. Poplar plantations in Hungary are the second largest in Europe and are used for some wood industries, such as packaging (pallets and boxes), furniture, plywood, fiber, and energy purposes (Komán et al., 2023). Furthermore, apart from being cultivated as a windbreak and pioneer vegetation for reclamation, due to its good physical and mechanical properties, black locust wood is also used for construction materials and bioenergy (Bijak & Lachowicz, 2021). Black locusts also supply around 21% of the total wood supply in Hungary (Nicolescu et al., 2018).

Cultivation of fast-growing species, especially non-native species, should consider many aspects, including economic, social, and ecological considerations. Black locust and poplar plantation in short-rotation coppice systems in Hungary have shown their ability to sequester carbon emissions from the atmosphere and store it in the above and below-ground biomass (Mulyana et al., 2024). In Germany, black locusts and poplars are promising species for mining reclamation (Quinkenstein & Jochheim, 2016).

Apart from black locusts securing the wood supply for industries, black locusts are also associated with environmental impacts. As the pioneer vegetation, black locusts have adapted to marginal land, and it is threatening the native dry and semi-dry grassland species in Central Europe (Vítková et al., 2017). Black locusts and poplar log production in short-rotation systems for bioenergy purposes have resulted in lower impacts on the environment, especially in releasing greenhouse gas (GHG) emissions to the atmosphere (Morales-Vera et al., 2022; Żelazna et al., 2019). Global warming potential (GWP) of bioenergy production (poplar and black locust) with short-rotation coppice system

in Hungary is 5.9 ton CO₂ eq/ha (Mulyana et al., 2025). Not only for bioenergy purposes, multifunctional poplar plantations (roundwood and woodchips) also release GHG emissions of around 45.1 kg CO₂ eq/oven dry ton whole tree (Laina et al., 2022). Even though black locust and poplar plantations have been proven to have lower impacts on the environment, research on life cycle assessment (LCA) on forestry operations in Hungary is still limited (Mulyana et al., 2023).

Furthermore, the objective of this study was to describe the potential environmental impacts on timber production of black locust and poplar plantations in Hungary. Specifically, we also elaborate on the environmental impacts based on activities (plantation establishment, thinning, and harvesting) and inputs (fuel, lubricant, fertilizer, and pesticide) in the forest operations to produce the timber from black locust and poplar plantations in Hungary.

II. MATERIAL AND METHOD

Black locust and poplar plantations can be managed to supply round wood or bioenergy. Globally, the poplar plantations that are dedicated to multipurpose, timber production, environmental protection, and biomass production were 18.3, 9.4, 2.9, and 0.9 million ha, respectively (Lovarelli et al., 2018). Furthermore, Lovarelli et al. (2018) explained that traditional poplar plantation (TPP) was different from the short-rotation coppice (SRC) or short-rotation forestry (SRF) systems in the length of rotation, wood utilization, tree management, and harvesting method. Data on black locust in Central Europe is still limited because black locust is an invasive species and its exact distribution is not yet known (Vítková et al., 2017).

A. Goal and Scope Definition

The objective of this study was to evaluate the environmental impact of black locust and poplar timber production for industrial purposes in Hungary. The intended audience

of this study are policymakers, forest managers, and researchers working in life cycle assessment and forest-based bioeconomy systems. The results of this study are intended to support decision-making related to sustainable timber production and its utilization. Furthermore, this study provides a methodological and data foundation for future LCA studies, especially for improving country-specific inventory data for the timber production system under long-rotation management. A number of studies conducted in European countries have demonstrated that timber production has led to various environmental consequences, including acidification, eutrophication, resource depletion, human toxicity (Dias et al. 2022; Lovarelli et al. 2018), and global warming potential (Prinz et al. 2018; Proto et al. 2017; Spinelli and Moura 2019). The LCA study on timber production has been conducted for various tree species, including eucalyptus (Dias et al. 2022), cryptomeria (Dias et al. 2022), birch (Kuka et al. 2020), pine (Bernardi et al. 2022; Dias et al. 2022; Kuka et al. 2019), and poplar

(Laina et al. 2022; Lovarelli et al., 2018).

The boundaries of the system under study varied across LCA studies of wood production, affecting the environmental impact assessment (Dias et al. 2022). In the context of birch and pine wood production in Latvia, the subsystems of timber production encompass seed production, seedling production, silvicultural operations, and logging operations (Kuka et al. 2019, 2020). In Japan, forest operations for timber production (Japanese cedar, hinoki cypress, Japanese larch, and Sakhalin fir) were grouped into planting, thinning, and final felling (Nakano et al. 2018). Conversely, in the context of industrial pine roundwood production in Brazil, forest operations were classified into the following categories: soil preparation, seedling plantation, forest management, forest harvesting, and infrastructure establishment (Ferro et al. 2018). In this research, the subsystems in timber production were divided into plantation establishment, growth maintenance, thinning, and harvesting (Figure 1).

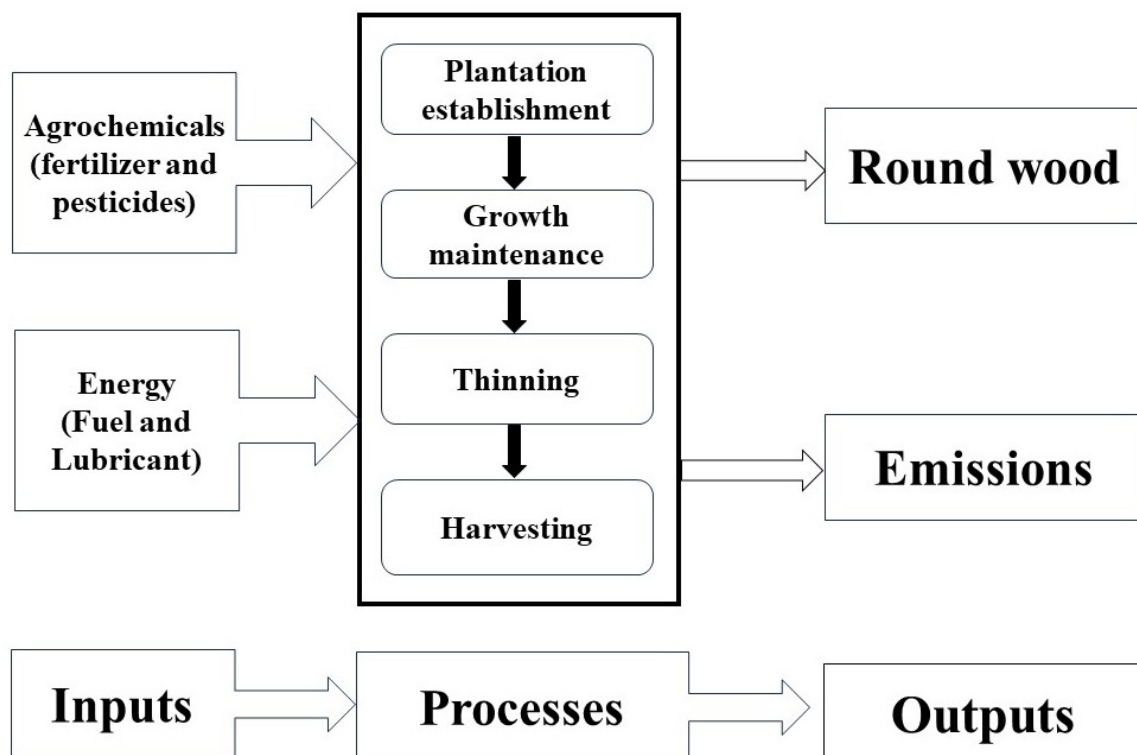


Figure 1. The system boundary of timber production

Generally, the forest operations in timber production can be described as follows:

- Plantation establishment: in plantation establishment, the activities are seed production and site preparation/pre-planting (Table 1). Seed production involved less utilization of mechanization (Kuka et al. 2019, 2020), but the site preparation activities for plowing, harrowing, and mechanical hole opening used some tractors (Bacenetti et al. 2016; Chiarabaglio et al. 2020).
- Growth maintenance: Growth maintenance activities include agro-technical tending and plant protection (Kuka et al. 2019, 2020).
- Thinning: In other studies, such as Kuka et al. (2019, 2020), the harvesting operation included thinning activities. In this study, the thinning operation is separated from harvesting activities because thinning has been conducted many times during a cycle rotation. In the thinning operation, the machines were applied to cut the trees.
- Harvesting: In this study, the harvesting operation is clear-cutting and conducted at the rotation's end. Harvesting methods in timber production are whole tree, tree length, and cut-to-length (De Francesco et al. 2022; Schweier et al. 2019; Spinelli et al. 2022). The purpose of the cutting method in the harvesting operation of the industrial

plantation is efficiency (Farooq et al. 2021).

According to Sahoo et al. (2021), the system boundary of cradle-to-grave in timber production can be divided into some groups as follows:

- Cradle-to-gate: the activities started with seedling production, forest management, harvesting, and transporting logs to the manufacturer.
- Gate-to-gate: the activities were timber yarding, sawing, drying, and transporting wood products to consumers.
- Gate-to-grave: the activities were transport to warehouses, transport to installation sites, consumer, demolition, transport to disposal site, and disposal of wood products' waste.

B. Functional Unit

The decision to employ a functional unit is a pivotal phase in the LCA process, as it entails assessing inputs and outputs. In the context of LCA studies in forestry operations, the functional unit has been examined through various parameters, including mass, energy, time, and area size (Mulyana and Hemida 2023). In addition, certain researchers have employed the functional unit of 1 m³ of timber production (Kuka et al. 2019; Proto et al. 2017; Sahoo et al. 2021). However, it should be noted that data collection for these studies was conducted within a 1 ha forest area, and the resulting data

Table 1. Characteristic in black locust and poplar timber production

Location	Species	System boundary	Silvicultural activities						References
			Seed production	Site preparation	Growth maintenance	Thinning	Harvesting	Others	
Brazil	<i>Pinus oocarpa</i>	Cradle-to-gate	√	√	√	√	√		Ferro et al. (2018)
Japan	<i>Abies sachalinensis</i> , <i>Chamaecyparis obtuse</i> , <i>Cryptomeria japonica</i> , <i>Larix kaempferi</i>	Cradle-to-gate	√	√	√	√	√		Nakano et al. (2018)
Latvia	<i>Pinus sylvestris</i>	Cradle-to-gate	√	√	√	√	√		Kuka et al. (2019)
Latvia	<i>Betula</i> spp	Cradle-to-gate	√	√	√	√	√		Kuka et al. (2020)
Italy	<i>Castanea sativa</i>	Gate-to-gate					√		Proto et al. (2017)
Portugal	<i>Pinus pinaster</i> , <i>Eucalyptus globulus</i> , <i>Cryptomeria japonica</i>	Cradle-to-gate		√	√	√	√		Dias et al. (2022)
USA	<i>Sequoia sempervirens</i>	Cradle-to-grave	√	√	√	√	√	√	Sahoo et al. (2021)

were subsequently converted to the specified 1 m³ of harvested wood (Kuka et al. 2020). Bernardi et al. (2022) employed the functional unit of 1 ha to assess the environmental impacts of logging operations in the Calabrian pine high forest in Italy.

According to Martínez-Blanco et al. (2015), the functional unit serves as the primary unit of analysis in LCA. This study employed the functional unit of 1 ha of timber production, aligning with the methods of Bacenetti et al. (2014, 2016b) and Cantamessa et al. (2022). These researchers utilize the functional unit of area (1 ha) to examine the LCA of agricultural production systems. Additionally, Polgár et al. (2018) employed the functional unit of 1 ha to assess the carbon footprint of various harvesting methods in energy plantations in Hungary.

C. Life Cycle Inventory

According to the International Standardization Organization 14044 (2006), life cycle inventory (LCI) is a phase in which data of both qualitative and quantitative nature is collected within the system boundary. The LCI is a critical component of life cycle assessment (LCA) processes, as it can significantly impact the study's results and conclusions (Kuka et al. 2020). Furthermore, Kuka et al. (2020) described that the LCI phase is often time-consuming due to the need for precise data collection. Despite the challenges associated with data collection, various methods, including measurement, calculation, and approximation for proxy data, can be employed to develop the LCI (Bjørn et al. 2018).

However, data collection for LCI is challenging due to limited data availability and accessibility. For instance, under Latvia's government regulations, harvesting pine trees is permitted when they reach ages 101–120 years. To obtain information on seedling production, planting establishment, and forest management of pine forests during the period 1900–2020, researchers relied on assumptions and estimations based on current silvicultural

practices (Kuka et al. 2019). Furthermore, Kuka et al. (2019) recommended that to get a more precise, comprehensive, and representative result of LCA, the assumptions should be avoided to reduce bias.

In this study, we employed the yield tables of black locust and poplar to estimate the volume of thinning and harvesting (Rédei et al. 2012, 2014). The utilization of a local yield table construction system has been applied in the collection of LCI data in the LCA of round wood production (*Abies sachalinensis*, *Chamaecyparis obtusa*, *Cryptomeria japonica*, and *Larix kaempferi*) in Japan (Nakano et al. 2018). Furthermore, data on fossil fuel consumption for machinery and agricultural chemicals (pesticides and fertilizer) can be collected from literature or databases (Oneil and Puettmann 2017; Zhang et al. 2020). In this research, due to the limitation of data on fuel consumption, we follow Cantamessa et al. (2022) to estimate fuel consumption using equation 1. Estimation through calculations from many data sources has also been applied in some research, such as in the Northwest United States (Oneil and Puettmann 2017) and China (Zhang et al. 2020)

$$F = Sc \times P \times d \times t \dots \dots \dots (1)$$

Where F is fuel consumption (kg/ha), Sc is specific fuel consumption (fixed to 0.25 kg/Kwh), P is maximum engine power (Kw), d is power utilization in %, and t is time (hours).

Power utilization in plantation establishment was 60%, and the maximum engine power ranged from 55–85 Kw (Cantamessa et al. 2022; Fiala and Bacenetti 2012). Moreover, the engine power of machinery for thinning and harvesting operations was 50–124 Kw, and the power utilization was from 64% to 67% (Cantamessa et al. 2022; De Francesco et al. 2022; Eisenbies et al. 2017; Spinelli et al. 2022). Furthermore, the consumption of pesticides was 4.5 L/ha (Glyphosphate), 4.8 L/ha (Pyretroid-comp.), 18.0 L/ha (fungicide), and fertilizer was 495 Kg/ha (urea superphosphate), 250 kg/ha (KCl) (González-García et al. 2014; Lovarelli et al. 2018). Lube consumption (hydraulic and

transmission oil) for thinning and harvesting operations was 30 l/1,000m³ (Athanasiadis et al. 1999).

D. Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) is calculated using software or manual calculation based on life cycle inventory data (Rosenbaum et al. 2018). The Sphera LCA for Experts Education License version 9.2.1.68. Software is a popular software in the study of life cycle assessment in European countries. The Sphera LCA for Experts Education License version 9.2.1.68. database modeling has been widely used by academia, researchers, practitioners, and policymakers to analyze the life cycle assessment of product processes (Kupfer et al. 2021). For example, Sphera LCA for Experts Education License version 9.2.1.68. Software has been used to analyze the LCA of forest operations, in both short- and long-rotation systems, in Hungary (Polgár 2023; Polgár et al. 2018, 2019) and Italy (Pierobon et al. 2015).

Furthermore, this study developed the plan or framework for product processes and life cycle impact assessment in Sphera LCA for Experts Education License version 9.2.1.68. Software (Figure 2).

III. RESULT AND DISCUSSION

A. Environmental impacts potential in timber production

Black locust and poplar plantations have been cultivated for a more extended rotation and with a reduced planting density compared to bioenergy production. According to the table yield of black locust (Rédei et al. 2014) and poplar (Rédei et al. 2012), the plantations were cultivated for 45 years. The silvicultural activities undertaken during the 45-year rotation period encompass the establishment of the plantations, maintenance of growth, and harvesting after the rotation (Table 2). The silvicultural practices employed during the 45-year rotation included the application

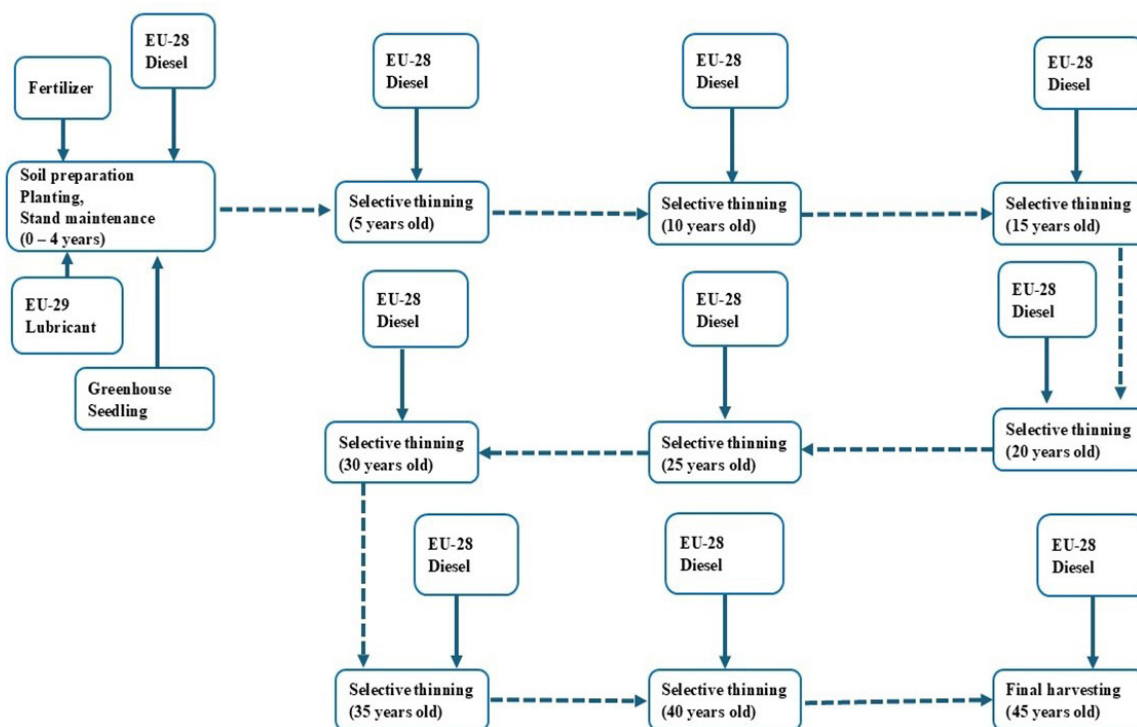


Figure 2. LCA plan of timber production using Sphera LCA for Experts Education License version 9.2.1.68. Software.

of fertilizers and pesticides in the initial year, followed by thinning activities at ages 5, 10, 15, 20, 25, 30, 35, and 40 years.

As illustrated in Table 2, the values of the environmental impact categories exhibited variation among the research sites. The values of these categories were found to be influenced by the inputs utilized during forestry operations. As presented in Table 2, the predominant environmental impact categories in timber production in black locust and poplar plantations were global warming potential (GWP) and ecotoxicity. In this study, the GWP for black locust and poplar were determined to be $4.0 \text{ E}10+03$ and $4.3 \text{ E}10+03 \text{ kg CO}_2 \text{ eq}$, respectively. Moreover, the GWP for poplar plantations in Italy ranged from $7.2 \text{ E}10+03$ to $10.5 \text{ E}10+03 \text{ kg CO}_2 \text{ eq}$ (Cantamessa et al. 2022; Chiarabaglio et al. 2020). According to Huang et al. (2015), the primary sources of carbon emissions from 1960 to 2009 were biomass

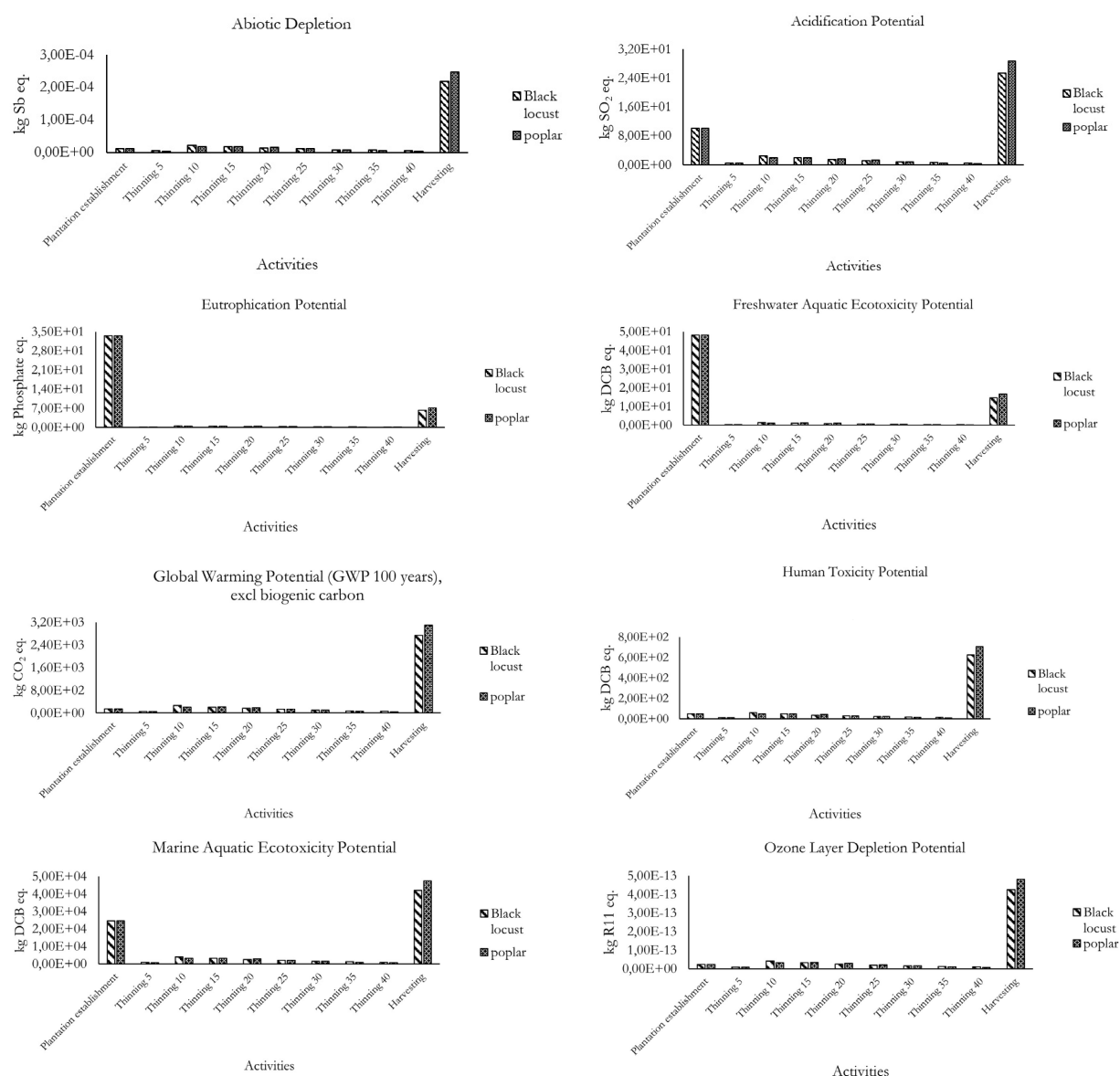
combustion/wildfires and fuel consumption. A detailed calculation using the Sphera LCA for Experts Education License version 9.2.1.68 Software revealed that the GWP is attributed to the use of mechanized methods in harvesting operations, thinning, and fuel consumption in plantation establishments.

In detail, the result of impact categories from Sphera LCA for Experts Education License version 9.2.1.68. Software showed that harvesting activity contributed to many impact categories such as abiotic depletion, acidification potential, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential, ozone layer depletion potential, photochemical ozone creation potential, and terrestrial ecotoxicity potential (Figure 3). Meanwhile, the fertilizer application affected the eutrophication potential and the freshwater aquatic ecotoxicity potential.

Table 2. Environmental impacts of timber production for industrial purposes

	This study		Cantamessa et al. (2022)	Chiarabaglio et al. (2020)
Location	Hungary	Hungary	Italy	Italy
Species	Poplar	Black locust	Poplar	Poplar
LCA analysis software	Sphera LCA for Experts Education License version 9.2.1.68.	Sphera LCA for Experts Education License version 9.2.1.68.	SIMAPRO v.8.0	SIMAPRO v.8.0
Database	USLCI	USLCI	Ecoinvent 3.0, Agrifootprint, ELCD, USLCI, and AudLCI	Ecoinvent 3.0, Agrifootprint, ELCD, USLCI, and AudLCI
Rotation	45 years	45 years	10 years	10 years
Purpose	Industrial	Industrial	Industrial (veneer)	Industrial
Soil	Sandy loamy	Sandy loamy	Sandy loamy	Sandy loamy
Tree density	400 trees/ha	400 trees/ha	250 – 300 trees/ha	250 – 300 trees/ha
System boundaries	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate
Stand management	a). plantation establishment b). growth management c). harvesting	a). plantation establishment b). growth management c). harvesting	a). soil preparation and planting b). cultivation c). harvesting	a). soil preparation and planting b). cultivation c). harvesting

	This study		Cantamessa et al. (2022)	Chiarabaglio et al. (2020)
Functional unit	Per unit area	Per unit area	Per unit area (ha)	Per unit area (ha)
GWP100 (IPCC) (kg CO ₂ eq)	(ha)	(ha)	10.5E+03	7.3E+03 (I-214 clones) 7.2E+03 (MSA clones)
	4.3E10+03	4.0E10+03		
ReCiPe midpoint				
- Terrestrial acidification (kgSO ₂ eq)	36.2	34.3	48.3	n.a
- Terrestrial ecotoxicity (kg 1,4-DCB)	1,260	1,235	18,503	
- Freshwater ecotoxicity (kg 1,4-DCB)	4,708	4,655	165	
- Marine ecotoxicity (kg 1,4-DCB)	21,756	21,432	205	
- Human toxicity (kg 1,4-DCB)	350.9	345.0	6,254	
- Water consumption (m ³)	-	-	17,460	
- Stratospheric ozone depletion (kg CFC11 eq)	0.0009	0.0008	0.016	
- Land use (m ² a crop eq)	190.2	177.6	140.4	
- Fossil resources scarcity (kg oil eq)	1,287.3	1,201.3	3,431.3	
Yield (m ³ /ha)	425	378	158	n.a



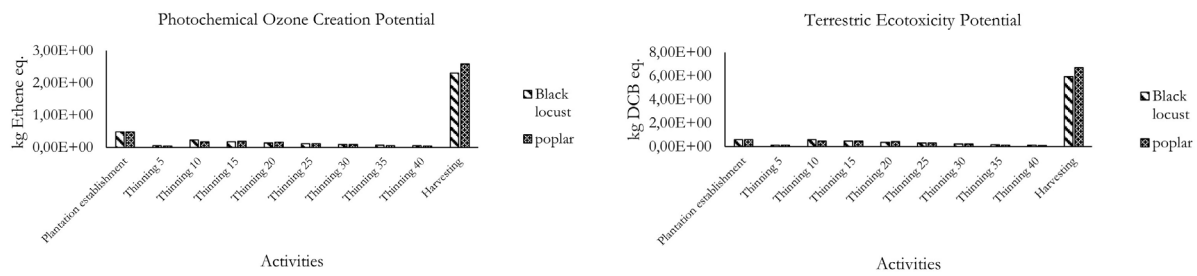


Figure 3. Environmental impacts during long-rotation plantation (45 years) in the CML method.

Table 3. Environmental impact distribution based on inputs in timber production (CML 2001 method)

Impact categories	Unit	Poplar			Black locust		
		Fuels	Lubricants	Fertilizer	Fuels	Lubricants	Fertilizer
Abiotic Depletion (ADP elements)	kg Sb eq.	3.39E-04	1.34E-07	0.00E+00	3.17E-04	1.34E-07	0.00E+00
Acidification Potential (AP)	kg SO ₂ eq.	3.94E+01	3.16E-03	8.91E+00	3.68E+01	3.16E-03	8.91E+00
Eutrophication Potential (EP)	kg Phosphate eq.	9.78E+00	2.47E-04	3.32E+01	9.13E+00	2.47E-04	3.32E+01
Freshwater Aquatic Ecotoxicity Potential (FAETP)	kg DCB eq.	2.29E+01	1.86E-02	4.74E+01	2.14E+01	1.86E-02	4.74E+01
Global Warming Potential (GWP 100 years), excl biogenic carbon	kg CO ₂ eq.	4.25E+03	1.05E+00	0.00E+00	3.97E+03	1.05E+00	0.00E+00
Human Toxicity Potential (HTP)	kg DCB eq.	9.70E+02	1.01E-01	1.84E+01	9.06E+02	1.01E-01	1.84E+01
Marine Aquatic Ecotoxicity Potential (MAETP)	kg DCB eq.	6.51E+04	7.44E+01	2.24E+04	6.07E+04	7.44E+01	2.24E+04
Ozone Layer Depletion Potential (ODP, steady state)	kg R11 eq.	6.60E-13	2.23E-15	0.00E+00	6.16E-13	2.23E-15	0.00E+00
Photochemical Ozone Creation Potential (POCP)	kg Ethene eq.	3.56E+00	4.67E-04	3.56E-01	3.32E+00	4.67E-04	3.56E-01
Terrestrial Ecotoxicity Potential (TETP)	kg DCB eq.	9.19E+00	4.44E-03	2.66E-01	8.58E+00	4.44E-03	2.66E-01

In this study, the detrimental environmental impacts have resulted dominantly from the harvesting operations. According to Kuka et al. (2019, 2020), logging operations producing pine and birch timber in Latvia resulted in more harmful environmental impacts than other silvicultural activities. A similar finding is reported by Klein et al. (2015), which shows that timber production has had detrimental environmental impacts. Harvesting using different logging methods (shortwood, chipwood, and whole-tree harvesting systems) has also negatively affected the environment (Laina et al. 2022; Laschi et al. 2016). The most significant greenhouse gas emissions in timber production of cedar (*Cryptomeria japonica*), hinoki cypress (*Chamaecyparis obtusa*),

larch (*Larix kaempferi*), and Sakhalin fir (*Abies sachalinensis*) in Japan resulted from harvesting operations (Nakano et al. 2018).

As shown in Table 3, the analysis indicates that fuel consumption had the dominant environmental impact during forestry operations. In this study, the carbon emissions were almost entirely attributable to fuel consumption. The significance of fuel consumption in mechanized on-farm operations, such as site preparation, fertilizer and pesticide application for growth maintenance, and timber harvesting, has been previously documented (Dijkman et al. 2018). Moreover, the carbon emission from fuel combustion and combined heating and power in China's forestry-pulp and paper industry resulted in 6.78 E+06 CO₂ eq (Zhao et al. 2019).

Consequently, reducing fuel consumption is a pivotal strategy to mitigate environmental degradation.

B. Carbon footprint in timber production

Despite the fact that the definition of carbon footprint remains open to interpretation, the concept has gained acceptance as a means of quantifying greenhouse gas (GHG) emissions released into the atmosphere, expressed as CO₂ equivalent (Choi et al. 2015). Initially, the concept of carbon footprint was introduced by Wackernagel and Rees (1996) as ecological footprint. As a component of the ecological footprint, the primary metric for calculating the carbon footprint is the average forest carbon sequestration (Mancini et al. 2016). In the development of the concept of the carbon footprint, it was incorporated into the environmental impact categories of life cycle assessment as global warming potential (Durojaye et al. 2020). Consequently, this study used the global warming potential to elucidate the carbon footprint of forest operations in timber production.

The carbon footprint associated with forest operations is attributable to two primary sources: indirect (off-site) and direct (on-site) emissions. Direct carbon emissions from forest operations stem from fuel combustion, while indirect emissions arise from electricity

or thermal energy consumption (Zhao et al. 2019). It is important to note that fertilizer use contributes significantly to the agricultural sector's carbon footprint (Siregar et al. 2015). This study used a comprehensive approach to estimate the carbon footprint, including both direct and indirect emissions.

As depicted in Figure 4, the contribution of carbon emissions from establishing black locust plantations, thinning, and harvesting is 4%, 27%, and 69%, respectively, of the total carbon emission. In a similar analysis of a poplar plantation, the distributions of carbon emissions during plantation establishment, thinning, and harvesting were 3%, 24%, and 73% of the total carbon emissions, respectively. A notable similarity between the black locust and poplar plantations is that harvesting accounts for more than two-thirds of total carbon emissions in both cases.

In timber production in Japan, the final harvesting phase contributes approximately 41-46% of total greenhouse gas (GHG) emissions (Nakano et al. 2018). In Austria, the total greenhouse gas (GHG) emissions from forest timber production were 492,096 tons of CO₂ eq., with harvesting and transportation contributing approximately 14% and 77%, respectively (Kühmaier et al. 2022). Furthermore, Kühmaier et al. (2022) found that the harvesting method using chainsaws resulted in lower greenhouse

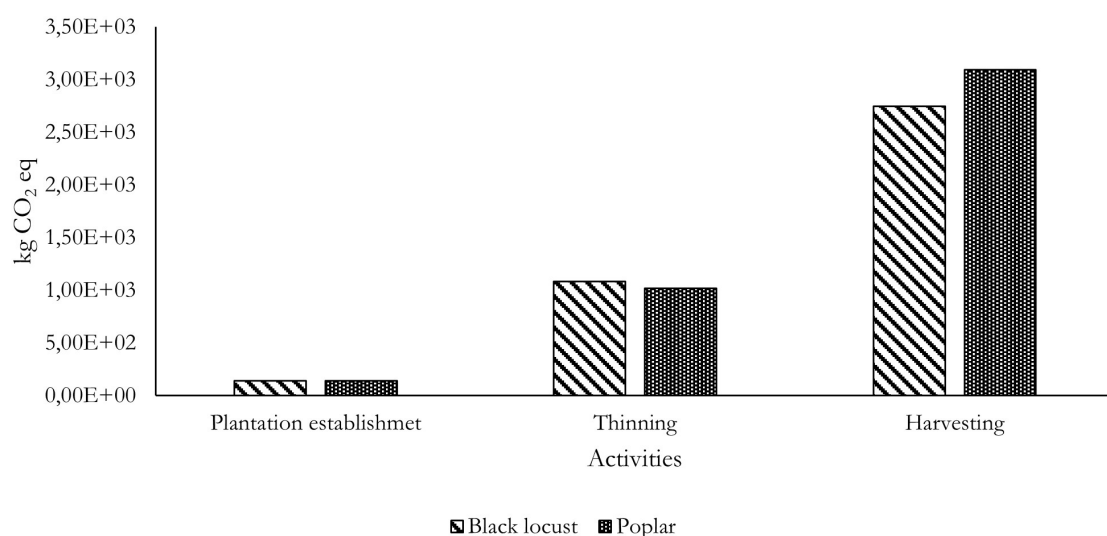


Figure 4. Contribution of the carbon footprint based on activities

gas (GHG) emissions compared to the use of harvesting machinery. Additionally, the distance between forests and industries was identified as contributing to high emissions levels during transportation.

IV. CONCLUSION

Forest operations have caused detrimental environmental impacts from the consumption of energy (fuel and lubricants) and agrochemicals (fertilizers and pesticides). Based on the CML 2001 method, from the ten impact categories, eight impact categories resulted from fuel consumption. Meanwhile, the eutrophication and freshwater aquatic ecotoxicity potential impact categories were primarily caused by fertilizer application.

From the carbon footprint perspective, fuel and lubricant consumption are the main contributors to greenhouse gas emissions. Furthermore, harvesting activity has caused greater environmental impacts than plantation establishment and thinning. Forest operations that use mechanization methods have consumed more fuel and had more detrimental impacts on the environment. The use of machines that emit lower levels of emissions during forest operations is expected to minimize environmental impact.

Based on the findings of this research, minimizing fuel consumption and agrochemical use can reduce detrimental impacts. However, further research should be conducted to elaborate on the equilibrium between optimum timber productivity and low environmental impacts. Due to limitations in the database of life cycle inventory for forest operations in Hungary, we have used relevant information from other Central European countries to assess the environmental impacts of forest operations. Therefore, in the future, each country should develop a database for forestry activities to provide a more accurate database of life cycle inventory.

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REFERENCES

- Athanassiadis, D., Lidestav, G., and Wästerlund, I. 1999. Fuel, Hydraulic Oil and Lubricant Consumption in Swedish Mechanized Harvesting Operations, 1996. *Journal of Forest Engineering*, 10(1), 59–66.
- Bacenetti, J., Bergante, S., Facciotto, G., and Fiala, M. 2016. Woody biofuel production from short rotation coppice in Italy: Environmental-impact assessment of different species and crop management. *Biomass and Bioenergy*, 94, 209–219. DOI: 10.1016/j.biombioe.2016.09.002
- Bernardi, B., Macrì, G., Falcone, G., Stillitano, T., Benalia, S., and De Luca, A. I. 2022. Assessment and Sustainability of Logging Operations in Calabrian Pine High Forests. *Forests*, 13, 403. DOI: 10.3390/f13030403
- Bijak, S., and Lachowicz, H. 2021. Impact of tree age and size on selected properties of black locust (*Robinia pseudoacacia* L.) wood. *Forests*, 12, 634. DOI: 10.3390/f12050634
- Bjørn, A., Moltesen, A., Laurent, A., Owsianiak, M., Corona, A., Birkved, M., and Hauschild, M. Z. 2018. Life Cycle Inventory Analysis. In M. Hauschild, R. Rosenbaum, and S. Olsen (Eds.), *Life Cycle Assessment* (pp. 117–165). Springer International Publishing. DOI: 10.1007/978-3-319-56475-3_9
- Cantamessa, S., Rosso, L., Giorcelli, A., and Chiarabaglio, P. M. 2022. The Environmental Impact of Poplar Stand Management: A Life Cycle Assessment Study of Different Scenarios. *Forests*, 13, 464. DOI: 10.3390/f13030464
- Chiarabaglio, P. M., Deidda, A., Bergante, S., Castro, G., Facciotto, G., Giorcelli, A., Pagliolico, S., and Carbonaro, C. 2020. Life Cycle Assessment (LCA): New poplar clones allow an environmentally sustainable cultivation. *Annals of Silvicultural Research*, 45(1), 72–82. DOI: 10.12899/asr-2017
- Choi, S.-W., Kim, H., and Kim, J. 2015. Development of ‘Carbon Footprint’ Concept and Its Utilization Prospects in the Agricultural and Forestry Sector. *Korean Journal of Agricultural*

- and *Forest Meteorology*, 17(4), 358–383. DOI: 10.5532/kjafm.2015.17.4.358
- De Francesco, F., Magagnotti, N., Kováč, B., Heger, P., Heilig, D., Heil, B., Kovács, G., Zemánek, T., and Spinelli, R. 2022. Integrated Harvesting of Medium Rotation Hybrid Poplar Plantations: Systems Compared. *Forests*, 13, 1873. DOI: 10.3390/f13111873
- Dias, A. M., Machado, J. S., Dias, A. M. P. G., Silvestre, J. D., and de Brito, J. 2022. Influence of the Wood Species, Forest Management Practice and Allocation Method on the Environmental Impacts of Roundwood and Biomass. *Forests*, 13, 1357. DOI: 10.3390/f13091357
- Dijkman, T. J., Basset-Mens, C., Antón, A., and Núñez, M. 2018. LCA of Food and Agriculture. In M. Hauschild, R. Rosenbaum, & S. Olsen (Eds.), *Life Cycle Assessment* (pp. 723–754). Springer International Publishing. DOI: 10.1007/978-3-319-56475-3_29
- Durojaye, O., Laseinde, T., and Oluwafemi, I. 2020. A Descriptive Review of Carbon Footprint. In T. Ahram, W. Karwowski, S. Pickl, & R. Taiar (Eds.), *Advances in Intelligent Systems and Computing* (Vol. 1026, pp. 960–968). Springer Verlag. DOI: 10.1007/978-3-030-27928-8_144
- Eisenbies, M. H., Volk, T. A., Espinoza, J., Gantz, C., Himes, A., Posselius, J., Shuren, R., Stanton, B., and Summers, B. 2017. Biomass, spacing and planting design influence cut-and-chip harvesting in hybrid poplar. *Biomass and Bioenergy*, 106, 182–190. DOI: 10.1016/j.biombioe.2017.09.003
- Elands, B. H. M., and Wiersum, K. F. 2001. Forestry and rural development in Europe: an exploration of socio-political discourses. *Forest Policy and Economics*, 3, 5–16. DOI: 10.1016/S1389-9341(00)00027-7
- Farooq, T. H., Shakoor, A., Wu, X., Li, Y., Rashid, M. H. U., Zhang, X., Gilani, M. M., Kumar, U., Chen, X., and Yan, W. 2021. Perspectives of plantation forests in the sustainable forest development of China. *Forest*, 14(2), 166–174. DOI: 10.3832/for3551-014
- Ferro, F. S., Silva, D. A. L., Icimoto, F. H., Lahr, F. A. R., and González-García, S. 2018. Environmental Life Cycle Assessment of industrial pine roundwood production in Brazilian forests. *Science of the Total Environment*, 640–641, 599–608. DOI: 10.1016/j.scitotenv.2018.05.262
- Fiala, M., and Bacenetti, J. 2012. Model for the economic, energy and environmental evaluation in biomass productions. *Journal of Agricultural Engineering*, 43(1), 5. DOI: 10.4081/jae.2012.e5
- González-García, S., Moreira, M. T., Dias, A. C., and Mola-Yudego, B. 2014. Cradle-to-gate Life Cycle Assessment of forest operations in Europe: Environmental and energy profiles. *Journal of Cleaner Production*, 66, 188–198. DOI: 10.1016/j.jclepro.2013.11.067
- Huang, Y., Shen, H., Chen, Y., Zhong, Q., Chen, H., Wang, R., Shen, G., Liu, J., Li, B., and Tao, S. 2015. Global organic carbon emissions from primary sources from 1960 to 2009. *Atmospheric Environment*, 122, 505–512. DOI: 10.1016/j.atmosenv.2015.10.017
- International Standardization Organization. 2006. *ISO 14044 Environmental management-Life cycle assessment-Requirements and guidelines*.
- John, C. A., Tan, L. S., Tan, J., Kiew, P. L., Shariff, A. M., and Abdul Halim, H. N. 2021. Selection of renewable energy in rural area via life cycle assessment-analytical hierarchy process (LCA-AHP): A case study of Tatau, Sarawak. *Sustainability*, 13, 11880. DOI: 10.3390/su132111880
- Kennedy, J. J., Thomas, J. W., and Glueck, P. 2001. Evolving forestry and rural development beliefs at midpoint and close of the 20th century. *Forest Policy and Economics*, 3, 81–95. DOI: 10.1016/S1389-9341(01)00034-X
- Klein, D., Wolf, C., Schulz, C., and Weber-Blaschke, G. 2015. 20 years of life cycle assessment (LCA) in the forestry sector: state of the art and a methodical proposal for the LCA of forest production. *International Journal of Life Cycle Assessment*, 20(4), 556–575. DOI: 10.1007/s11367-015-0847-1
- Komán, S., Németh, R., and Báder, M. 2023. An Overview of the Current Situation of European Poplar Cultures with a Main Focus on Hungary. *Applied Sciences*, 13, 12922. DOI: 10.3390/app132312922
- Kühmaier, M., Kral, I., and Kanzian, C. 2022. Greenhouse Gas Emissions of the Forest Supply Chain in Austria in the Year 2018. *Sustainability (Switzerland)*, 14, 792. DOI: 10.3390/su14020792
- Kuka, E., Cirule, D., Andersone, I., Miklasevics, Z., and Andersons, B. 2019. Life cycle inventory for currently produced pine roundwood. *Journal of Cleaner Production*, 235, 613–625. DOI: 10.1016/j.jclepro.2019.07.004
- Kuka, E., Cirule, D., Andersone, I., Miklasevics, Z., and Andersons, B. 2020. Life cycle inventory for currently harvested birch roundwood.

- European Journal of Wood and Wood Products*, 78(5), 859–870. DOI: 10.1007/s00107-020-01544-7
- Kupfer, T., Baitz, M., Colodel, C., Kokborg, M., Scholl, S., Rudolf, M., Bos, U., Bosch, F., Gonzalez, M., Schuller, O., Hengstler, J., Stoffregen, A., Thylmann, D., and Koffler, C. 2021. *GaBi Databases & Modelling Principles*. <https://sphaera.com/wp-content/uploads/2020/04/Modeling-Principles-GaBi-Databases-2021.pdf>
- Laina, R., Herrero, S. J., Corona, B., Tolosana, E., de la Fuente, M. T., and San Miguel, G. 2022. Economic and environmental assessment of a multifunctional poplar plantation for roundwood and wood chip production in Spain. *Forest Systems*, 31(1), e002. DOI: 10.5424/fs/2022311-18485
- Laschi, A., Marchi, E., and González-García, S. 2016. Forest operations in coppice: Environmental assessment of two different logging methods. *Science of the Total Environment*, 562, 493–503. DOI: 10.1016/j.scitotenv.2016.04.041
- Lovarelli, D., Fusi, A., Pretolani, R., and Bacenetti, J. 2018. Delving the environmental impact of roundwood production from poplar plantations. *Science of the Total Environment*, 645, 646–654. DOI: 10.1016/j.scitotenv.2018.06.386
- Mancini, M. S., Galli, A., Niccolucci, V., Lin, D., Bastianoni, S., Wackernagel, M., and Marchettini, N. 2016. Ecological Footprint: Refining the carbon Footprint calculation. *Ecological Indicators*, 61, 390–403. DOI: 10.1016/j.ecolind.2015.09.040
- Morales-Vera, R., Vásquez-Ibarra, L., Scott, F., Puettmann, M., and Gustafson, R. 2022. Life Cycle Assessment of Bioethanol Production: A Case Study from Poplar Biomass Growth in the U.S. Pacific Northwest. *Fermentation*, 8, 734. DOI: 10.3390/fermentation8120734
- Mulyana, B., and Hemida, M. (2023). Life cycle assessment in Indonesia forestry sector: A scoping review. *Global Forest Journal*, 1(1), 51–59. DOI: 10.32734/gfj.v1i01.13254
- Mulyana, B., Polgár, A., and Vityi, A. 2023. Research trends in the environmental assessment of poplar plantations in Hungary: A bibliometric analysis. *Ecocycles*, 9(3), 23–32. DOI: 10.19040/ecocycles.v9i3.339
- Mulyana, B., Polgár, A., and Vityi, A. 2024. Forest Carbon Modeling in Poplar and Black Locust Short Rotation Coppice Plantation in Hungary. *Jurnal Sylva Lestari*, 12(2), 324–337. DOI: 10.23960/jsl.v12i2.883
- Mulyana, B., Vityi, A., and Polgár, A. 2025. Life cycle assessment of bioenergy production from short-rotation coppice plantation in Hungary. *Journal of Forest Science*, 71(5), 237–249. DOI: 10.17221/10/2025-JFS
- Nakano, K., Shibahara, N., Nakai, T., Shintani, K., Komata, H., Iwaoka, M., and Hattori, N. 2018. Greenhouse gas emissions from round wood production in Japan. *Journal of Cleaner Production*, 170, 1654–1664. DOI: 10.1016/j.jclepro.2016.10.024
- Nambiar, E. K. S. 2015. Forestry for rural development, poverty reduction and climate change mitigation: We can help more with wood. *Australian Forestry*, 78(2), 55–64. DOI: 10.1080/00049158.2015.1050776
- Nicolescu, V. N., Hernea, C., Bakti, B., Keserű, Z., Antal, B., and Rédei, K. 2018. Black locust (*Robinia pseudoacacia* L.) as a multi-purpose tree species in Hungary and Romania: a review. *Journal of Forestry Research*, 29(6), 1449–1463. DOI: 10.1007/s11676-018-0626-5
- Oneil, E., and Puettmann, M. E. 2017. A life-cycle assessment of forest resources of the pacific Northwest, USA. *Forest Products Journal*, 67(5–6), 316–330. DOI: 10.13073/FPJ-D-17-00011
- Pierobon, F., Zanetti, M., Grigolato, S., Sgarbossa, A., Anfodillo, T., and Cavalli, R. 2015. Life cycle environmental impact of firewood production - A case study in Italy. *Applied Energy*, 150, 185–195. DOI: 10.1016/j.apenergy.2015.04.033
- Polgár, A. 2023. Carbon footprint and sustainability assessment of wood utilisation in Hungary. *Environment, Development and Sustainability*. DOI: 10.1007/s10668-023-03571-9
- Polgár, A., Horváth, A., Mátyás, K. S., Horváth, A. L., Rumpf, J., and Vágvolgyi, A. 2018. Carbon footprint of different harvesting work systems in short rotation energy plantations. *Acta Silvatica et Lignaria Hungarica*, 14(2), 113–126. DOI: 10.2478/aslh-2018-0008
- Polgár, A., Kovács, Z., Fodor, V. E., and Bidló, A. 2019. Environmental Life-Cycle Assessment of Arable Crop Production Technologies Compared to Different Harvesting Work Systems in Short Rotation Energy Plantations. *Acta Silvatica et Lignaria Hungarica*, 15(2), 55–68. DOI: 10.2478/aslh-2019-0005
- Prinz, R., Spinelli, R., Magagnotti, N., Routa, J., and Asikainen, A. 2018. Modifying the settings of CTL timber harvesting machines to reduce fuel consumption and CO2 emissions. *Journal of Cleaner Production*, 197, 208–217. DOI: 10.1016/j.jclepro.2018.06.210

- Proto, A. R., Bacenetti, J., Macrì, G., Fiala, M., and Zimbalatti, G. 2017. Mechanisation of different logging operations: Environmental impact assessment using life cycle assessment (LCA) approach. *Chemical Engineering Transactions*, 58, 229–234. DOI: 10.3303/CET1758039
- Proto, A. R., Bacenetti, J., Macrì, G., and Zimbalatti, G. 2017. Roundwood and bioenergy production from forestry: Environmental impact assessment considering different logging systems. *Journal of Cleaner Production*, 165, 1485–1498. DOI: 10.1016/j.jclepro.2017.07.227
- Quinkenstein, A., and Jochheim, H. 2016. Assessing the carbon sequestration potential of poplar and black locust short rotation coppices on mine reclamation sites in Eastern Germany - Model development and application. *Journal of Environmental Management*, 168, 53–66. DOI: 10.1016/j.jenvman.2015.11.044
- Rédei, K., Csiha, I., Keseru, Z., Rásó, J., Kamandiné Végh, Á., and Antal, B. 2014. Growth and Yield of Black Locust (*Robinia pseudoacacia* L.) Stands in Nyírség Growing Region (North-East Hungary). *South-East European Forestry*, 5(1). DOI: 10.15177/see-for.14-04
- Rédei, K., Keserű, Z., and Rásó, J. 2012. Practice-Oriented Yield Table for White Poplar Stands Growing under Sandy Soil Conditions in Hungary. *South-East European Forestry*, 3(1), 33–40. DOI: 10.15177/see-for.12-04
- Rosenbaum, R. K., Hauschild, M. Z., Boulay, A. M., Fantke, P., Laurent, A., Núñez, M., and Vieira, M. 2018. Life cycle impact assessment. In M. Hauschild, R. Rosenbaum, & S. Olsen (Eds.), *Life Cycle Assessment: Theory and Practice* (pp. 167–270). Springer International Publishing. DOI: 10.1007/978-3-319-56475-3_10
- Sahoo, K., Bergman, R., and Runge, T. 2021. Life-cycle assessment of redwood lumber products in the US. *International Journal of Life Cycle Assessment*, 26(8), 1702–1720. DOI: 10.1007/s11367-021-01937-7
- Sadaghiani, S., Mafakheri, F., and Chen, Z. 2023. Life Cycle Assessment of Bioenergy Production Using Wood Pellets: A Case Study of Remote Communities in Canada. *Energies*, 16, 5697. DOI: 10.3390/en16155697
- Schweier, J., Magagnotti, N., Labelle, E. R., and Athanassiadis, D. 2019. Sustainability Impact Assessment of Forest Operations: a Review. *Current Forestry Reports*, 5(3), 101–113. DOI: 10.1007/s40725-019-00091-6
- Siregar, K., Tambunan, A. H., Irwanto, A. K., Wirawan, S. S., and Araki, T. 2015. A Comparison of Life Cycle Assessment on Oil Palm (*Elaeis guineensis* Jacq.) and Physic Nut (*Jatropha curcas* Linn.) as Feedstock for Biodiesel Production in Indonesia. *Energy Procedia* 65, 65, 170–179. DOI: 10.1016/j.egypro.2015.01.054
- Spinelli, R., Magagnotti, N., De Francesco, F., Kováč, B., Heger, P., Heilig, D., Heil, B., Kovács, G., and Zemánek, T. 2022. Cut-to-Length Harvesting Options for the Integrated Harvesting of the European Industrial Poplar Plantations. *Forests*, 13, 1478. DOI: 10.3390/f13091478
- Spinelli, R., and Moura, A. C. de A. 2019. Decreasing the fuel consumption and CO2 emissions of excavator-based harvesters with a machine control system. *Forests*, 10, 43. DOI: 10.3390/f10010043
- Vítková, M., Müllerová, J., Sádlo, J., Pergl, J., and Pyšek, P. 2017. Black locust (*Robinia pseudoacacia*) beloved and despised: A story of an invasive tree in Central Europe. *Forest Ecology and Management*, 384, 287–302. DOI: 10.1016/j.foreco.2016.10.057
- Wackernagel, M., and Rees, W. 1996. *Our Ecological Footprint, Reducing Human Impact on the Earth*. New Society Publisher.
- Żelazna, A., Kraszkiewicz, A., Przywara, A., Łagód, G., Suchorab, Z., Werle, S., Ballester, J., and Nosek, R. 2019. Life cycle assessment of production of black locust logs and straw pellets for energy purposes. *Environmental Progress & Sustainable Energy*, 38(1), 163–170. DOI: 10.1002/ep.13043
- Zhang, X., Zhang, W., and Xu, D. 2020. Life cycle assessment of complex forestry enterprise: A case study of a forest-fiberboard integrated enterprise. *Sustainability (Switzerland)*, 12, 4147. <https://doi.org/10.3390/su12104147>
- Zhao, Q., Ding, S., Wen, Z., and Toppinen, A. 2019. Energy flows and carbon footprint in the forestry-pulp and paper industry. *Forests*, 10, 725. <https://doi.org/10.3390/f10090725>

STERILIZATION AND INDUCTION CALLUS OF KLUWIH TEAK (*Tectona grandis* f. *abludens*) USING IN VITRO CULTURE

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STERILIZATION AND INDUCTION CALLUS OF KLUWIH TEAK (*Tectona grandis* f. *abludens*) USING IN VITRO CULTURE. *Tectona grandis* f. *abludens* or kluwih teak is a variety of teak endemic to Java, especially found in Desa Selang Gunung Kidul and Desa Loh Putih, Kecamatan Dlingo Bantul -Yogyakarta, where currently only six trees are found. Due to very low population size of this teak variety, efforts to conserve them are indispensable. The action conservation was achieved through *in vitro* propagation methods (embryogenesis). However, the main problems with *in vitro* techniques are known especially with explant sterilization and callus induction. This study aimed to analyze the response of mercury chloride (HgCl₂) immersion time to explant sterilization and analyze the response of a combination of 2,4-D Plant Growth Regulators (PGR) and kinetin to embryogenic callus formation. The data analysis method used a Completely Randomised Design (CRD) for explants sterilization consisting of 300 mg/L HgCl₂ treatment in 0; 15; 20; 25 and 30 minutes and Complete Randomised Factorial Design (CFRD) consisting of 2,4-D: 0; 1.5; 3 mg/L and kinetin: 0; 0.5; 1; 1.5 mg/L for callus induction. The results of the explant sterilization study showed that immersion treatment of 300 mg /L HgCl₂ for 15 minutes resulted in the highest sterile explants of 90% at 15 day after planting (DAP). The results of callus induction research showed that 0 ppm 2,4-D treatment combined with 1.5 mg/L kinetin resulted in the highest callus percentage of 73.33% and the highest callus formation score was 1.53 at 12 WAP (week after planting).

Keywords: *Tectona grandis* f. *abludens*, kluwih teak. *in vitro*, sterilization, embryogenic callus induction

STERILISASI DAN INDUKSI KALUS JATI KLUWIH (*Tectona grandis* f. *abludens*) PADA KULTUR IN VITRO. *Tectona grandis* f. *abludens* atau jati kluwih merupakan forma jati yang unik serta endemik Jawa khususnya di Gunung Kidul dan Bantul Daerah Istimewa Yogyakarta yang hanya ditemukan enam individu pohon. Kendala utama regenerasi alami forma tersebut diduga karena memiliki hambatan fisik dan fisiologis. Aksi konservasi nyata agar forma tersebut tidak punah dapat dilakukan melalui pendekatan propagasi *in vitro* (embriogenesis) yang diharapkan menjadi salah satu solusi. Permasalahan utama dalam riset propagasi *in vitro* adalah sterilisasi eksplan dan induksi kalus. Riset ini bertujuan menganalisis respon waktu perendaman merkuri klorida (HgCl₂) terhadap sterilisasi eksplan dan menganalisis respon kombinasi Zat Pengatur Tumbuh (ZPT) 2,4-D dan kinetin terhadap pembentukan kalus embriogenik. Metode analisis data yang digunakan adalah Rancangan Acak Lengkap (RAL) untuk sterilisasi eksplan yang terdiri atas perlakuan HgCl₂ 300 mg/L dalam waktu 0; 15; 20; 25 dan 30 menit serta Rancangan Acak Lengkap Faktorial (RALF) yang terdiri atas 2,4-D: 0; 1,5; 3 mg/L dan kinetin: 0; 0,5; 1; 1,5 mg/L untuk induksi kalus. Hasil penelitian sterilisasi eksplan menunjukkan perlakuan perendaman 300 mg/l HgCl₂ selama 15 menit menghasilkan eksplan steril tertinggi 90% pada 15 hari setelah tanam (HST). Hasil penelitian induksi kalus menunjukkan perlakuan 0 ppm 2,4-D yang dikombinasikan 1,5 ppm kinetin menghasilkan persentase kalus tertinggi 73,33% dan skor perkembangan kalus tertinggi sebesar 1,53 pada 12 MST (Minggu Setelah Tanam).

Kata kunci: *Tectona grandis* f. *abludens*, jati kluwih, *in vitro*, sterilisasi, induksi kalus embriogenik

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I. INTRODUCTION

Teak (*Tectona* sp.) is a commercially important wood species widely employed in the transportation (Tripathi et al., 2016), building (Herzog et al., 2012), and furniture and craft sectors (Bastian & Rahadiyanti, 2023). In 2019, the teak wood sector in Indonesia had substantial growth of 8.35%, with an export value of US\$1.95 billion (Gunadi, 2021). Teak species are indigenous to Southeast and South Asia, particularly Java, with a limited distribution outside Java. Fauzi et al. (2021) recognized four species of teak globally: *Tectona grandis*, *T. hamiltoniana*, *T. philippinensis*, and *T. grandis* f. *abludens* (teak kluwih), the last being native to Indonesia. Fauzi et al. (2021) states that kluwih teak is indigenous to Gunung Kidul and Bantul (Yogyakarta). *Tectona grandis* f. *abludens*, locally known as "jati kluwih," is found primarily in the Dlingo, Bantul, and Selang areas of Gunungkidul, Yogyakarta. Jati kluwih can reach a height of 10–20 m, with a canopy that tends to branch heavily and has a rounded umbrella shape with wavy leaves resembling those of kluwih (*Artocarpus incise*) or breadfruit (*Artocarpus altilis*). Jati kluwih was first discovered and identified by Santi and Rujiman as one of four types of teak that differ from ordinary teak (*T. grandis*). These differences can be seen in leaf shape, tree cross-section, bark shape, petiole length, leaf edge shape, ovary size, and epidermis shape. The results of surveys and observations conducted by the author in 2020–2022 in Selang and Dlingo Villages, Yogyakarta, found only six individuals in community yards/gardens.

Insufficient understanding of kluwih teak's ecology, phenology, reproduction, and culture hinders its advancement and utilization. Particularly concerning reproduction, kluwih teak is believed to have challenges in seed and embryo production. Ex situ conservation and artificial propagation are essential strategies for sustaining its existence. Using in vitro methods to grow plants from callus (somatic embryogenesis) is a good way to quickly produce a lot of seedlings (Thorpe, 2007).

The primary challenge in *in vitro* propagation is the generation of sterile explants from mature trees utilized as explant sources. Research by Fauzan (2017) found that soaking *T. grandis* side shoot cultures in 300 mg/l HgCl₂ (mercury chloride) for 3 minutes was the best way to sterilize them, resulting in an 85% success rate in keeping them free from contamination. Furthermore, the efficacy of embryogenic callus induction is significantly affected by the combination of growth regulators, necessitating the optimization of the planting media formulation. Previous studies on somatic embryogenesis in annual woody plants were done by Supriyati et al. (2016), Faizy et al. (2019), Tripathi et al. (2021), Bisht et al. (2024), Liu et al. (2024), and the *Tectona* genus (*T. grandis*) by Arsyad et al. (2020) using auxin (2,4-D) and cytokinin (BAP, Kinetin) formed the basic groundwork for this research on growing kluwih teak. The in vitro method of embryogenesis commences with the callus phase. Callus comprises a conglomeration of undifferentiated cells (Hartmann et al., 2014). Auxin and cytokinin, as growth regulators, are employed to generate embryogenic callus. Auxin helps with callus growth, making chlorophyll, forming roots and shoots, and creating embryos, while cytokinin encourages cell division, the formation of organs, and the growth of shoots.

Research and development of the kluwih teak (*T. grandis* f. *abludens*) is currently still in its early stages, particularly in terms of in vitro propagation through tissue culture. Although numerous studies have been conducted on its close relative, *Tectona grandis*, specific research on the kluwih teak has never been reported, either on physiological mechanisms or the effects of plant growth regulators (PGRs) on cell and tissue development. The current research approach, somatic embryogenesis, is considered a promising strategy, as it is expected to produce large numbers of plants while maintaining their genetic purity. In addition, several studies on the controlled use of mercuric chloride as a sterilant have demonstrated its effectiveness and

safety for use. This study aimed to (i) analyze the effect of HgCl_2 immersion duration on the sterilization of teak kluwih explants and (ii) examine the interaction of growth regulators, namely auxin (2,4-D) and cytokinin (kinetin), on the induction of *T. grandis* f. *abludens* callus.

II. MATERIALS AND METHODS

A. Material

Young stem explants were obtained from duplicate mother plants constructed from grafting and planted in the greenhouse of the BRIN Chemistry and Bioprocess Laboratory, BJ. Habibie Science and Technology Area, Serpong, Tangerang Selatan in July 2022 to produce many adventitious shoots. The *T. grandis* f. *abludens* scion was obtained from the Manggala Wanabakti collection of the Ministry of Environment and Forestry, Jakarta, planted in 1981, located at latitude and longitude $-6^{\circ}12'25.56''$ S, $106^{\circ}47'58.56''$ E ($\pm -6.2071, 106.7996$), elevation $\pm 16-17$ m asl, with an average annual rainfall of 2100–2150 mm per year.

Creating duplicate mother plants began with scion preparation by pruning plagiotropic branches with pruning shears and allowing them to grow for two months. The scion is then grafted onto a three-month-old teak rootstock and grown in a plastic incubator within a greenhouse at a temperature of $27-43^{\circ}\text{C}$, with humidity exceeding 70%, and a light intensity of 2000 – 6000 lux. The stem sections from the new shoots that grew after one month were then used as explants for sterilization in the laboratory.

B. Experiment 1: Sterilization

The sterilization experiment is categorized into two steps: outside of the LAF (Laminar Air Flow) and inside the LAF. The outside of the LAF is prepared by excising the explant hairs stem using a scalpel. The explants were subsequently sectioned, cleansed with detergent, and thoroughly rinsed. Sterilization within the LAF starts with washing the explants three times with sterile water. The explants were

subsequently immersed in HgCl_2 (MERCK) at a concentration of 300 mg/L for a specified duration 0, 15, 20, 25, 30 minutes. The explants were subsequently cleaned with sterile water three times, submerged in a 3% clorox solution for five minutes, and then rinsed again with sterile water three times. The explants were subsequently immersed in a 3% clorox solution for 2 minutes, washed three times with sterile water, and then dried using sterile tissue paper. The initiation and planting of sterilized explants were conducted on Murashige and Skoog media (MS0).

C. Experiment 2: Embryogenic callus induction

The explants utilized were sterile specimens from the explant sterilization experiment, aged three weeks post-initiation. The explants were subsequently subcultured in the designated callus induction medium. The planting was done in a clean airflow cabinet, and then the subcultures were kept in a controlled environment at 25°C , with 76% humidity, and in the dark.

Designing experiments of sterilization used a Completely Random Experimental Design (CRD) to test how long to soak the explants in HgCl_2 , with times of 0, 15, 20, 25, and 30 minutes. Each treatment was conducted 27 to 30 times, contingent upon the availability of explants. Each replicate was grown in an individual test tube utilizing MS0 medium. Designing experiments Induction of embryogenic callus was a Completely Factorial Randomized Experimental Design (CFRD). Factor 1 is the concentration of auxin (2,4-D), including three levels: 0, 1.5, and 3 ppm. Factor 2 is the amount of cytokinin (kinetin) used, which has four levels: 0, 0.5, 1, and 1.5 ppm. This creates 12 different treatment combinations, and each combination is tested three times, with each test involving 5 experimental units.

D. Data Collection

d. 1 Exp. 1: Sterilization of explants. Observations were conducted every three days during a period of fifteen days. The variables

monitored included the quantity of explants infected with fungus, bacteria, instances of browning, and the number of sterile explants.

d.2 Exp. 2: Induction of embryogenic callus. We conducted observations weekly for a duration of 12 weeks. The recorded parameters included the quantity of explants survive, number of callus, callus development, color, and a cellular examination of the callus. At the end of the examination, we conducted observations using a VHX 970 F digital microscope with a magnification range of 100-200X.

E. Analysis

Observation data were analyzed using Microsoft Excel to ascertain the proportion of explants contaminated with fungus, contaminated with bacteria, exhibiting browning, remaining sterile, as well as the percentages of viable and callus explants. The parameter of each treatment was analyzed using the analysis of variance (ANOVA) test using SPSS 27, followed by the Duncan Multiple Range Test (DMRT) at $\alpha=0.01$. The examination of callus development characteristics employed the Kruskal-Wallis test, followed by the Dunn post hoc test (Bonferroni-Dunn test) at $\alpha=0.01$. Data analysis was accomplished using the following formulas (Fauzan et al., 2017).

1. Explants sterilization

The percentage of fungal contamination (%) =

$$\frac{\text{the number of contaminated fungi}}{\text{The number of planted}} \times 100\% \dots\dots\dots(1)$$

The percentage of bacterial contamination (%) =

$$\frac{\text{The number of bacteria contaminated}}{\text{The number of planted}} \times 100\% \dots\dots\dots(2)$$

The percentage of browning (%) =

$$\frac{\text{The number of browning}}{\text{The number of planted}} \times 100\% \dots\dots\dots(3)$$

The percentage of steril (%) =

$$\frac{\text{The number of browning}}{\text{The number of planted}} \times 100\% \dots\dots\dots(4)$$

2. Induction of embryogenic calli

The percentage of survive (%) =

$$\frac{\text{The number of survive}}{\text{The number of planted}} \times 100\% \dots\dots\dots(5)$$

The percentage of callus (%) =

$$\frac{\text{The number of callus}}{\text{The number of planted}} \times 100\% \dots\dots\dots(6)$$

3. Callus development

The assessment of callus development (callus structure) is conducted using scoring, as adapted from Karomah (1998):

- 0 The callus has not formed or the explant is dead
- 1 Callus structure like sponge/cotton
- 2 A compact callus structure is formed
- 3 A compact nodular callus structure is formed
- 4 A freeable callus structure is formed (easily separable and grainy like sand)
- 5 A nodular, freeable callus structure is formed

III. RESULTS AND DISCUSSION

A. Sterilization of Explant

The ANOVA test (Table 1) indicated that none of the treatments significantly affected the percentage of explants infected with fungus or exhibiting browning. All treatments showed a minimal incidence of fungal contamination. Explants under the H0 T0 treatment exhibited fungal presence at 3 days after planting (DAP), whereas the H300 T15 treatment had fungal indications after 6 DAP. Initial symptoms included the appearance of white hyphae (fine threads) on the explants.

Likewise, the browning remains minimal across all treatments. The H0 T0 and H300 T15 treatments exhibited a browning percentage of 3.33%, the H300 T20 treatment displayed a browning percentage of 14.07%, the H300 T25 treatment recorded a browning percentage of 3.70%, and the H300 T30 treatment showed a browning percentage of 0.00%.

Explants exhibiting browning (Figure 1C) are distinguished by the emergence of a brown color on the explants, which subsequently causes the medium to likewise turn brown over time. Prolonged sterilization with HgCl_2 will adversely impact the explants due to cellular damage (Farooq et al., 2001)

Table 1 indicates that all the treatments exerted a highly significant influence on both the parameter of explants infected with bacteria and the percentage of sterile. Bacterial contamination is characterized by the presence of white or yellow mucus (Figure 1 B). The prolonged soaking period in HgCl_2 resulted in a larger percentage of bacterially infected explants and a reduced number of sterile explants.

The DMRT findings in Table 2 for the H300 T15 treatment indicated optimal outcomes, with bacterial explants at 3.33% and sterile explants at 90.00%. The treatment exhibited no significant difference compared to the control without HgCl_2 , although it was considerably different from the treatments H300 T20, H300 T25, and H300 T30. The H300 T15 treatment

achieved the highest sterilization rate and the lowest contamination rate. This result indicates that immersion in HgCl_2 for 15 minutes decreases the bacterial percentage and enhances the sterile percentage relative to the absence of HgCl_2 immersion. In contrast to the treatment of H300 T20, H300 T25, and H300 T30, there is a propensity for prolonged soaking to elevate the proportion of contaminated bacteria. The soaking of explants facilitates the ingress of pollutants into them. During soaking, explants may sustain injuries from cutting, which can serve as entry points for pollutants.

Some study uses HgCl_2 as a sterilant agent because it is associated with several mechanisms in killing bacteria and fungi. According to dos Santos (2018), Hg^{2+} ions can disrupt glutamate transport, resulting in excessive production of ROS (O^{2-} and H_2O^{2-}). Heavy metals such as Hg^{2+} ions can inhibit DNA polymerase and RNA polymerase enzymes, resulting in disruption of DNA replication and gene transcription (Ren et al., 2024). Due to the effects mentioned above, HgCl_2 can be used as a surface sterilization

Table 1. Summarizes the findings of the ANOVA from the sterilization experiment

Parameters	HgCl_2
Percentage of explants contaminated with fungi	0.2500 ^{ns}
Percentage of explants contaminated with bacteria	0.0001 ^{**}
Percentage of explants browning	0.0800 ^{ns}
Percentage of sterile explants	0.0001 ^{**}

Note: ns = not significant, * = significant, ** = very significant

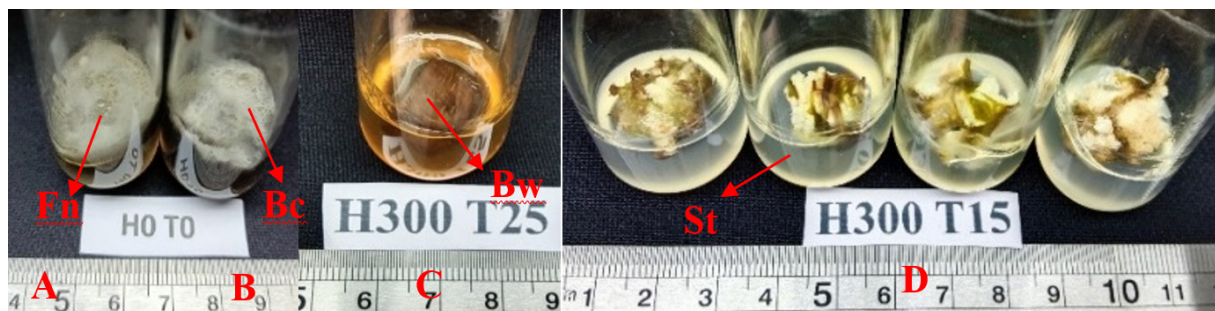


Figure 1. Fungal (A), bacterial (B), browning (C), and sterile (D) explants. Notes: Fn: fungal, Bc: bacterial, Bw: browning, St: sterile

Table 2. DMRT results of the percentage of bacterial contaminated explants and sterile explants

HgCl ₂ immersion time (minutes)	Bacterial contamination (%)	Fungus Contamination (%)	Browning (%)	Sterile (%)
0 minutes (H0 T0)	16.67 ^b	3.57 ^a	4.28 ^a	73.33 ^a
15 minutes (H300 T15)	3.33 ^b	6.07 ^a	2.50 ^a	90.00 ^a
20 minutes (H300 T20)	85.93 ^a	0.00 ^a	14.28 ^a	0.00 ^c
25 minutes (H300 T25)	77.78 ^a	0.00 ^a	3.57 ^a	18.52 ^{bc}
30 minutes (H300 T30)	65.00 ^a	0.00 ^a	0.00 ^a	35.00 ^b

Notes: Numbers in the same column, followed by the same letter, indicate that they are not significantly different at the 1% test level (DMRT).

agent for plant explants. In addition, HgCl₂ can also cause explant death, so controlling the dose and optimal exposure time is important.

Both internal and environmental variables influence the success rate of sterilization. The internal factors that influence sterilization include the type of plant, the part of the plant used, and the size of the explant. A significant of explants infected with bacteria is believed to result from the presence of fine stem hairs (trichomes) on the explant source. Explant components with trichomes, when utilized as a source of explants, may serve as a habitat for bacteria. Consequently, trichomes on the explants must be excised and sterilized (Yuliani et al., 2018). Furthermore, trichomes serve as a physical barrier, impeding the penetration of sterilant into the explant tissue.

The explant portion also influences the success rate of sterilization. Hardarani dan Nisa (2022) assert that node explants have a higher level of contamination compared to leaf explants. The results of a study by Webster et al. (2003) also stated that using leaf explants resulted in lower levels of fungal and bacterial contamination compared to shoot explants. Furthermore, the findings of Hand et al. (2016) also showed that the position of nodes on the explant significantly influenced the occurrence of bacterial and fungal contamination and the ability to grow. In node explants, the sterilant solution fails to penetrate the folds of the book,

allowing pollutants in these areas to persist. Therefore, initial treatment is necessary before sterilization in the laboratory. Nugraheni et al. (2019) used the fungicide Pyraclostrobin 50 g.kg⁻¹ + Metiram 550 g.kg⁻¹ by spraying it on the explants every week for three months, which was proven to be effective in increasing the success of sterilization of sengon shoots. Conversely, in leaf explants, there exists optimal surface contact between the sterilant and the explant. The size of the explant also influences the outcomes achieved. Explants that are excessively tiny lead to the rapid demise of meristem tissue, while those that are overly large possess an increased surface area that may harbor more contaminants.

Another important factor is that there was no preparation before sterilizing the explants, such as growing *T. grandis* f. *abludens* in a greenhouse and continuously using bactericides and fungicides on it. The sterilization process does not involve any previous treatment. This is in accordance with the statement of Yu and Reed (1995) and Hand (2016) that using plants grown in greenhouses aims to reduce contaminants. The degree of worker precision correlates with the efficacy of the sterilization procedures conducted. Employees with elevated precision will enhance the efficacy of sterilization. Additional affecting elements include the utilization of instruments and a sterile atmosphere (Onwubiko et al., 2013).

B. Callus Induction

1. Percentage of survive

The ANOVA findings for the percentage of living cells and callus formation during the callus induction of *T. grandis* f. *abludens* at week twelve are displayed in Table 3. The treatment of D0K0 and D0K1 exhibits a percentage of life that is not substantially different from D0K1.5; however, the treatment of D0K0.5 demonstrates a considerable difference when compared to the other three treatments. The survival rate in the D0K0.5 treatment was 8.33%. This is attributable to bacterial contamination. Bacterial contamination in

the D0K0.5 treatment was identified two weeks post-planting, and by four weeks, the majority of the explants perished. The bacterial contaminants in the D0K0.5 The treatment are presumed to be internal pollutants. Internal pollutants manifest during a timeframe of a few days to one month post-planting. Internal pollutants cannot be eliminated with surface sterilization, as this contamination resides within the plant tissue(Lestari, 2011). The signs of internal contamination resulting from the D0K0.5 treatment included the emergence of yellowish-white mucus exudates on the explant pieces, leading to chemosis as seen in Figure 2.

Table 3. Recapitulation of ANOVA of callus induction of *T. grandis* f. *abludens*

Dependent of Variable: Percentage of survive					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	64475.000 ^a	12	5372,917	38,493	0,000 ^{**}
Auksin (2,4-D)	34234,722	2	17117,361	122,632	0,000 ^{**}
Sitokinin (Kinetin)	4374,306	3	1458,102	10,446	0,000 ^{**}
Auksin * Sitokinin (2,4-D + Kinetin)	8748,611	6	1458,102	10,446	0,000 ^{**}
Error	3350,000	24	139,583		
Total	67825,000	36			
a. R Squared = .951 (Adjusted R Squared = .926)					
Dependent Variable: Percentage of callus					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	19675.000 ^a	12	1639,583	7,949	0,000 ^{**}
Auksin (2,4-D)	6612,500	2	3306,250	16,030	0,000 ^{**}
Sitokinin (Kinetin)	3252,083	3	1084,028	5,256	0,006 ^{ns}
Auksin * Sitokinin (2,4-D + Kinetin)	6504,167	6	1084,028	5,256	0,001 ^{**}
Error	4950,000	24	206,250		
Total	24625,000	36			
a. R Squared = .799 (Adjusted R Squared = .698)					

Notes: ^{ns} = not significant, * = significant, ** = very significant

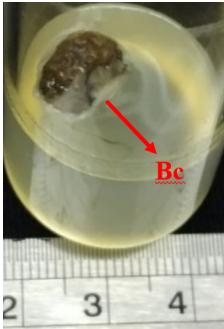


Figure 2. D0K0.5 treatment affected by bacteria at 2 weeks after planting (WAP). Bc : Bacterial

Table 4. DMRT outcomes regarding the impact of the combined treatment of 2,4-D and kinetin on the percentage of survive of *T. grandis* f. *abludens*

Tretaments	2,4-D (ppm)	Kinetin (ppm)	Survive (%) (Sterile)
D0K0	0	0	86.67 a
D0K0.5	0	0.5	8.33 b
D0K1	0	1	86.67 a
D0K1.5	0	1.5	80.00 a
D1.5K0	1.5	0	0.00 b
D1.5K0.5	1.5	0.5	0.00 b
D1.5K1	1.5	1	0.00 b
D1.5K1.5	1.5	1.5	0.00 b
D3K0	3	0	0.00 b
D3K0.5	3	0.5	0.00 b
D3K1	3	1	0.00 b
D3K1.5	3	1.5	0.00 b

Notes: Numbers in the same column, followed by the same letter, indicate that they are not significantly different at the 1% DMRT level

The DMRT in Table 4 shows that using 2,4-D at 0 ppm with kinetin at 0-1.5 ppm significantly increases the number of healthy explants compared to other treatments. The incorporation of 2,4-D concentrations ranging from 1.5 to 3 ppm, in conjunction with kinetin at 0 to 1.5 ppm, appears to diminish the proportion of viable explants. The balance of auxin and cytokinin concentrations greatly influences the ability of explants to maintain and sustain life and grow well. These two hormones regulate metabolism, cell division, and the response to oxidative stress. Auxin plays a crucial role

in maintaining tissue viability by regulating the polar flow of hormones and enhancing the activity of antioxidant enzymes, such as superoxide dismutase (SOD) and catalase (CAT) (Montalvo et al., 2022).. Furthermore, optimal auxin-cytokinin concentrations are also known to modulate epigenetic pathways and ROS metabolism, thereby protecting cells under active metabolic conditions without inducing oxidative stress, and thus contributing to the maintenance of explant vitality in vitro (Zhang et al., 2025).

A combination of 2,4-D at 0 ppm with kinetin between 0 and 1.5 ppm results in a high survival rate, likely because the natural auxin in the explant tissue is strong enough, and adding kinetin helps cells divide. According to the research conducted by Illahi et al. (2022), the incorporation of 2,4-D at a concentration of 6 mg/l results in a 12% increase in the browning of explants, whereas a concentration of 4 mg/l leads to a 4% increase in browning in callus from *Diospyros discolor* leaves. Akkenapally (2024) also found that in *Madhuca longifolia* var. *latifolia* (Roxb.) plants, using more than 2 mg/L of 2,4-D led to less callus growth. The elevated concentration of 2,4-D in the medium induces toxicity in the explants, resulting in mortality.

The treatment of D1.5K0; D1.5K0.5; D1.5K1; D3K0; D3K0.5; and D3K1.5 is believed to cause mortality, as indicated by explants that fail to grow and develop and display browning, due to excessive application of the ZPT 2,4-D. Giving 2,4-D in high amounts creates harmful phenolic chemicals that can reduce the health of explants or cause browning, which might result in their death (Fitriani et al., 2019). Potent exogenous auxin 2,4-D poses a significant risk due to its capacity to trigger the production of ethylene gas (Waryastuti et al., 2017). Liu et al. (2024) found that the browning of callus from the woody plant *Juglans mandshurica* from China may be linked to the interaction between phenylalanine ammonia-lyase (PAL), polyphenols, and polyphenol oxidase (PPO). In this process, PAL helps produce polyphenols, which PPO then oxidizes to create brown quinones, instead of just increasing the number of polyphenols. In this process, PAL helps create polyphenols, which are then changed by PPO into brown quinones, instead of just increasing the number of polyphenols.

2. Percentage of Callus

The DMRT in Table 5 shows that using 2,4-D at 0 ppm with kinetin at 0.5 - 1.5 ppm increases the amount of callus explants. The best callus percentage happens with 2,4-D at 0 ppm and kinetin at 1.5 ppm, reaching 73.33%.

The findings of Arsyad et al. (2022) on *Tectona grandis*, which utilized 2 ppm thidiazuron to achieve 100% callus formation with a favorable structure, stand in contrast. Adding 2,4-D in amounts from 1.5 to 3 ppm along with kinetin at 0.5 to 1.5 ppm seems to reduce the number of survival explants. (Kim et al., 2025) found that using more than 3 mg/L of 2,4-D can reduce the success of callus production in coffee plants by up to 28.57%, while the best results come from using 0.5 mg/L of 2,4-D combined with 1 mg/L of kinetin, which gives a success rate of 86.84%. The best callus percentage happens when 2,4-D is at 0 ppm and kinetin is at 1.5 ppm, resulting in 73.33%. Adding 2,4-D in amounts between 1.5 to 3 ppm, along with kinetin at 0.5 to 1.5 ppm, seems to reduce the number of healthy explants. Explants of *T. grandis* f. *abludens* showed a reaction two weeks after being planted, which was marked by swelling around the edges of the damaged explants (Figure 3). This happens because the growth of the cells is influenced by hormones from within the plant and by kinetin added to the growth medium. Endogenous and exogenous auxin influence cell wall plasticity, leading to cell expansion and elongation. Auxin works by turning on specific proteins in the plant's outer layer, which help move H⁺ ions into the cell wall, causing the cells to grow and stretch (Taiz and Zeiger 2012). H⁺ ions trigger specific enzymes, which disrupt certain hydrogen bonds within the cellulose chain that forms the cell wall. As a result, water permeates the plant's cells via osmosis, leading to their elongation.

The D0K0 treatment (control) shows an average callus percentage of 0.00%, probably because there aren't enough natural hormones in the explant needed to encourage callus growth. Adding exogenous kinetin to the media can help activate the natural hormones in the cells, which encourages the growth of the explant tissue. The D0K0.5, D0K1, and D0K1.5 treatments can produce callus in kluwih teak without needing 2,4-D. The callus growth in these treatments has enough auxin for callus formation and only needs kinetin to

Table 5. Results of DMRT on the effect of the combination treatment of 2,4-D and kinetin on the percentage of callus in *T. grandis* f. *abludens*

Treatments	2,4-D (ppm)	Kinetin (ppm)	Callus (%)
D0K0	0	0	0.00 b
D0K0.5	0	0.5	8.33 b
D0K1	0	1	33.33 b
D0K1.5	0	1.5	73.33 a
D1.5K0	1.5	0	0.00 b
D1.5K0.5	15	0.5	0.00 b
D1.5K1	1.5	1	0.00 b
D1.5K1.5	1.5	1.5	0.00 b
D3K0	3	0	0.00 b
D3K0.5	3	0.5	0.00 b
D3K1	3	1	0.00 b
D3K1.5	3	1.5	0.00 b

Notes: Numbers in the same column, followed by the same letter, indicate that they are not significantly different at the 1% DMRT level

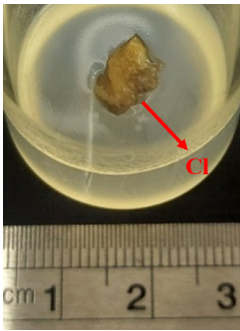


Figure 3. The first signs of the callus appearing. Cl : Callus

develop. The D0K1.5 treatment exhibited a substantial difference from all other treatments, achieving the greatest callus percentage of 73.33% on day 12 post-subculture. The notable rise in the proportion of explants producing callus in the D0K1.5 treatment is attributed to the compatibility of endogenous hormone concentrations with exogenous kinetin in promoting cell division in the leaf tissue of kluwih teak plants.

The aforementioned is distinct from the treatment. D1.5K0; D1.5K0.5; D1.5K1; D1.5K1.5; D3K0; D3K0.5; D3K1; D3K1.5. The inclusion of 2,4-D often does not induce explant callus development (0.00%) but results in the demise of all explants, evidenced by a color shift from green to brown. The brown

color is believed to result from an excessive concentration of 2,4-D. This aligns with the findings of(Wijaya et al., 2024), which indicate that providing 2,4-D at excessive concentrations suppresses callus development and induces toxicity in the explants, thereby diminishing their capacity to generate callus.

Physiologically, callus formation in plant explants is the result of the interaction between auxin and cytokinin in cells that regulate dedifferentiation and cell reprogramming so that they can live (totipotent). Auxin plays a role in inducing cell division through the activation of the AUX/IAA–ARF signal transduction pathway, which triggers the expression of division-related genes such as CYCD3 and WOX11, thereby restoring the

parenchymal cells to a young state (Montalvo et al., 2022). Cytokinin functions to regulate cell differentiation and morphogenesis by activating the CRE1/AHK–ARR-B type pathway, which increases the synthesis of nuclear division regulatory proteins and prevents the formation of lignin in the tissue (Liu et al., 2025). When the ratio of auxin and cytokinin is in a balanced state, a hormonal signal crosstalk occurs that stabilizes the expression of the LBD16 and BBM genes, thereby accelerating dedifferentiation and the formation of embryonic callus that is competent for organogenesis (Andrade et al., 2025)). Current research indicates that to maintain the stable pluripotent status of callus, a combination of auxin and cytokinin is administered to modulate ROS metabolism and epigenetic pathways, such as DNA methylation in regenerative gene promoters (Zhang et al., 2025). Therefore, it can be concluded that auxin and cytokinin, working together and synergistically, determine the direction of callus formation and play a crucial role in preparing cells for subsequent regeneration.

3. Callus development

The observed callus's development encompasses its structure, coloration, and cellular characteristics. The Kruskal-Wallis analysis (Table 6) indicates that all treatments exert a highly significant influence on the parameters of callus formation. The asymptotic significance value of 0.005, which is below 0.01, indicates this.

The results from the Dunn post hoc test (Table 7) show that treatment D0K1.5 is significantly different from treatment D0K0 (Control) and from treatments with 2,4-D at concentrations between 1.5 ppm and 3 ppm along with kinetin at 0 to 1.5 ppm. However, treatment D0K1.5 does not show a significant difference when compared to treatments D0K0.5 and D0K1. Still, treatment D0K1.5 has a better average callus score than treatments D0K0.5 and D0K1. However, treatment D0K1.5 does not demonstrate a significant difference when compared to treatments D0K0.5 and D0K1. Nonetheless, treatment D0K1.5 has a superior average callus score relative to treatments D0K0.5 and D0K1.

Table 6. Results of the Kruskal-Wallis test on the development of callus *T. grandis* f. *abludens*

Statistical test			
Kruskal-Wallis H			26.494
df			11
Asymp.Sig			0.005
Monte Carlo Sig	Sig		0.001 ^c
	99% Confidence Interval		
	Lower Bound		0.000
	Upper Bound		0.002

Table 6. Results of Dunn's test on the development of calus *T. grandis* f. *abludens*

No.	Treatment	P-value	Result
1	D0K0-D1.5K0 (2,4-D 0 Kinetin 0 – 2,4-D 1.5 Kinetin 0)	1.00	Not significant
2	D0K0-D1.5K0.5 (2,4-D 0 Kinetin 0 – 2,4-D 1.5 Kinetin 0.5)	1.00	Not significant
3	D0K0-D1.5K1 (2,4-D 0 Kinetin 0 – 2,4-D 1.5 Kinetin 1)	1.00	Not significant
4	D0K0-D1.5K1.5 (2,4-D 0 Kinetin 0 – 2,4-D 1.5 Kinetin 1.5)	1.00	Not significant
5	D0K0-D3K0 (2,4-D 0 Kinetin 0 – 2,4-D 3 Kinetin 0)	1.00	Not significant
6	D0K0-D3K0.5 (2,4-D 0 Kinetin 0 – 2,4-D 3 Kinetin 0.5)	1.00	Not significant

No.	Treatment	P-value	Result
7	D0K0-D3K1 (2,4-D 0 Kinetin 0 – 2,4-D 3 Kinetin 1)	1.00	Not significant
8	D0K0-D3K1.5 (2,4-D 0 Kinetin 0 – 2,4-D 3 Kinetin 1.5)	1.00	Not significant
9	D0K0-D0K0.5 (2,4-D 0 Kinetin 0 – 2,4-D 0 Kinetin 0.5)	0.325	Not significant
10	D0K0-D0K1 (2,4-D 0 Kinetin 0 – 2,4-D 1 Kinetin 1)	0.037	Not significant
11	D0K0-D0K1.5 (2,4-D 0 Kinetin 0 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
12	D3K0.5-D3K1 (2,4-D 3 Kinetin 0.5 – 2,4-D 3 Kinetin 1)	1.000	Not significant
13	D3K0.5-D3K1.5 (2,4-D 3 Kinetin 0.5 – 2,4-D 3 Kinetin 1.5)	1.000	Not significant
14	D1.5K0-D0K0.5 (2,4-D 1.5 Kinetin 0 – 2,4-D 0 Kinetin 0.5)	0.325	Not significant
15	D1.5K0.5-D0K0.5 (2,4-D 1.5 Kinetin 0.5 – 2,4-D 0 Kinetin 0)	0.325	Not significant
16	D1.5K1-D0K0.5 (2,4-D 1.5 Kinetin 1 – 2,4-D 0 Kinetin 0.5)	0.325	Not significant
17	D1.5K1.5-D0K0.5 (2,4-D 1.5 Kinetin 1.5 – 2,4-D 0 Kinetin 0.5)	0.325	Not significant
18	D3K0-D0K0.5 (2,4-D 3 Kinetin 0 – 2,4-D 0 Kinetin 0.5)	0.325	Not significant
19	D3K0.5-D0K0.5 (2,4-D 3 Kinetin 0.5 – 2,4-D 0 Kinetin 0.5)	0.325	Not significant
20	D3K1-D0K0.5 (2,4-D 3 Kinetin 1 – 2,4-D 0 Kinetin 0.5)	0.325	Not significant
21	D3K1.5-D0K0.5 (2,4-D 3 Kinetin 1.5 – 2,4-D 0 Kinetin 0.5)	0.325	Not significant
22	D3K1-D3K1.5 (2,4-D 3 Kinetin 1 – 2,4-D 3 Kinetin 1.5)	1.000	Not significant
23	D1.5K0-D0K1 (2,4-D 1.5 Kinetin 0 – 2,4-D 0 Kinetin 1)	0.037	Not significant
24	D1.5K0.5-D0K1 (2,4-D 1.5 Kinetin 0.5 – 2,4-D 0 Kinetin 1)	0.037	Not significant
25	D1.5K1-D0K1 (2,4-D 1.5 Kinetin 0.5 – 2,4-D 0 Kinetin 1)	0.037	Not significant
26	D1.5K1.5-D0K1 (2,4-D 1.5 Kinetin 1.5 – 2,4-D 0 Kinetin 1)	0.037	Not significant
27	D3K0-D0K1 (2,4-D 3 Kinetin 0 – 2,4-D 0 Kinetin 1)	0.037	Not significant
28	D3K0.5-D0K1 (2,4-D 3 Kinetin 0.5 – 2,4-D 0 Kinetin 1)	0.037	Not significant
29	D3K1-D0K1 (2,4-D 3 Kinetin 1 – 2,4-D 0 Kinetin 1)	0.037	Not significant
30	D3K1.5-D0K1 (2,4-D 3 Kinetin 1.5 – 2,4-D 0 Kinetin 1)	0.037	Not significant
31	D1.5K0-D0K1.5 (2,4-D 1.5 Kinetin 0 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
32	D1.5K0.5-D0K1.5 (2,4-D 1.5 Kinetin 0.5 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
33	D1.5K1-D0K1.5 (2,4-D 1.5 Kinetin 1 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
34	D1.5K1.5-D0K1.5 (2,4-D 1.5 Kinetin 1.5 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
35	D3K0-D0K1.5 (2,4-D 3 Kinetin 0 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
36	D3K0.5-D0K1.5 (2,4-D 3 Kinetin 0.5 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
37	D3K1-D0K1.5 (2,4-D 3 Kinetin 1 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
38	D3K1.5-D0K1.5 (2,4-D 3 Kinetin 1.5 – 2,4-D 0 Kinetin 1.5)	0.001	Significant
39	D1.5K0-D1.5K0.5 (2,4-D 1.5 Kinetin 0 – 2,4-D 1.5 Kinetin 0.5)	1.00	Not significant
40	D1.5K0-D1.5K1 (2,4-D 1.5 Kinetin 0 – 2,4-D 1.5 Kinetin 1)	1.00	Not significant
41	D1.5K0-D1.5K1.5 (2,4-D 1.5 Kinetin 0 – 2,4-D 1.5 Kinetin 1.5)	1.00	Not significant
42	D1.5K0-D3K0 (2,4-D 1.5 Kinetin 0 – 2,4-D 3 Kinetin 0)	1.00	Not significant
43	D1.5K0-D3K0.5 (2,4-D 1.5 Kinetin 0 – 2,4-D 3 Kinetin 0.5)	1.00	Not significant
44	D1.5K0-D3K1 (2,4-D 1.5 Kinetin 0 – 2,4-D 3 Kinetin 1)	1.00	Not significant

No.	Treatment	P-value	Result
59	D1.5K1.5-D3K1 (2,4-D 1.5 Kinetin 1.5 – 2,4-D 3 Kinetin 1)	1.00	Not significant
60	D1.5K1.5-D3K1.5 (2,4-D 1.5 Kinetin 1.5 – 2,4-D 3 Kinetin 1.5)	1.00	Not significant
61	D3K0-D3K0.5 (2,4-D 3 Kinetin 0 – 2,4-D 3 Kinetin 0.5)	1.00	Not significant
62	D3K0-D3K1 (2,4-D 3 Kinetin 0 – 2,4-D 3 Kinetin 1)	1.00	Not significant
63	D3K0-D3K1.5 (2,4-D 3 Kinetin 0 – 2,4-D 3 Kinetin 1.5)	1.00	Not significant
64	D0K0.5-D0K1 (2,4-D 0 Kinetin 0.5 – 2,4-D 0 Kinetin 1)	0.269	Not significant
65	D0K0.5-D0K1.5 (2,4-D 0 Kinetin 0.5 – 2,4-D 0 Kinetin 1.5)	0.017	Not significant
66	D0K1-D0K1.5 (2,4-D 0 Kinetin 1 – 2,4-D 0 Kinetin 1.5)	0.199	Not significant

Table 8. Average callus developmen

Treatments 2,4-D (ppm)	Kinetin (ppm)				Average
	K0 = 0	K0.5 = 0.5	K1 = 1	K1.5 = 1.5	
D0 = 0	0.00	0.17	0.67	1.53	0.59
D1.5 = 1.5	0.00	0.00	0.00	0.00	0.00
D3 = 3	0.00	0.00	0.00	0.00	0.00
Average	0.00	0.06	0.23	0.51	

The mean values presented in Table 8 reflect the progression of callus (callus quality), demonstrating a range of values from 0 to 1, indicating that the callus development is predominantly necrotic and occurs in the sponge or cork phase. In the D0K0 treatment, callus development receives an average score of 0, indicating the absence of callus formation. In the D0K0 treatment, the majority of explants exhibited no growth or development, resulting in a standstill. This may result from the extremely low levels of endogenous hormones in the D0K0 treatment, which impede the growth activity necessary for callus formation.

In treatment D0K0.5, the callus formation has an average score of 0.17. The average, which is near zero, results from the significant mortality of explants in treatment (D0K0.5) caused by bacterial contamination. The bacterial contamination in treatment D0K0.5 is believed to have originated from the explant tissue itself. Treatment D0K1 exhibits callus formation with an average score of 0.67. The diminished

average in treatment D0K1 is attributable to the insufficient application of kinetin, a plant growth regulator, leading to inadequate callus formation.

In treatment D0K1.5, the callus development exhibits an average score of 1.53, with the callus morphology illustrated in Figure 4B. The callus seen in Figure 4B has a dense structure. Compact callus is characterized by the presence of nodular protrusions and cannot be separated into single cells because the small-sized cells are very close together and have a dense and rigid texture (Julianti et al., 2021). This type of callus is a type 2 primary callus consisting mainly of elongated parenchymal cells (101-165 µm), with large intercellular spaces, developing vacuoles, and cell walls about 1.9 mm thick between two adjacent cells and showing intense and irregular growth (Bartos et al., 2018). These callus characteristics are an early indicator of the potential for further growth in somatic embryogenesis. Callus texture can vary from compact to crumbly, depending on the type of

plant, the composition of the nutrient media, growth regulators, and the environmental conditions of the culture (Pierik, 1997). Crumbly callus is usually more widely used for tissue propagation (Sitorus et al., 2011). The majority of the callus in treatment D0K1.5 exhibits a compact structure (score 2) at 12 WAP; however, one explant displays a nodular compact callus morphology (Figure 5) at the same time point, potentially influenced by various factors, including the genotype of the explant and its individual responsiveness. Furthermore, Isah (2016) stated that embryogenic tissue induction depends on many factors, including the selection of appropriate explants (juvenile or mature), culture media, added plant growth regulators, other growth substances, and the physical environment.

The color of the callus serves as an indication of the cellular status, reflecting whether the cells are actively dividing or have

ceased proliferation (Afiah et al., 2022). The D0K0.5 treatment yielded a whitish-green callus. The presence of green callus signifies ongoing cellular division, suggesting that if it progresses to the regeneration stage, it can advance to further phases.

The D0K1 treatment, the majority of the calli exhibited a brown coloration at 12 WAP. The brown color was attributed to the media's stress, which suggested that the calli would have a deeper hue compared to fresh calli. The D0K1.5 treatment, the majority of the calli exhibited a yellow color at 12 WAP. The yellow hue signifies that the calli possess proficient division capability. Yellow calli indicate that there are flavonoid pigments in the cells of the callus (Qahtan et al., 2022). A little portion of the calli in the D0K1.5 treatment exhibited a white coloration. White calli signify that the embryonic tissue is devoid of chloroplasts, yet possesses a substantial starch content.

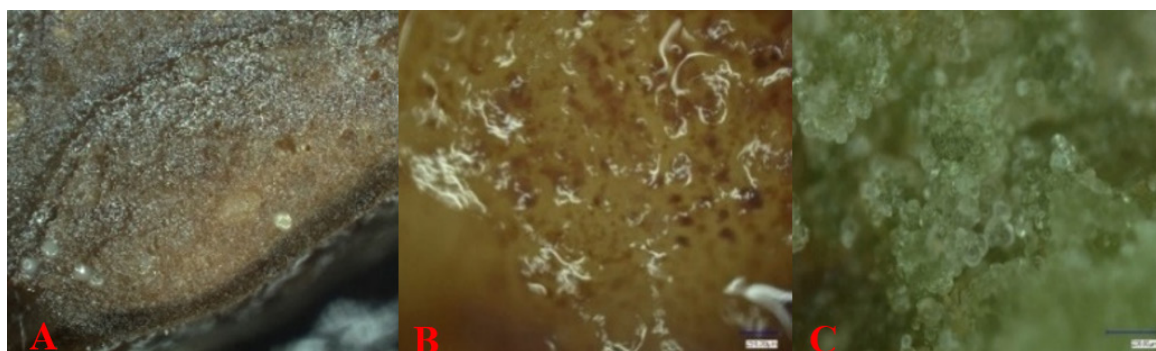


Figure 4. Callus shapes under the microscope; Score 0 (A), Score 2 (B), Score 3 (C)

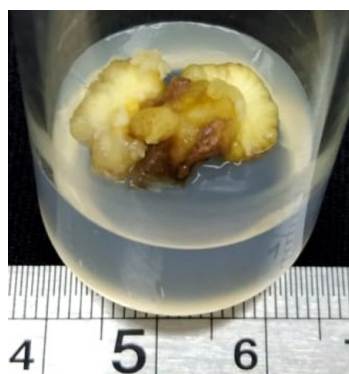


Figure 5. Score 3 (Compact nodular callus)

Stasolla et al. (2002) said that in some conifers, embryogenic tissue is made up of a group of small, clear cells full of cytoplasm that have underdeveloped filamentous embryos with well-formed suspensors and distinct embryos, while non-embryogenic tissue has brown or green parenchymal cells that lack any special structure. The earlier findings indicate that the callus is mainly in the growth stage, but a small amount of round callus with the ability to develop into embryos was also observed. Subsequent callus formation remains under ongoing observation. Further work on technological factors, including subculture in new mediums and the optimization of growth regulator use, is necessary.

Callus form substantially influenced somatic embryo development and callus proliferation, according to (Chang et al., 2025). A detailed study on the species *Quercus alina* showed that the combination of callus shape, genetic type, and growth medium together explained 60.9% of the differences observed. Specifically, the shape of the callus was the biggest factor, explaining 50.2% ($p < 0.001$) of the differences, indicating it had the strongest effect on how fast the callus grew. The genetic type also played a significant role, explaining 10.1% ($p < 0.001$), suggesting that differences in genetics within the species can greatly affect the growth process. Specifically, callus morphology was the primary component, accounting for 50.2% ($p < 0.001$) of the variation, hence demonstrating the most significant influence on the proliferation rate. Genotype had a significant effect on the differences observed, making up 10.1% ($p < 0.001$), which indicates that the genetic differences within the species can greatly affect how well it grows. In contrast to the other two variables, the impact of medium formulation was minimal, accounting for -0.1% ($p = 0.395$) of the variation (Chang et al., 2025).

IV. CONCLUSION

The H300 T15 treatment (300 ppm HgCl_2 for 15 minutes) is the best method for sterilizing young kluwih teak stems, producing

the highest number of sterile explants at 90% by 15 days after planting. The optimal concentration for callus induction was achieved with a combination of 0 ppm, 2,4-D, and 1.5 ppm, resulting in the greatest callus percentage of 73.33% and a callus development score of 1.53. Utilizing HgCl_2 at a concentration of 300 ppm for a duration of 15 minutes is preferable for the sterilization of immature kluwih teak stems. Preliminary treatment is required prior to the sterilization of explants, including their placement in a greenhouse and the application of bactericides and fungicides. Optimization of 2,4-D at a concentration of <1.5 ppm and kinetin > 1.5 ppm is essential for the induction of jati kluwih callus. More research is needed on the fungi and bacteria that affect kluwih teak to improve how well sterilizing materials work. The results of this research represent an initial step that has the potential to significantly contribute to future conservation and vegetative propagation strategies for kluwih teak. Scientifically, this technology helps develop efficient in vitro culture methods and is a basis for studies on the physiology and molecular basis for somatic embryo formation. These findings are also helpful for plant breeding programs using biotechnological approaches, such as genetic transformation or somaclonal selection, to produce superior genotypes. They can be implemented in mass seed propagation, thus supporting efforts to develop national genetic resources.

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REFERENCES

- Afiyah, N.N., Surya, M.I., Ismaini, L., Azizah, E., Saputro, N.W. 2022. Inisiasi kalus secara *in vitro* dari daun *Talinum paniculatum* (Jacq.) Gaertn. *Buletin Kebun Raya*. 23(5): 121-130. <https://doi.org/10.55981/bkr.2022.201>.

- Akkenalapally, S., Mudalkar, S., Bodiga, S., Sundaram, R., & Bokam, A. kumar. (2024). In vitro callus generation and somatic embryogenesis from leaf explant of *Madhuca longifolia* var *latifolia* (Roxb.) A. Chev. *Vegetos*, 0123456789. <https://doi.org/10.1007/s42535-024-01044-6>
- Andrade, C. M. L., Bismara, B. A. P. P., Santos, F. P., Yonamine, M., de Souza Crippa, J. A., Hallak, J. E. C., Alves, F. H. F., Pasqual, M., & Stein, V. C. (2025). Establishment of *Psychotria viridis* Ruiz & Pav. callus cultures, plantlet regeneration and in vitro production of the hallucinogenic indole alkaloid N,N-dimethyltryptamine. *Plant Cell, Tissue and Organ Culture*, 161(3). <https://doi.org/10.1007/s11240-025-03061-y>
- Arsyad, M. A., Immalasari, N. R., & Larekeng, S. H. (2020). Aplikasi variasi konsentrasi media MS dan Thidiazuron pada induksi kalus pucuk jati (*Tectona grandis*) secara *in vitro*. *Jurnal Galung Tropika*, 9(2), 163–173. <https://doi.org/10.31850/jgt.v9i2.627>
- Bartos, P. M. C., Gomes, H. T., Gomes, S. M., Vasconcelos Filho, S. C., Teixeira, J. B., & Scherwinski-Pereira, J. E. (2018). Histology of somatic embryogenesis in *Coffea arabica* L. *Biologia*, 73(12), 1255–1265. <https://doi.org/10.2478/s11756-018-0131-5>
- Bastian, F., & Rahadiyanti, M. (2023). Kajian pengaruh penggunaan kayu jati sebagai material pembuatan furnitur di era modern. *Kreasi*, 6(1), 1–4. <https://doi.org/10.37715/kreasi.v6i1.3727>
- Bisht, A., Singh, L., Singh, B., Bisht, M., Pandey, A., Bhatt, I. D., & Pande, V. (2024). In vitro propagation of endemic species *Mabonia jaunsarensis* Ahrendt through callus culture. *Applied Biochemistry and Biotechnology*, 196(1), 113–128. <https://doi.org/10.1007/s12010-023-04524-8>
- Chang, M., Yang, N., Yang, X., Zhang, Q., Zhou, H., Ge, Y., & Li, G. (2025). Optimizing proliferation and synchronization for somatic embryogenesis in *Quercus aliena*. *Plant Cell, Tissue and Organ Culture*, 161(1). <https://doi.org/10.1007/s11240-025-03030-5>
- dos Santos, A. A., Ferrer, B., Gonçalves, F. M., Tsatsakis, A. M., Renieri, E. A., Skalny, A. V., Farina, M., Rocha, J. B. T., & Aschner, M. (2018). Oxidative stress in methylmercury-induced cell toxicity. *Toxics*, 6(3), 1–15. <https://doi.org/10.3390/toxics6030047>
- Faizy, E., Moradi, A., & Masoumi Asl, A. (2019). Controlling secondary somatic embryogenesis in Persian Oak (*Quercus brantii* L.) using hormonal compounds and media. *Journal of Agricultural Science and Technology*, 21(3), 615–626.
- Farooq, S. A., Farooq, T. T., & Rao, T. V. (2001). Micropropagation of *Annona squamosa* L. using nodal explants. *Pakistan Journal of Biological Sciences*, 5(1), 43–46. <https://doi.org/10.3923/pjbs.2002.43.46>
- Fauzan, Y. S. A., Supriyanto, & Tajuddin, T. (2017). Efektivitas merkuri klorida (HgCl₂) pada sterilisasi tunas samping jati (*Tectona grandis*) *in vitro*. *Jurnal Bioteknologi & Biosains Indonesia (JBBi)*, 4(2), 25. <https://doi.org/10.29122/jbbi.v4i2.2540>
- Fauzi, M. A., Hasna, T. M., Setiadi, D., & Adinugraha, H. A. (2021). Variasi morfologi empat spesies jati (*Tectona* sp.) di Asia Tenggara: Potensi pemuliaan pohon dan bioteknologinya. *Biota : Jurnal Ilmiah Ilmu-Ilmu Hayati*, 5(2), 115–123. <https://doi.org/10.24002/biota.v5i2.2946>
- Fitriani, Y., Wijana, G., & Darmawati, I. A. P. (2019). Teknik sterilisasi dan efektivitas 2,4-D terhadap pembentukan kalus esplans daun nilam (*Pogostemon cablin* Benth) *in vitro*. *Journal Agric. Sci. and Biotechnol*, 8(1), 41–52. <https://ojs.unud.ac.id/index.php/JASB>
- Gunadi. (2021). Prospek dan strategi bersaing pada industri furniture berbahan baku kayu jati. *Jurnal Ilmiah M-Progress*, 11(1), 48–62. <https://doi.org/10.35968/m-pu.v11i1.601>
- Hand, C. R., Wada, N., Stockwell, V., & Reed, B. M. (2016). Node position influences viability and contamination in hazelnut shoot explants. *In Vitro Cellular and Developmental Biology - Plant*, 52(6), 580–589. <https://doi.org/10.1007/s11627-016-9791-4>
- Hartmann, H. T., Kester, D. E., Davies, F. T., & Geneve, R. L. (2014). *Hartmann & Kester's plant propagation : principles and practices*.
- Herzog, T., Natterer, J., Schweitzer, R., Volz, M., Winter, W. (2012). *Timber construction* (4th Editio). Birkhauser Verlag AG.
- Illahi, A. K., Ratnasari, E., & Dewi, S. K. (2022). Pengaruh 2, 4-D terhadap pertumbuhan kalus daun *Diospyros discolor* Willd pada media MS secara *in vitro*. *Lentera Bio: Berkala Ilmiah Biologi*, 11(3), 369–377.
- Isah, T. (2016). Induction of somatic embryogenesis in woody plants. *Acta Physiologiae Plantarum*,

- 38(5). <https://doi.org/10.1007/s11738-016-2134-6>
- Julianti, R., Nurchayati, Y., Setiari, N., & Studi Biologi, P. (2021). Pengaruh konsentrasi sukrosa dalam medium MS terhadap kandungan flavonoid kalus tomat (*Solanum lycopersicum* syn. *Lycopersicon esculentum*). *Journal of Biological Sciences*, 8(1), 141–149. <https://doi.org/10.24843/metamorfosa.2020.v08.i01.p015>
- Kim, H. J., Yun, C. M., Lee, S., Gu, H. S., Kim, Y. H., Kim, J. H., Kim, K. K., Kim, S. B., Lee, K. M., Hong, C. O., Son, H. J., Park, H. C., & Kim, Y. J. (2025). Establishment of *in vitro* cell culture and caffeine production from coffee (*Coffea arabica* L.). *Journal of Applied Biological Chemistry*, 68(1), 24–30. <https://doi.org/10.3839/jabc.2025.004>
- Lestari, E. G. (2011). Peranan Zat Pengatur Tumbuh dalam Perbanyakan Tanaman melalui Kultur Jaringan. *Jurnal AgroBiogen*, 7(1), 63. <https://doi.org/10.21082/jbio.v7n1.2011.p63-68>
- Liu, C., Li, A., Fan, X., Qin, B., & Zhang, L. (2024). Explant browning during callus induction of *Juglans mandshurica* might be caused by the cooperation of PAL, polyphenol and PPO. *South African Journal of Botany*, 174, 937–945. <https://doi.org/10.1016/j.sajb.2024.09.072>
- Liu, Cheng, L., Tang, L., Yang, L., Jiang, Z., Song, X., Kang, Q., Yao, D., Chen, S., Ru, J., Zhang, L., Wu, G., & Yuan, H. (2025). Transcriptome and endogenous hormone analysis reveals the molecular mechanism of callus hyperhydricity in flax (*Linum usitatissimum* L.). *International Journal of Molecular Sciences*, 26(11), 1–13. <https://doi.org/10.3390/ijms26115360>
- Montalvo, J. R., Quintana-Escobar, A. O., Méndez-Hernández, H. A., Aguilar-Hernández, V., Brito-Argáez, L., Galaz-Ávalos, R. M., Uc-Chuc, M. A., & Loyola-Vargas, V. M. (2022). Auxin-cytokinin cross talk in somatic embryogenesis of *Coffea canephora*. *Plants*, 11(15). <https://doi.org/10.3390/plants11152013>
- Nugraheni, Y. M. M. A., Uli, R., Sianturi, D., & Bramasto, Y. (2019). Pre sterilization effect towards the successful of the initiation of sengon explant shoots. *Jurnal Perbenihan Tanaman Hutan*, 7(1), 5–54. <https://doi.org/10.20886/bptpth.2019.7.1.45-54>
- Onwubiko, N. C., Onwubiko, N. C., Nkogho, C. S., Anyanwu, C. P., & Onyeishi, G. C. (2013). Effect of different concentration of sterilant and exposure time on sweet potato (*Ipomoea batatas* Lam) explants. *International Journal of Current Microbiology and Applied Sciences*, 2(8), 14–20. <http://www.ijcmas.com>
- Pierik, R. L. M. (1997). *In Vitro Culture of Higher Plants*. Springer Netherlands. <https://books.google.co.id/books?id=eUWe9894KzwC>
- Qahtan, A. A., Faisal, M., Alatar, A. A., & Abdel-Salam, E. M. (2022). Callus-mediated high-frequency plant regeneration, phytochemical profiling, antioxidant activity and genetic stability in *Ruta chalepensis* L. *Plants*, 11(12). <https://doi.org/10.3390/plants11121614>
- Ren, Q., Guo, X., Yang, D., Zhao, C., Zhang, X., & Xia, X. (2024). A wide survey of heavy metals-induced *in-vitro* DNA replication stress characterized by rate-limited replication. *Current Research in Toxicology*, 6(January), 100152. <https://doi.org/10.1016/j.crttox.2024.100152>
- Sitorus, E. N., Hastuti, E. D., & Setiari, N. (2011). Induksi kalus binahong (*Basella rubra* L.) secara *in vitro* pada media Murashige & Skoog dengan konsentrasi sukrosa yang berbeda. *Bioma*, 13(1), 1–7.
- Stasolla, C., Kong, L., Yeung, E. C., & Thorpe, T. A. (2002). Maturation of somatic embryos in conifers: Morphogenesis, physiology, biochemistry, and molecular biology. *In Vitro Cellular and Developmental Biology - Plant*, 38(2), 93–105. <https://doi.org/10.1079/IVP2001262>
- Thorpe, T. A. (2007). History of plant tissue culture. *Molecular Biotechnology*, 37(2), 169–180. <https://doi.org/10.1007/s12033-007-0031-3>
- Tripathi, M. K., Tripathi, N., Tiwari, S., Tiwari, G., Mishra, N., Bele, D., Patel, R. P., Sapre, S., & Tiwari, S. (2021). Optimization of different factors for initiation of somatic embryogenesis in suspension cultures in sandalwood (*Santalum album* L.). *Horticulturae*, 7(5), 1–15. <https://doi.org/10.3390/horticulturae7050118>
- Tripathi, S., Shukla, S. R., Shashikala, S., & Sardar, A. (2016). Role of teak and other hardwoods in shipbuilding as evidenced from literature and shipwrecks. *Current Science*, 111(7), 1262–1268.
- Waryastuti, D. E., Setyobudi, L., & Wardiyati, T. (2017). Effects of 2,4-d and bap concentration levels on ms media for embryogenic callus induction of Java turmeric (*Curcuma xanthorrhiza* roxb.). *Jurnal Produksi Tanaman*, 5(1), 140–149.

- Wijaya, N. R., Suharto, D., & Sudrajad, H. (2024). Pengaruh BAP dan 2,4 D terhadap inisiasi dan pertumbuhan kalus pulesari (*Alyxia reinwardtii* Blume). *Jurnal Pertanian Agros*, 26(1), 38. <https://doi.org/10.37159/jpa.v26i1.4159>
- Yuliani, Y., Dewi, S. K., & Rachmadiarti, F. (2018). The morphological, anatomical, and physiological characteristics of *Elephantopus scaber* as explant source for tissue culture. *Atlantis Press*, 1(Icst), 61–66. <https://doi.org/10.2991/icst-18.2018.13>
- Zhang, Y., Zhang, T., Zheng, Y., Wang, J., Luo, C., Li, Y., & Liu, X. (2025). Physiological and transcriptomic analyses reveal regulatory mechanisms of adventitious root formation in in vitro culture of *Cinnamomum camphora*. *International Journal of Molecular Sciences*, 26(15), 1–22. <https://doi.org/10.3390/ijms26157264>

THE PHYSICAL PROPERTIES AND COLOR CHANGES OF TREATED FAST-GROWING WOODS WITH BORON COMPOUNDS, CHITOSAN, AND HEATING

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THE PHYSICAL PROPERTIES AND COLOR CHANGES OF TREATED FAST-GROWING WOODS WITH BORON COMPOUNDS, CHITOSAN, AND HEATING. Boric acid preservative is known to be easily leached when exposed to rain during exterior use. So, it needs to be combined with other treatments to improve its performance. This research aimed to evaluate the effects of boric acid preservative, chitosan, and heat treatments on physical properties, preservative leaching, and weathering resistance of two fast-growing woods. Manii (*Maesopsis eminii* Engl.) and mindi (*Melia azedarach* Linn.) woods were impregnated with 5% boric acid preservative at a pressure of 7 kg cm⁻² for 4 hours. The next step involved a second-stage impregnation with chitosan (at a 2% concentration) and a mixed combination of boric acid-chitosan, under the same pressure and duration. The final step was heat treatment at 70 °C and 140 °C under atmospheric conditions for 4 hours. The retention of boric acid in manii and mindi woods was 18,1 ± 0,8 kg m⁻³ and 12,7 ± 0,9 kg m⁻³, respectively. The interaction of boric acid, chitosan, and heat treatments significantly affected the density, water absorption, leaching, wood dimensional stability, shrinkage, and wood resistance to weathering. Impregnation with a boric acid-chitosan mixture and heating at 140 °C (M140) successfully increased the density, ASE, and reduced water absorption and leaching in manii and mindi woods.

Keywords: Boric acid, chitosan, impregnation, physical properties, weathering

IDENTIFIKASI DAN PEMETAAN SISTEM DUSUNG SEBAGAI AGROFORESTRI BERBASIS BUDAYA LOKAL DI KOTA AMBON, PROVINSI MALUKU, INDONESIA. SIFAT FISIS DAN PERUBAHAN WARNA KAYU CEPAT TUMBUH DENGAN PERLAKUAN SENYAWA BORON, KITOSAN, DAN PEMANASAN. Bahan pengawet asam borat dikenal mudah tercuci jika terkena hujan pada penggunaan eksterior. Oleh karena itu, perlu kombinasi dengan perlakuan lain untuk memperbaiki performanya. Penelitian ini bertujuan untuk mengevaluasi efek pengawetan asam borat, kitosan, dan pemanasan terhadap sifat fisis, ketercucian bahan pengawet, dan ketahanan terhadap paparan alami pada kedua jenis kayu cepat tumbuh. Kayu manii (*Maesopsis eminii* Engl.) dan mindi (*Melia azedarach* Linn.) diimpregnasi dengan pengawet asam borat 5% pada tekanan 7 kg cm⁻² selama 4 jam. Proses selanjutnya adalah melakukan impregnasi tahap kedua dengan kitosan (konsentrasi 2%) dan kombinasi antara asam borat-kitosan, pada tekanan dan durasi yang sama. Tahap terakhir yaitu perlakuan pemanasan pada suhu 70 °C dan 140 °C pada tekanan ruang selama 4 jam. Retensi asam borat pada kayu manii dan mindi masing-masing sebesar 18,1 ± 0,8 kg m⁻³ dan 12,7 ± 0,9 kg m⁻³. Interaksi antara asam borat, kitosan, dan perlakuan panas berpengaruh signifikan terhadap kerapatan, penyerapan air, ketercucian, stabilitas dimensi kayu, penyusutan, dan ketahanan kayu terhadap paparan alami. Impregnasi kombinasi campuran (asam borat-kitosan) dan pemanasan pada suhu 140 °C (M140) mampu meningkatkan kerapatan, ASE, mengurangi penyerapan air, dan ketercucian pada kayu manii dan mindi.

Kata kunci: Asam borat, impregnasi, kitosan, paparan alami, sifat fisis kayu

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I. INTRODUCTION

Manii (*Maesopsis eminii* Engl.) and mindi (*Melia azedarach* Linn.) are fast-growing wood species commonly found in community forests and widely used for construction purposes (Haryanto et al. 2021). Manii wood has an air-dry density of 0.39 g cm⁻³ (Sadiyo et al., 2017) and a specific gravity of 0.42, but it exhibits low natural durability (durability class V) (Muslich & Rullianty, 2016). Meanwhile, mindi wood belongs to strength class II–III and has a specific gravity of 0.53, however, its durability remains relatively low (durability class IV) (durability class IV) (Herawati et al., 2021). Although fast-growing species can be harvested within a relatively short rotation period, they generally exhibit lower wood quality, particularly in terms of density (Suri et al., 2021a) and durability (Fauziyyah et al., 2023). Therefore, effective wood modification strategies are needed to enhance the quality and durability of fast-growing wood species.

Improvements in the quality of fast-growing species can be achieved through preservation, thermal treatment, or a combination of both. One commonly used preservative is boric acid (H₃BO₃), which effectively increases wood resistance to fungi, insects, and termites (Percin et al., 2015). However, boric acid impregnation has a limitation, namely its susceptibility to water leaching under exterior exposure conditions (Verly et al., 2020). This reduces preservative retention and compromises long-term protection. This limitation necessitates the use of complementary materials or wood modification technologies to mitigate boric acid leaching.

Chitosan represents a promising complementary material to address this limitation. Chitosan is a bio-based and renewable derivative of chitin, primarily sourced from crustaceans and mollusks. It is widely recognized as a potential environmentally friendly wood preservative due to its natural abundance, sustainable availability, and inherent antibacterial and antifungal properties (Zivonic et al., 2015).

Chitosan, particularly when combined with other compounds (such as alginate, caffeine, and nitrilotris(methylenephosphonic acid)), has shown potential in enhancing the physical performance of wood, including thermal stability and structural integrity. Chitosan has been reported to improve caffeine fixation and reduce leaching, thereby increasing material stability. Modified chitosan systems can also improve fire-related properties by reducing heat release characteristics (Walsh-Korb et al., 2022; Woźniak et al., 2022; Cho et al., 2022). Chitosan, with its polysaccharide structure ((C₆H₁₁NO₄)_n), can be used as a natural adhesive (Winarto, 2014). Electrostatic interactions between chitosan and cellulose hydroxyl groups facilitate the bonding of chitosan to wood. Hydroxyl groups form hydrogen bonds with chitosan (Patel et al., 2013). Heat treatment can reduce the hygroscopic behavior of wood and lower its moisture content, thereby improving its dimensional stability. In addition, thermal modification can enhance resistance to preservative leaching and alter wood mass through chemical changes in cell wall components (Hill et al., 2021).

The combination of boron compounds, chitosan, and heat treatment has the potential to improve the performance of fast-growing wood species. The interaction among boron, chitosan, and heat treatment may contribute to wood performance through complementary mechanisms. Istriana and Priadi (2021) reported improved performance in boron–chitosan heat-treated (140 °C) wood compared with untreated and boron-only treated samples. Boric acid reduces fungal-induced weight loss, while chitosan suppresses microbial growth and reduces boron leaching. Heat treatment degrades hemicellulose and increases wood hydrophobicity, thereby reducing moisture availability and improving dimensional stability. Heating in combination with boron treatment can convert boric acid into metaboric acid (HBO₂) at around 138 °C, promoting crystallization and reducing preservative leachability (Kaur et al., 2021).

Although previous studies have examined boron compounds, chitosan, and heat treatment in wood modification, most investigations have focused on individual applications or partial combinations, such as boron–heat or chitosan–heat treatments. The fully integrated interaction among boric acid, chitosan, and heat treatment, particularly using sequential impregnation techniques, has not been widely explored, highlighting the need for a systematic evaluation of their combined application. A more comprehensive understanding of how these combined treatments perform is therefore required, particularly regarding their potential to enhance the quality of fast-growing wood species. The novelty of this study lies in the integration of boric acid, chitosan, and heat treatment through different impregnation strategies, including sequential and mixed treatments. In addition, this study provides a systematic comparison of these treatment approaches in manii and mindi woods, which have received limited attention in previous wood modification studies.

This research aimed to evaluate the effects of boric acid preservative, chitosan, and heat treatments on the physical properties, preservative leaching, and weathering resistance of two fast-growing woods.

II. MATERIALS AND METHODS

A. Location and Materials

This research was conducted in several laboratories within the Faculty of Forestry and Environment, IPB University. Wood sample preparation was carried out at the workshop. The impregnation process was conducted at the Laboratory of Drying and Preservation. The heat treatment tests were conducted at the Laboratory of Physical Properties, and the weathering test was carried out in an outdoor exposure area located near the Laboratory of Termites, Faculty of Forestry and Environment, IPB University.

Two fast-growing wood species, manii (*Maesopsis eminii* Engl.) and mindi (*Melia*

azedarach Linn.) were used in this study. Manii wood was obtained from a tree approximately 15 meters in height and 50 cm in diameter from the arboretum of the Faculty of Forestry and Environment, IPB University. Mindi wood was obtained from a sawmill at UD. Sumber Jaya, Bogor. Manii and mindi woods were processed into boards using a circular table saw with a thickness of 6 cm. The boards were dried in an experimental kiln at 50°C to a moisture content (MC) of 14%.

Specimens were prepared for density (2 cm × 2 cm × 2 cm), water absorption, leaching, and dimensional stability tests (2.5 cm × 2.5 cm × 10 cm), as well as weathering tests (2 cm × 7.5 cm × 15 cm). Five specimens were prepared for each treatment combination and used for subsequent analyses.

In addition, analytical-grade boric acid (H_3BO_3) was obtained from Supelco, Denmark, which was then dissolved in distilled water at 5% concentration. Chitosan powder derived from shrimp shells was supplied by PT. Biotech Surindo, Cirebon, acetic acid by Merck, and alcohol. Boric acid solutions were made at 5% concentration for impregnation I, while 2% chitosan was used for impregnation II. In addition, A mixture containing 5% boric acid and 2% chitosan was used for the single-impregnation treatment. The 2% chitosan solution was prepared by dissolving 20 g of chitosan powder (60 mesh) in 10 mL of acetic acid under continuous stirring. Subsequently, 700 ml of distilled water was added. The chitosan solution was then transferred to a 1000 ml measuring cylinder and homogenized at 23000 rpm for 5 minutes. Distilled water was then added, while constantly stirring, to bring the total volume up to 1000 ml. The solution was then allowed to stand for 24 hours (Istriana, 2024; Istriana & Priadi, 2021).

B. Methods

1. Impregnation and Heating

The test samples were dried in a heating oven at a temperature of 60 °C until 15% MC. The impregnation process was conducted in

two stages, followed by heat treatments at temperatures of 70 °C or 140 °C for 4 hours, as shown in Table 1. Boric acid impregnation was carried out in a pressurized tank at 7 kg cm⁻² for 4 hours (Lestari, 2020). The samples were weighed before (W_0) and after the impregnation (W_1) to determine the retention (R) of boric acid according to Equation 1. Subsequently, chitosan impregnation was performed under the same pressure conditions (7 kg cm⁻²) for 4 hours (Istriana, 2024).

$$R = (W_1 - W_0) : V \times C \dots\dots\dots(1)$$

Where:

R = retention (kg m⁻³)

W_0 = sample weight before impregnation (kg)

W_1 = sample weight after impregnation (kg)

V = sample volume (m³)

C = boric acid concentration (%)

After impregnation, the wood samples were heat-treated in a Memmert oven at either 70 °C or 140 °C for 4 h under atmospheric pressure. The samples were oven-dried at 103 ± 2 °C

before and after the second impregnation to determine the weight percent gain (WPG) using Equation 2.

$$WPG = (W_2 - W_1) : W_1 \times 100 \dots\dots\dots(2)$$

Where:

WPG = weight percent gain of the sample (%)

W_2 = dry weight after impregnation (g)

W_1 = dry weight before impregnation (g)

2. Physical Properties Test

Wood density was determined according to the British Standard (BS 1957). Water absorption and leaching tests were conducted in accordance with ASTM D 1413-76 (ASTM 1976). The leaching value was calculated using Equation 3, which represents the difference in oven-dry weight after impregnation and after immersion. Water absorption was calculated using Equation 4, based on the difference between the weight after each immersion and its oven-dry weight.

Table 1. Treatment combination on manii and mindi woods without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mix boric acid+chitosan (M), and heating temperatures (70 °C and 140 °C)

Treatment code	Impregnation I	Impregnation II	Heat treatment (°C)
N70	-	-	70
N140	-	-	140
B70	Boric acid	-	70
B140	Boric acid	-	140
C70	-	Chitosan	70
C140	-	Chitosan	140
BC70	Boric acid	Chitosan	70
BC140	Boric acid	Chitosan	140
CB70	Chitosan	Boric acid	70
CB140	Chitosan	Boric acid	140
M70	Boric acid+Chitosan		70
M140	Boric acid+Chitosan		140

$$L = (W_{ob} - W_{oa}) : W_{ob} \times 100 \dots\dots\dots(3)$$

Where:

- L = leaching (%)
 W_{oa} = oven dry weight after soaking (g)
 W_{ob} = oven dry weight before soaking (g)

$$WA = ((W_{wa} - W_{ob}) : W_{ob} \times 100 \dots\dots\dots(4)$$

Where:

- WA = water absorption (%)
 W_{wa} = wet weight after soaking (g)
 W_{ob} = oven dry weight before soaking (g)

Test samples were immersed in distilled water gradually for 2 hours, 24 hours, and 48 hours. Each immersion period was interrupted by oven-drying at a temperature of 103 ± 2 °C until a constant weight was achieved. The samples were weighed before and after immersion under both wet and oven-dry conditions. The anti-swelling efficiency (ASE) was calculated using Equation 5. Tangential and radial shrinkage were determined from the dimensional changes between wet and oven-dry conditions using Equation 6. The tangential-radial shrinkage ratio was calculated using Equation 7

$$ASE = (S_u - S_t) : S_u \times 100 \dots\dots\dots(5)$$

Where:

- ASE = the anti-swelling efficiency (%)
 S_u = the swelling of the untreated sample (%)
 S_t = the swelling of the treated sample (%)

$$SD = (D_b - D_a) : D_b \times 100 \dots\dots\dots(6)$$

Where:

- SD = the shrinkage (%)
 D_b = dimension (tangential, radial) before oven drying (cm)
 D_a = dimension (tangential, radial) after oven drying (cm)

$$T/R = SD_t : SD_r \times 100 \dots\dots\dots(7)$$

Where:

- T/R = the shrinkage ratio
 SD_t = the tangential shrinkage (%)
 SD_r = the radial shrinkage (%)

3. Color Changes and Weathering Test

The color of the wood was evaluated before and after treatments using a CanoScan 4400F scanner. The scanned images were analyzed using the CIELab color system. L^* , a^* , and b^* values were determined at three points on each sample surface using Adobe Photoshop CS3. Parameter L^* indicated light (+) or dark (-), a^* indicated reddish (+) or greenish (-), and b^* indicated yellowish (+) or bluish (-) colors (Cao et al., 2021). The changes in L^* , a^* , and b^* , (ΔL , Δa , and Δb , respectively) were calculated using Equations 8-10. Total color change (ΔE) was calculated using Equation 11 (Hidayat et al., 2021). The color change (ΔE) was classified according to Table 2.

$$\Delta L = L_1 - L_0 \dots\dots\dots(8)$$

$$\Delta a = a_1 - a_0 \dots\dots\dots(9)$$

$$\Delta b = b_1 - b_0 \dots\dots\dots(10)$$

$$\Delta E = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2} \dots\dots\dots(11)$$

Where:

- L_1, a_1, b_1 = the values of L^* , a^* , and b^*
 L_0, a_0, b_0 = the values before the treatments

The weathering test was conducted following the procedure described by Kim et al. (2016). Test samples were placed on an exposure rack at a 45° angle, oriented towards the east. The weathering period lasted 90 days, from June to August 2022. The primary parameters measured were wood color changes before and after weathering, along with alterations in weight. Weight loss was evaluated to assess the effectiveness of the modification treatments in reducing wood degradation. Weight loss was measured on days 30, 60, and 90. Concurrently with weight loss, moisture content was

Table 2. Classification of color change (ΔE)

Color change	Description
$(0 < \Delta E \leq 0.5)$	Negligible
$(0.5 < \Delta E \leq 1.5)$	Slightly perceivable
$(1.5 < \Delta E \leq 3.0)$	Noticeable
$(3.0 < \Delta E \leq 6.0)$	Appreciable
$(6.0 < \Delta E \leq 12)$	Very appreciable

assessed using a moisture meter. Initial sample weights were recorded and compared with weights measured after 30, 60, and 90 days of weathering. Finally, weight loss was calculated using Equation 12.

$$WL = (W_m - W_n) : W_m \times 100 \dots\dots\dots(12)$$

Where:

WL = the weight loss (%)

W_m = the wood weight on day-m (g)

W_n = the wood weight on day-n (g)

C. Analysis

The obtained data on retention and weight percent gain were analysed descriptively using Microsoft Excel software. The data from various tests on the impregnation of manii and mindi wood with boric acid, chitosan, and heat treatment were analyzed using IBM SPSS 26 based on a factorial completely randomized design. Factor A (wood species) had 2 types (manii and mindi), Factor B (impregnation) had 6 levels (without impregnation, boric acid, chitosan, boric acid-chitosan, chitosan-boric acid, boric acid+chitosan), and Factor C was heat treatment, which had 2 levels (70 °C and 140 °C). When significant differences were detected by ANOVA, Duncan's multiple range test was performed at a 95% confidence level.

III. RESULT AND DISCUSSION

A. Evaluation of Impregnation Results

The success of impregnation can be assessed by retention values and weight percent

gain. Preservative retention is a key parameter for effective wood preservation. Our findings indicate that boric acid retention reached $18.1 \pm 0.8 \text{ kg m}^{-3}$ in manii wood and $12.7 \pm 0.9 \text{ kg m}^{-3}$ in mindi wood. The retention value required by the SNI 01-5010.1-1999 standard (Indonesian National Standard) was a minimum of 8.2 kg m^{-3} for interior use and 11.3 kg m^{-3} for exterior use. The higher retention observed in manii wood may be related to its lower specific gravity (0.42) compared with mindi wood (0.53) (Muslich & Rullianty, 2016; Krisdianto et al., 2013). Mindi wood, with its higher specific gravity, generally requires greater pressure or longer treatment duration for effective preservative penetration, due to its denser anatomical structure and reduced permeability. In addition, retention can also be influenced by moisture content, preservative characteristics, and wood density (Syahrial et al., 2022). The retention of preservatives in wood determines its effectiveness in protecting against wood-destroying organisms (Vachlepi et al., 2015).

Weight percent gain (WPG) represents the percentage increase in wood weight after impregnation compared to its initial weight. Figure 1 shows that the highest WPG values for both wood species were obtained with the boric acid–chitosan mixture treatment combined with heating at 70 °C (M70), reaching 68.08% in manii wood and 57.61% in mindi wood. Conversely, the lowest WPG values for both wood types were observed with the chitosan-only treatment combined with heating at 140 °C (C140), which were 30.79% for manii wood and 17.36% for mindi wood.

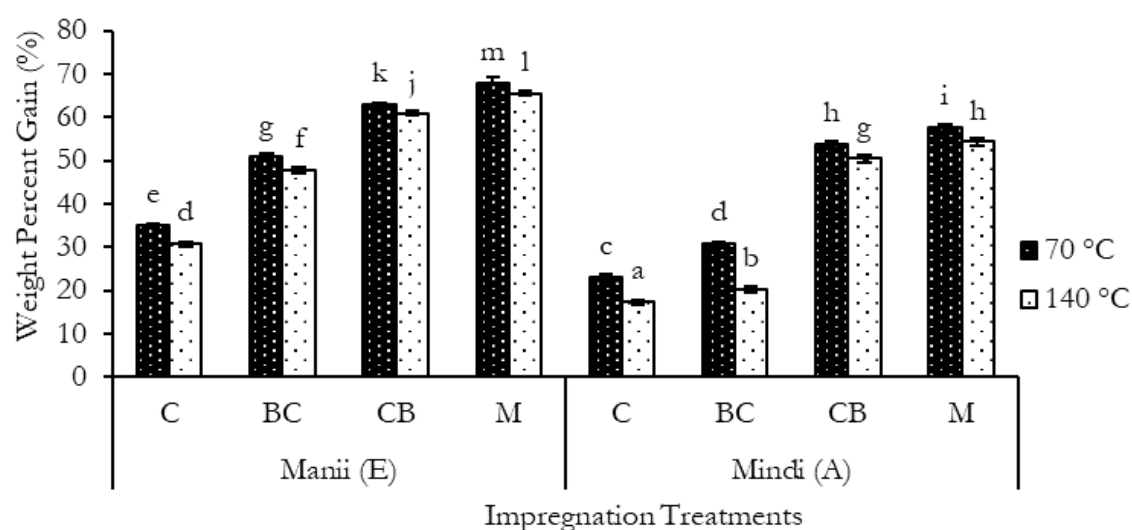


Figure 1. Weight percent gain of manii and mindi wood treated with chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

The analysis of variance result at a 95% confidence level shows that the interaction of wood type, impregnating agent, and heat treatment has a very significant effect on WPG ($F(5, 96) = 28.487, p < 0.001$). Duncan's test shows that the WPG for the boric acid-chitosan mixture with 70 °C heating (M70) was significantly higher than for that treated with chitosan with 70 °C heating (C70), boric acid-chitosan with 70 °C heating (BC70), and chitosan-boric acid with 70 °C heating (CB70) in both wood types. This indicates that the boric acid-chitosan mixed system (M) resulted in greater penetration into the wood lumen and void spaces compared to the sequential impregnation treatments (BC and CB). In the mixed system (boric acid-chitosan mixture), boron ions can diffuse into the chitosan matrix and interact with amino groups ($-NH_2$) through physicochemical interactions such as electrostatic attraction or complex formation, which may help stabilize boron within the chitosan matrix (Hammi et al., 2023) and facilitate the simultaneous diffusion of both compounds into the lumen and partially into the cell wall structure. In contrast, during sequential impregnation treatments (BC and

CB), a portion of boric acid may be leached out during the second impregnation step. Boric acid has high water solubility, making it prone to leaching from wood (Cahyono et al., 2020).

Test samples heated at 140 °C showed lower WPG compared to those heated at 70 °C for both wood types. This is likely due to the evaporation of some impregnants and the degradation of certain wood chemical components, particularly hemicellulose, at higher temperatures. Heating at elevated temperatures promotes the degradation of extractives and cell-wall components, particularly hemicellulose (Gokhan & Denis, 2019).

B. Physical Properties

Wood density increased in both manii and mindi woods following the applied treatments. Figure 2 shows that the highest density values were obtained in the boric acid-chitosan mixture treatment heated at 140 °C (M140). The densities reached 0.63 g cm^{-3} for manii wood and 0.64 g cm^{-3} for mindi wood. Untreated manii and mindi woods exhibited the same density value of 0.45 g cm^{-3} . The ANOVA test shows that heating significantly affects the

wood's density ($F(1,96) = 12,09$, $p = 0.001$). Mixture treatment with 140 °C heating (M140) significantly increased wood density by up to 39% for manii wood and 22% for mindi wood (Figure 2). The increase in density may result from the deposition of preservative compounds within the wood structure, filling cell voids, and adding mass to the wood matrix. Furthermore, the analysis of variance results show that wood density is influenced by the interaction between wood species and impregnation ($F(5, 96) = 11.99$, $p < 0.001$). Density tended to increase with increasing boric acid concentration in the

impregnation solution. A positive relationship between boric acid concentration and retention. Similarly, Fidan & Adanur (2019) reported a density value of 5% boric acid of 0.54 g cm^{-3} , slightly higher than the control (0.53 g cm^{-3}). This trend is consistent with the retention and WPG results observed in this study, where higher preservative uptake contributed to increased mass within the wood structure.

Heating at temperatures between 120 °C – 150 °C causes wood to lose its extractives (Todaro et al., 2015). High temperatures can also alter wood cell wall components, including

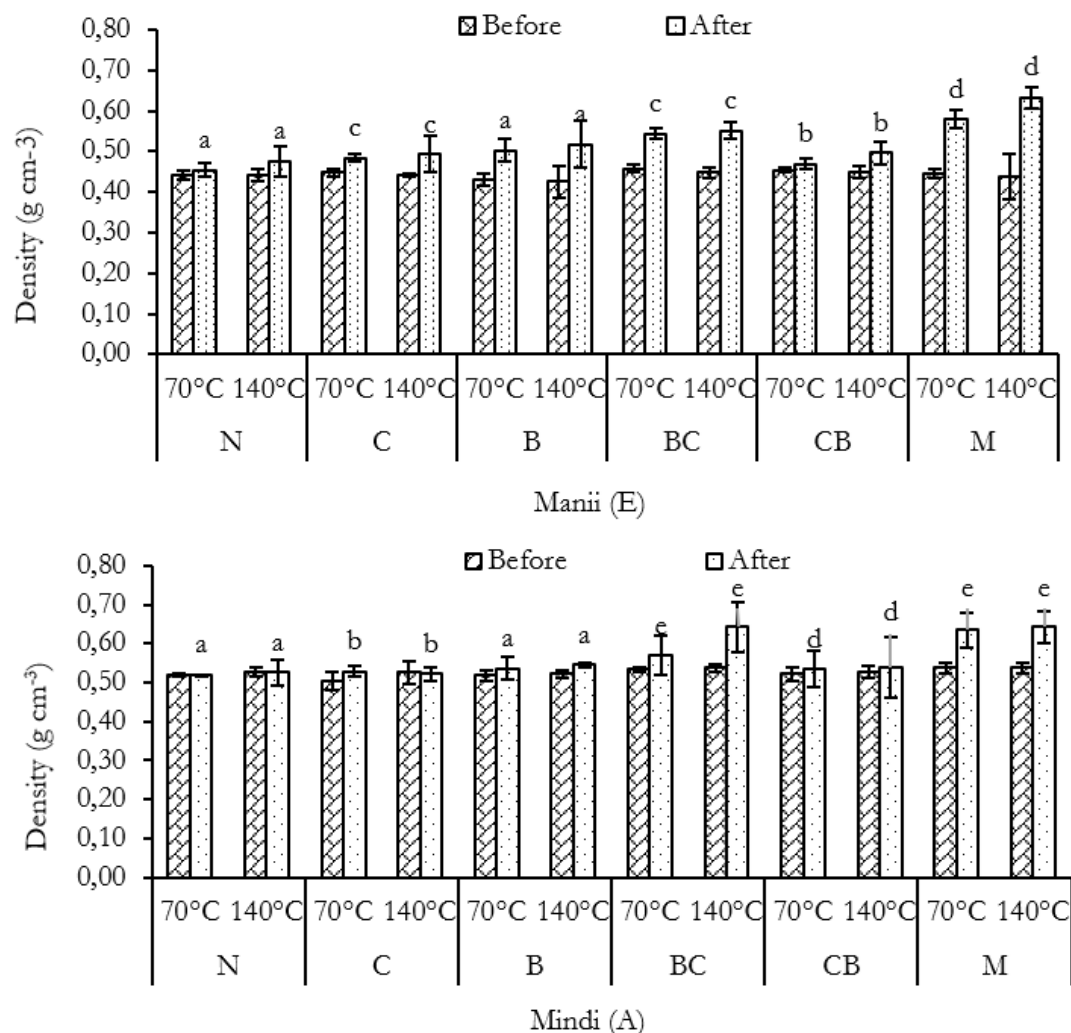


Figure 2. Density of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

cellulose (Cahyono et al., 2021). The increase in density after heat treatment may be attributed to moisture loss, which reduces wood volume. As density is the ratio of mass to volume, this volume reduction can increase density. Differences in density between manii and mindi wood may also be related to variations in anatomical structure, which influence the penetration and distribution of preservative compounds.

Figure 3 shows that water absorption (WA) in the test samples decreased after the impregnation. The lowest WA values after

48 hours of immersion for both manii and mindi woods were observed in the boric acid-chitosan mixture with 140 °C heating (M140), which were 7.99% for manii wood and 7.37% for mindi wood. The lower WA in the M140 treatment may be attributed to the combined effect of boric acid, chitosan, and heat treatment, which limit water penetration and reduce wood hygroscopicity. Previous studies have reported that wood treated with boron can reduce hygroscopicity, water absorption, and shrinkage value (Demirel et al., 2018).

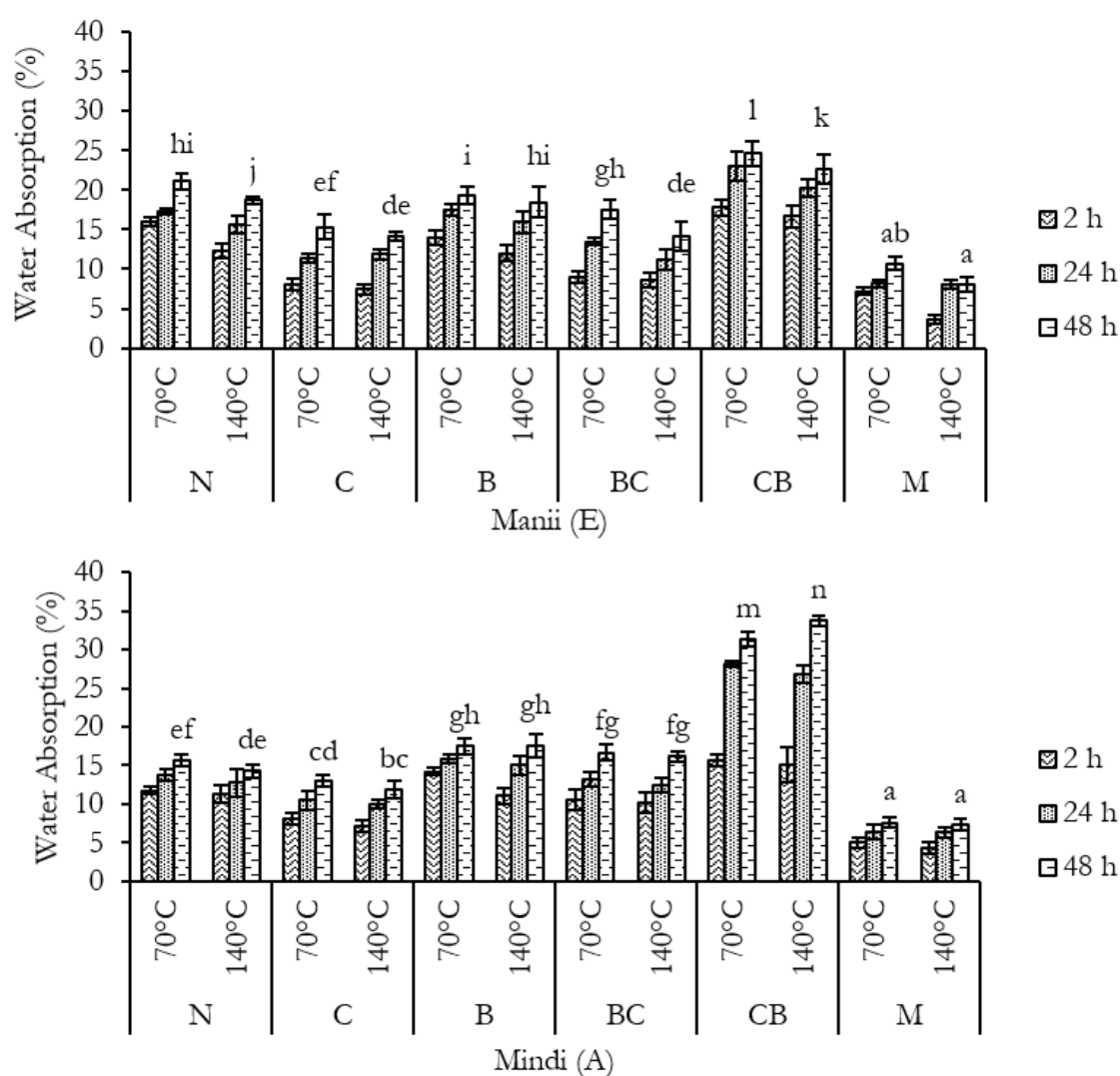


Figure 3. Water absorption of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C. Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

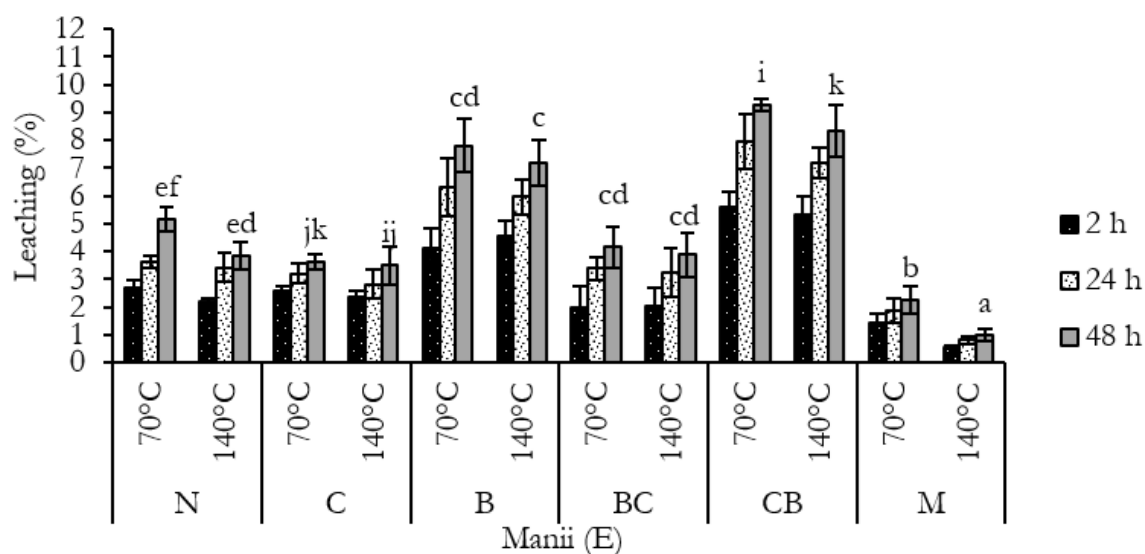
This is supported by the analysis of variance results, explaining that WA is influenced by the interaction between wood species, impregnation treatment, and heating ($F(5, 96) = 2.43$, $p = 0.041$). Both manii and mindi woods exhibited significantly lower WA values when subjected to the boric acid-chitosan mixture (M) and the chitosan impregnation treatment (C), compared to the untreated woods (control) (N70). Chitosan treatment reduced the hygroscopicity of wood, leading to a decrease in its equilibrium moisture content across all relative humidity levels (Papadopoulos et al., 2020). This is attributed to the chitin, which blocks the hydrophilic hydroxyl groups of the cellulose and reduces the hygroscopicity of the treated wood. Papadopoulos et al. (2020) demonstrated that the use of chitosan compounds resulted in a 23.8% reduction in total wood sorption. However, the higher WA observed in CB-treated (chitosan-boric acid) samples suggests that the response may depend on the treatment sequence and interactions between the impregnated compounds. The sequential chitosan-boron treatment may potentially affect water penetration and absorption.

Heat treatment at 140 °C (N140) also resulted in lower water absorption compared to heating at 70 °C (N70), suggesting that higher temperatures reduced the wood's water absorption (Lestari, 2020). The lower water

absorption is attributed to the reduction of free hydroxyl (-OH) groups during heat treatment, which decreases wood hygroscopicity, as reported for sengon and jabon woods (Priadi et al., 2019). Increased cellulose crystallinity after heat treatment limits the accessibility of water molecules to the cell wall, thereby reducing water absorption (Darmawan et al., 2017). Similar increases in cellulose crystallinity following heat treatment (160 °C, 180 °C, 200 °C, and 220 °C for 2 hours) have been reported in Royal Paulownia wood, supporting the reduction in water absorption (Kim et al., 2018).

Leaching is an important parameter in evaluating the fixation and long-term performance of wood preservatives. Figure 4 shows that chitosan can reduce preservative leaching by up to 30%, particularly in samples impregnated with the boric acid-chitosan mixture followed by heat treatment at 140 °C. The lowest leaching values after 48 hours of immersion were observed in the boric acid-chitosan mixture with 140 °C heating (M140), which were 0.99% for manii wood and 1.003% for mindi wood. The analysis of variance indicates that the leaching value after 48 hours is significantly influenced by the interaction between wood species and impregnation treatment ($F(5, 96) = 14.26$, $p < 0.001$).

The leaching values of the boric acid-chitosan mixture (M) and the boric acid-



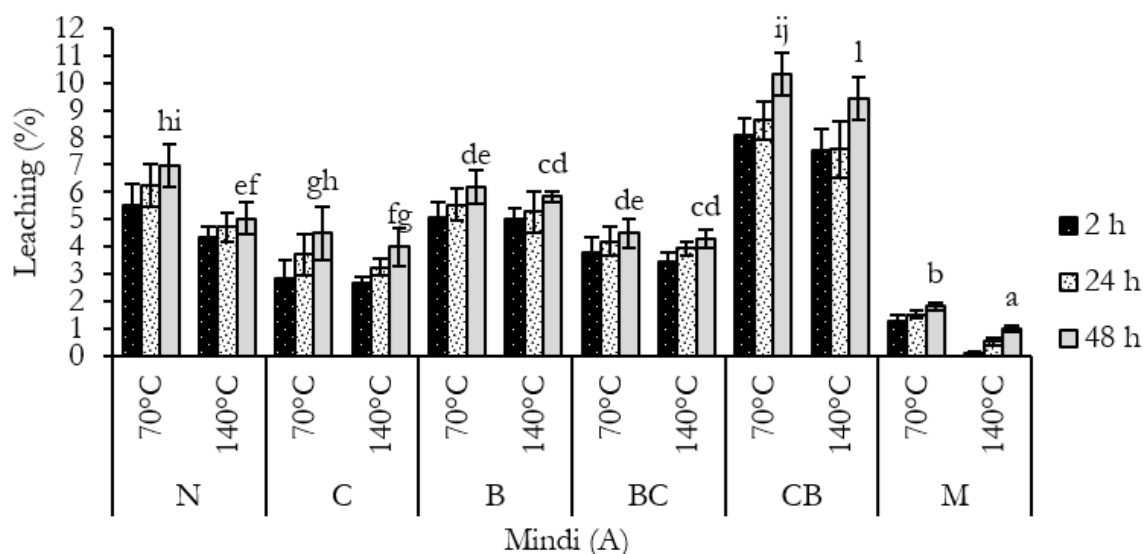


Figure 4. Leaching of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

chitosan (BC) were significantly lower than those of the untreated samples (N70) after 48 h of immersion. Among the treatments, the M140 treatment showed the lowest leaching values. Chitosan can bond to cellulose polymers and occupy void spaces within the wood structure, which may hinder preservative migration and contribute to lower leaching. Treated wood with chitosan exhibits lower leaching compared to that of treated wood with PEG (Nowrouzi et al., 2015). Boron ions may interact with the amino groups ($-NH_2$) of chitosan through physicochemical interactions, promoting boron fixation within the wood structure and thereby reducing its susceptibility to leaching (Hammi et al., 2023). However, the higher leaching observed in CB (chitosan-boric acid) samples may be related to the relatively soluble nature of boron compounds. Boron that is not strongly retained within the wood structure may migrate during water exposure and subsequently leach out.

The impregnation of boric acid, chitosan, and heat modification has been proven to improve the dimensional stability of manii and mindi woods. The highest anti-swelling

efficiency (ASE) values after 48 hours of immersion were observed with the treatment of boric acid-chitosan mixture with 140 °C heating (M140), which was 44.64% for manii wood and 46.89% for mindi wood (Figure 5). The analysis of variance revealed that the ASE after 48 hours value is influenced by the interaction between wood species, impregnation, and heat treatment ($F(5,96) = 9.37$, $p < 0.001$).

Manii (E) wood showed positive anti-swelling efficiency (ASE) values with the impregnation treatment of boric acid-chitosan mixture (M) and boric acid-chitosan double impregnation treatment (BC). These results were significantly different from the untreated samples (N70). This improvement suggests that the combined treatment (boric acid, chitosan, and heat treatment) reduced the wood's susceptibility to moisture-induced swelling, thereby enhancing dimensional stability. Similar improvements in ASE have been reported in fir and beech wood treated with chitosan, supporting the role of chitosan in reducing moisture-induced swelling (Nowrouzi et al., 2015). This effect is attributed to chitosan treatment decreasing the hydrophilic nature of wood, as chitin forms a coating over

the wood's cellulose (Papadopoulos et al., 2020). Heat treatment also contributed to improved dimensional stability by reducing hygroscopicity and increasing cellulose crystallinity, which together limit moisture uptake and subsequent swelling. In addition, partial degradation of hemicellulose during heating further stabilizes the wood structure (Vybohova et al., 2018).

Boric acid, chitosan impregnation, and heat treatment reduced the dimensional shrinkage of manii and mindi woods (Figure 6). Manii wood (E) treated with the boric acid-chitosan mixture

at 140 °C (M140) exhibited lower shrinkage values compared to that without impregnation (N70), specifically 1.25% (tangential shrinkage) and 1.07% (radial shrinkage). Similarly, mindi wood (A) showed values of 3.42% (tangential shrinkage) and 2.92% (radial shrinkage) under the same treatment. The lower shrinkage observed in the radial direction compared to the tangential direction is influenced by the resistance of the wood rays (Susdiyanti et al., 2023).

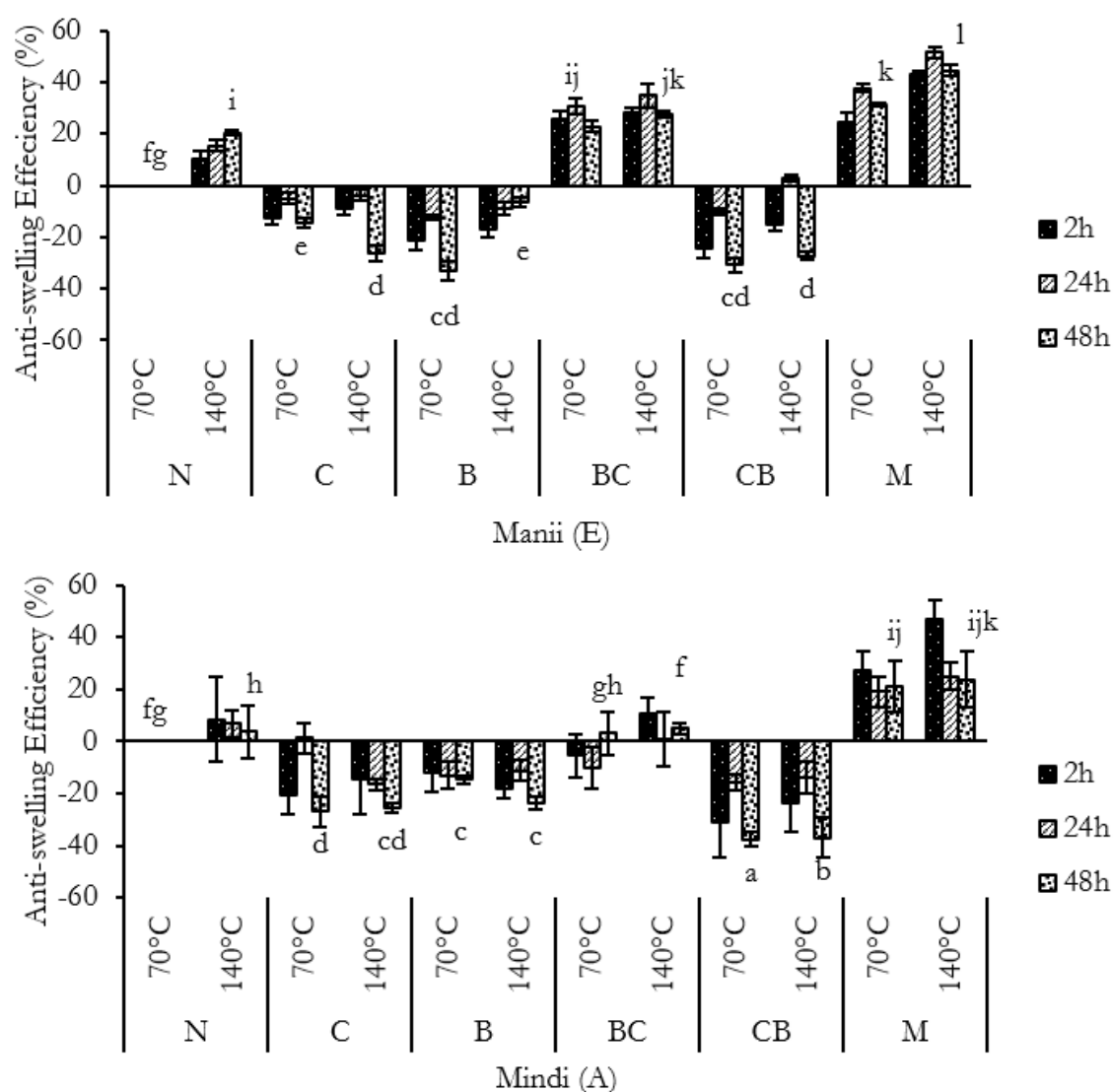


Figure 5. Anti-swelling efficiency of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

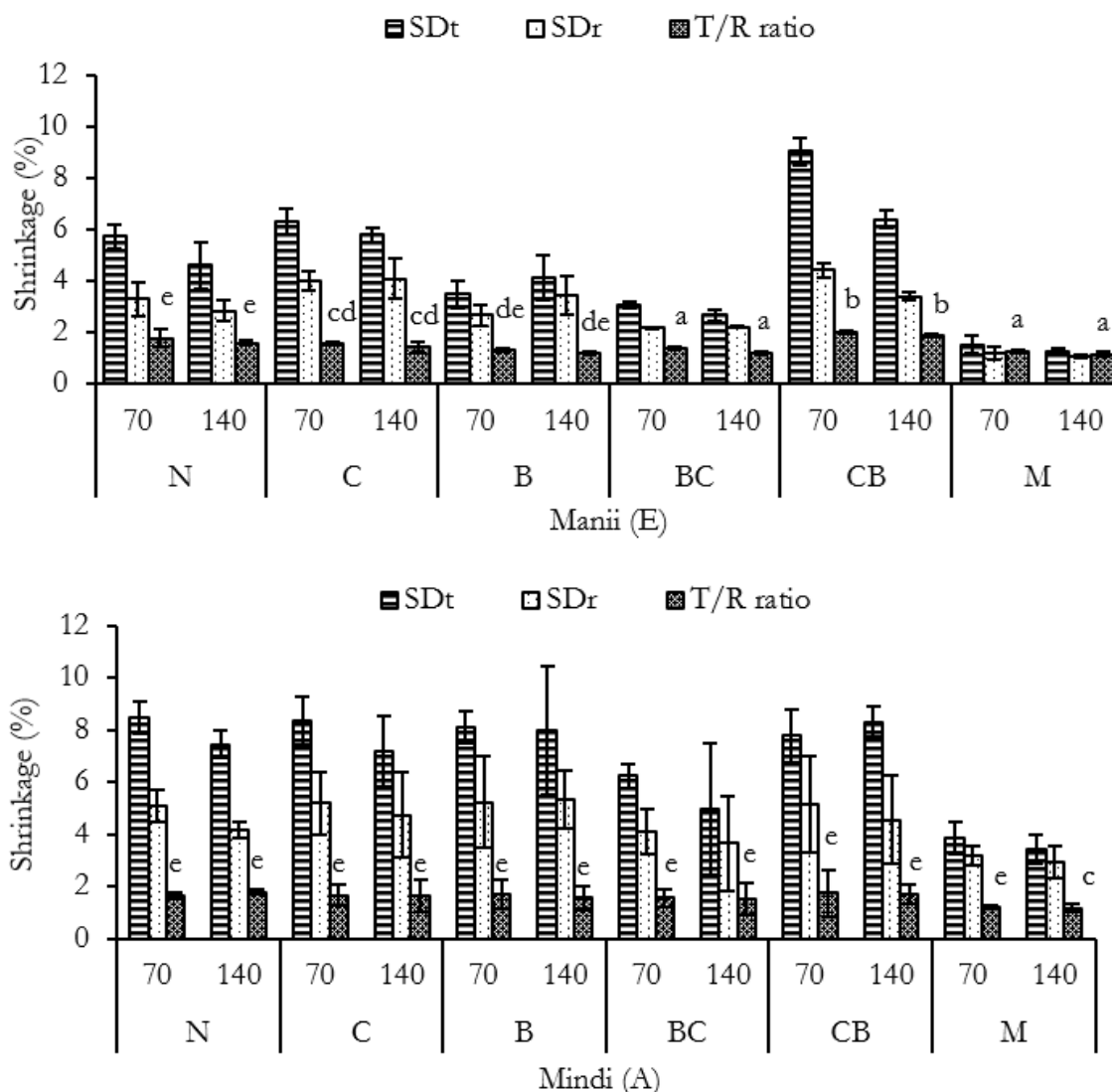


Figure 6. Shrinkage of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

The analysis of variance revealed that the T/R ratio value is influenced by the interaction between wood species and impregnation ($F(5,96) = 9.00, p < 0.001$). The boric acid-chitosan mixture treatment with 140 °C heating (M140) resulted in significantly lower T/R shrinkage ratios compared to those without impregnation (N140), which were 1.17 for manii and 1.18 for mindi woods. The lower T/R ratio suggests a more uniform dimensional response during moisture fluctuations, reflecting improved dimensional stability. Similar reductions in T/R ratio following heat treatment (180 °C

for 4 hours) have been reported in *Pterocarpus macrocarpus*, supporting the stabilizing effect of thermal modification on wood dimension (Yang & Liu, 2020). Similar reductions in shrinkage after heat treatment (170 °C) were reported for *eastern beech wood* compared to controls (Kol et al., 2017). This improvement is associated with the partial degradation of hemicellulose and cellulose during heat treatment, which decreases the number of accessible hydroxyl groups and reduces wood hygroscopicity, thereby limiting shrinkage.

C. Color Changes and Weathering

Modification using boric acid, chitosan impregnation, and heating caused color changes in manii and mindi woods. Figure 7 shows that manii wood without boric acid or chitosan impregnation became slightly darker at 140 °C (EN140) than at 70 °C (EN70). Heat treatment has been reported to decrease the lightness (L^*) of oak, birch, and pine woods (Barcik et al., 2015). Boric acid treatment (B70 and B140) resulted in brighter wood than the untreated samples (N70 and N140), which is consistent with previous findings for manii wood by Priadi et al. (2022).

The a^* value slightly decreased, indicating a reduction in red coloration. Additionally, a slight increase in the b^* value resulted in a more yellow appearance. These color changes in wood are attributed to the formation of carbonyl groups from the oxidation of hydroxyl groups within phenolic components, or the formation of quinoid structures from adjacent hydroxyl groups (Wei et al., 2017). The color darkening observed after heat treatment is associated with hemicellulose degradation and intensified thermal reactions, including interactions between reducing sugars and amino compounds, as well as decarboxylation and dehydration, leading to the formation of chromophoric substances such as quinones.

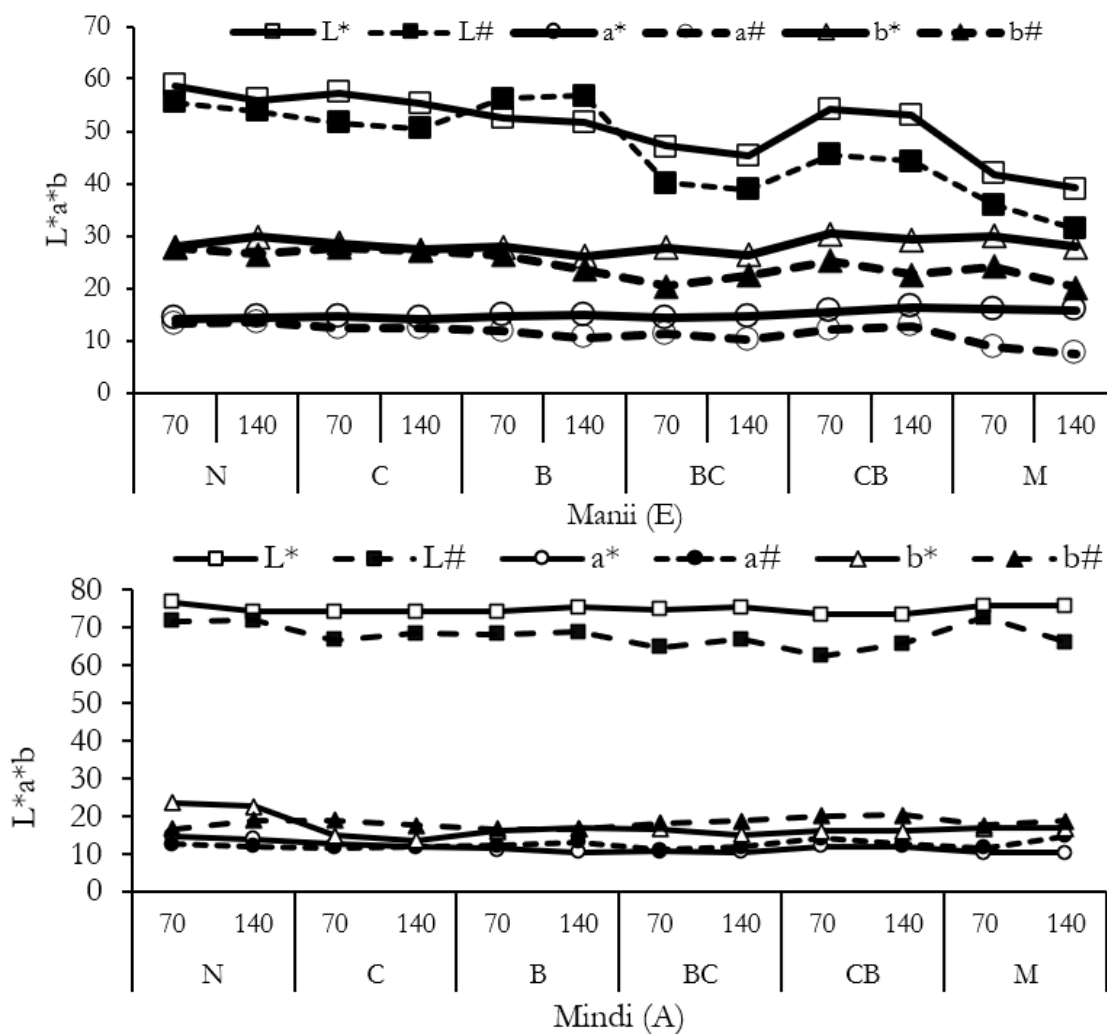


Figure 7. The L^*a^*b of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C).

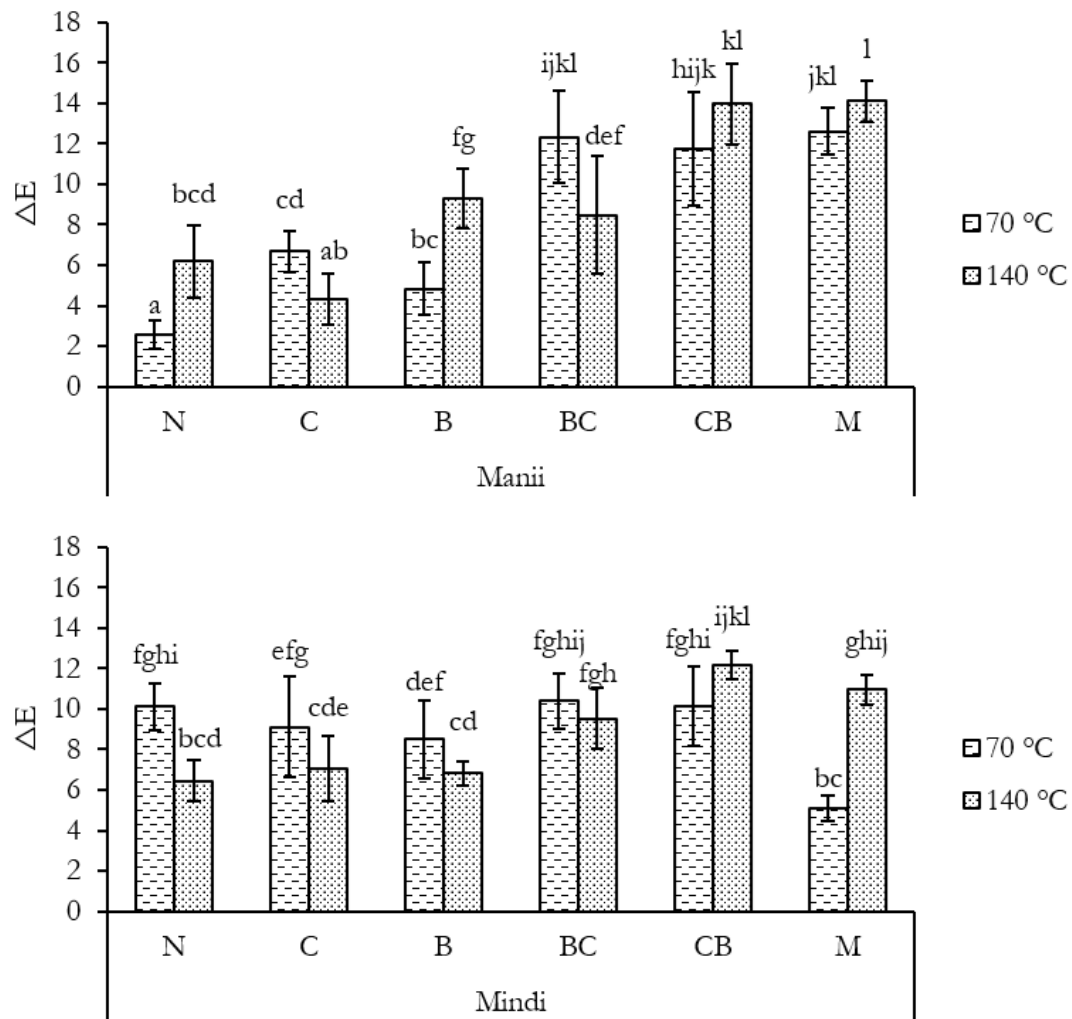


Figure 8. The ΔE of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C. Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.)

Figure 8 shows that manii wood treated with the boric acid-chitosan mixture at 140 °C (M140) underwent the largest color change (ΔE) of 14.11. This value falls within the $\Delta E \geq 12$ range, indicating a very high color contrast. Meanwhile, mindi wood subjected to the same boric acid-chitosan mixture treatment at 140 °C (M140) exhibited its largest color change (ΔE) of 10.95. This value reflects a pronounced color modification, corresponding to a high color difference ($6 \leq \Delta E < 12$). Despite these color changes, all treatments retained the natural grain pattern of the wood, thereby preserving the aesthetic value of wood products.

In the weathering test (Figure 10), untreated (N), BC, and M treatments showed a decrease in L^* values, indicating darker wood, whereas B and CB treatments exhibited an increase in L^* , resulting in a brighter appearance in both manii and mindi woods. The increase in L^* values in the B and CB treatments may be attributed to the colorless nature of boron compounds and their susceptibility to leaching (Verly et al., 2020), which limits the formation of a protective surface layer against photodegradation, resulting in higher brightness during exposure. Additionally, all treatments exhibited lower a^* and b^* values, indicating a shift toward greener

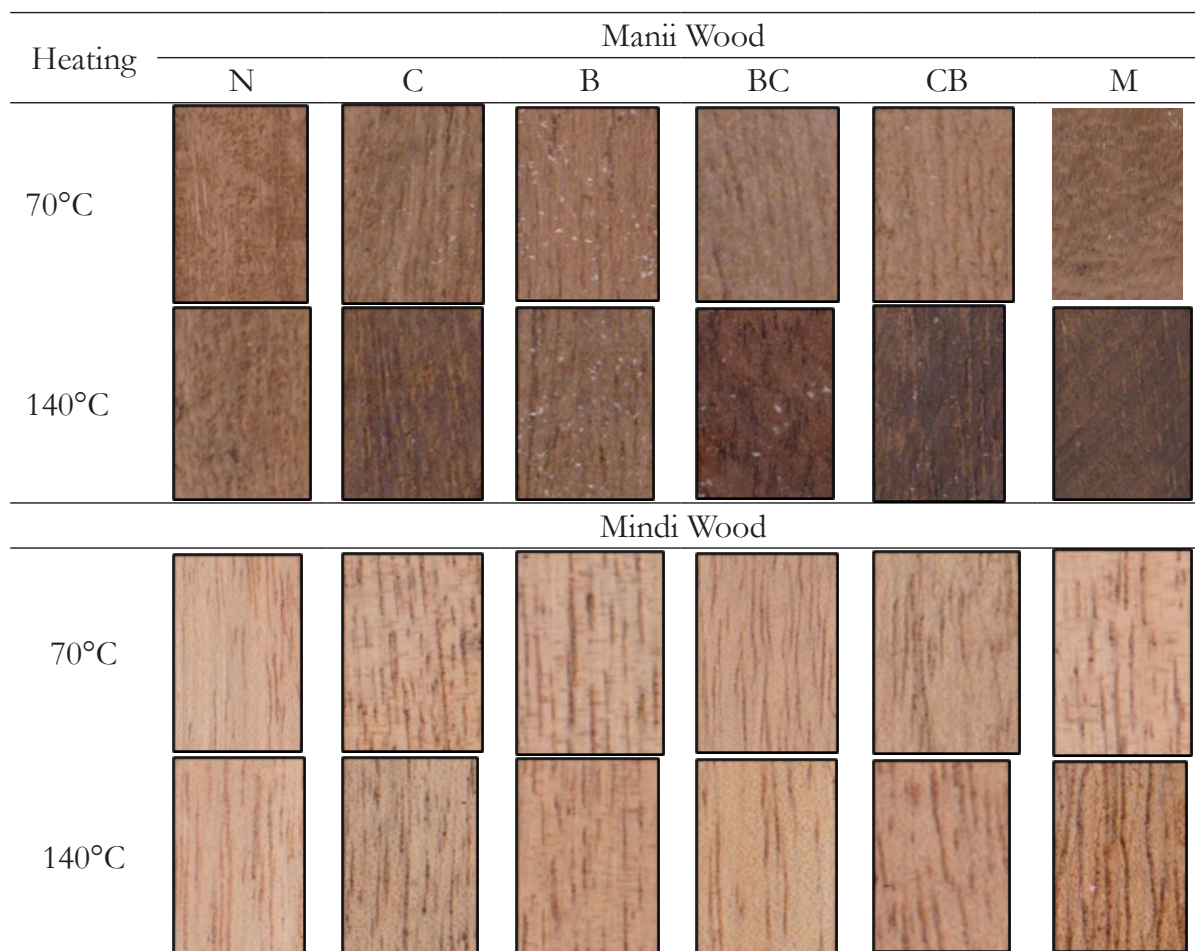


Figure 9. The color changes of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.).

and bluer color tones during weathering. Turkoglu et al. (2015) suggest that changes in wood's redness (a^*) are due to alterations in extractive content, while changes in yellowness (b^*) are linked to lignin modifications. These observed color changes are influenced not only by weathering factors but also by fungal activity attacking the wood during weathering, particularly in the untreated samples.

Figure 11 shows that 90 days of weathering led to fading in wood color. Specifically, manii and mindi wood treated with the boric acid-chitosan mixture at 140 °C (M140) underwent color changes (ΔE) of 5.14 and 14.15, respectively. These results indicate moderate color ($3 \leq \Delta E < 6$) alteration in manii wood and substantial color modification ($\Delta E \geq 12$) in mindi wood after weathering.

The variations in weight loss (WL) in wood during weathering may result from the combined effects of fungal colonization, leaching of extractives, and degradation of cell wall components under fluctuating environmental conditions. Weight changes during weathering (Figure 13) showed that both manii and mindi woods gained weight between days 30 and 60, likely due to the absorption of rainwater (June–August 2022). Subsequently, a decrease in weight was observed by day 90 (September 2022). This observation is supported by data from BMKG (2022) concerning rainfall in Bogor Regency, which indicated substantial rainfall from June to August, reaching 77 mm/day to 132 mm/day, while rainfall decreased to 66.3 mm/day in March.

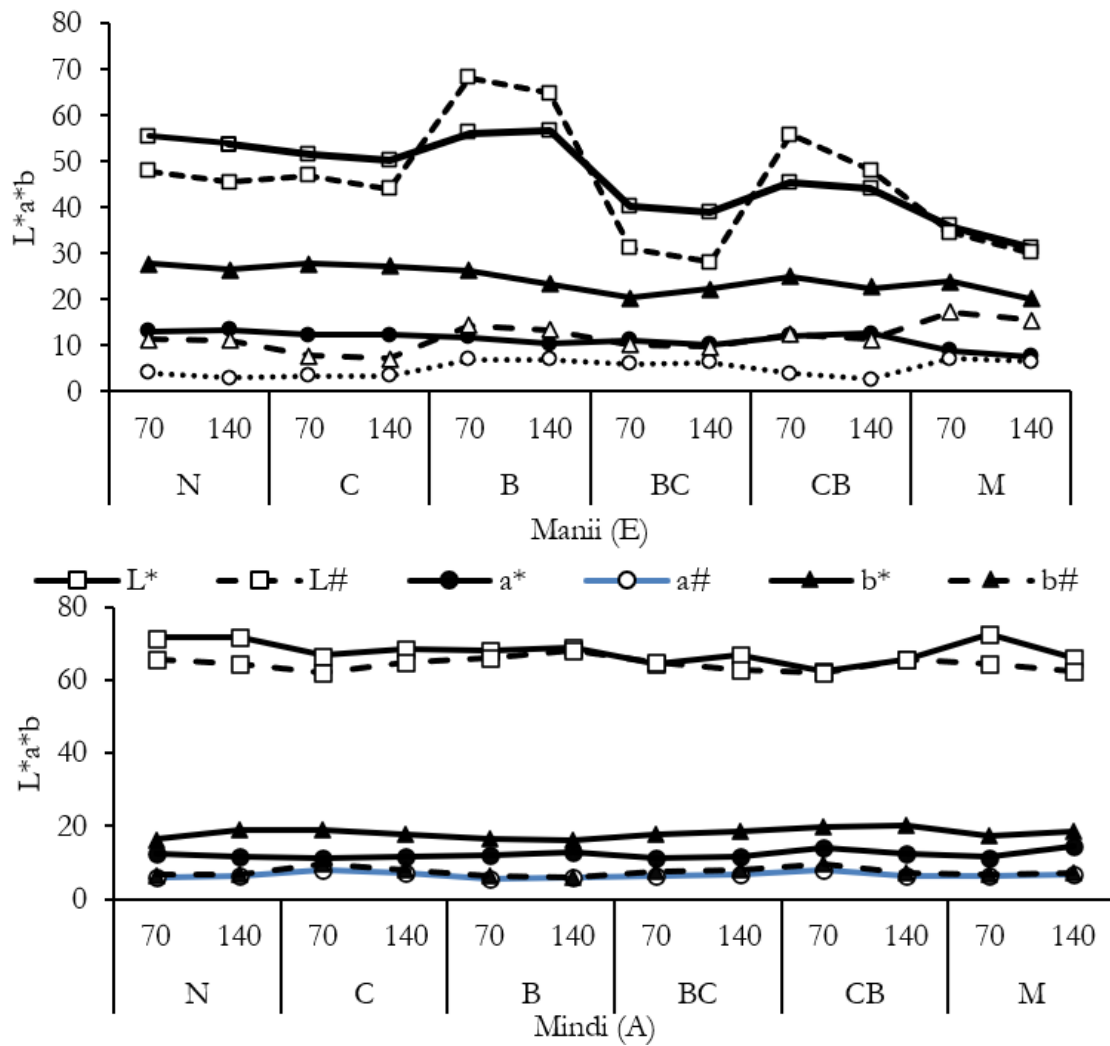
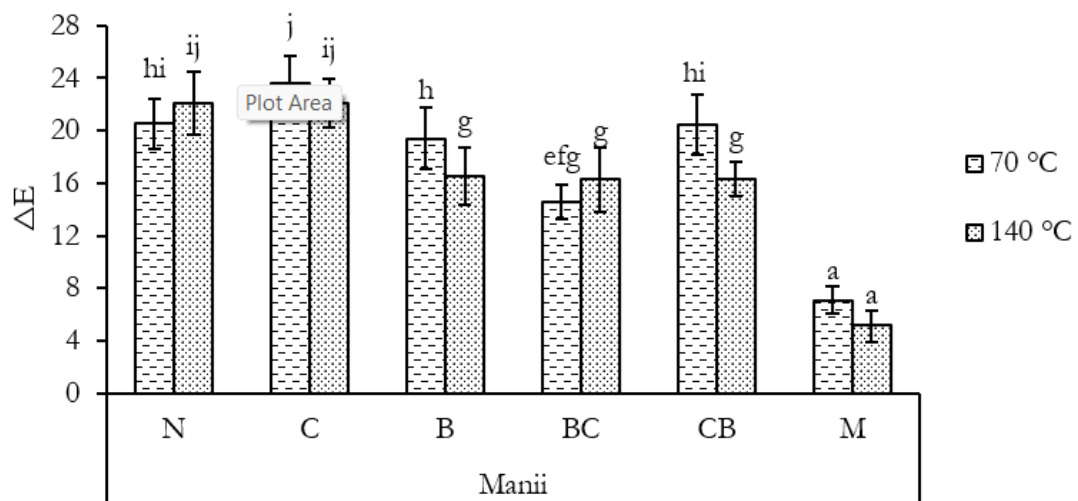


Figure 10. The L*a*b after weathering of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C).



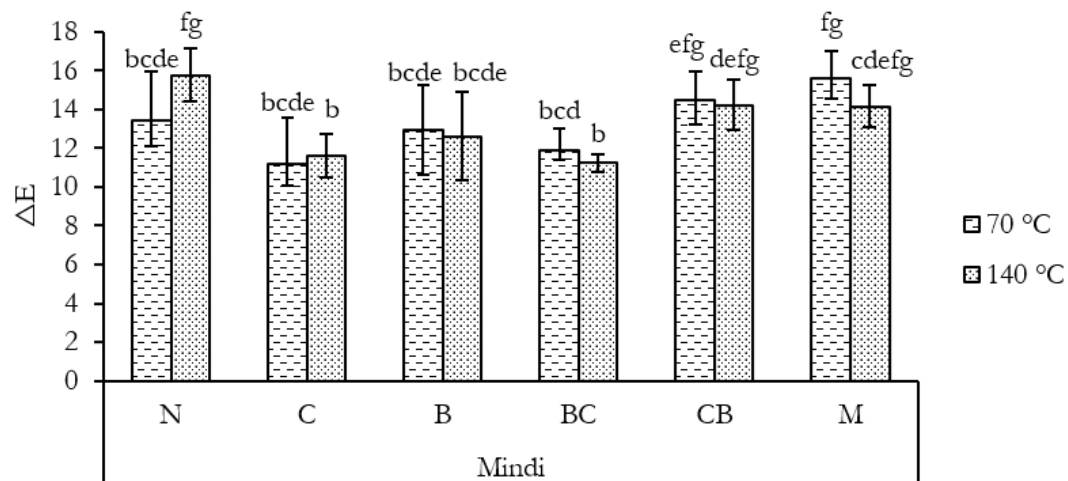


Figure 11. The ΔE after weathering of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.).



Figure 12. The color changes after weathering of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C).

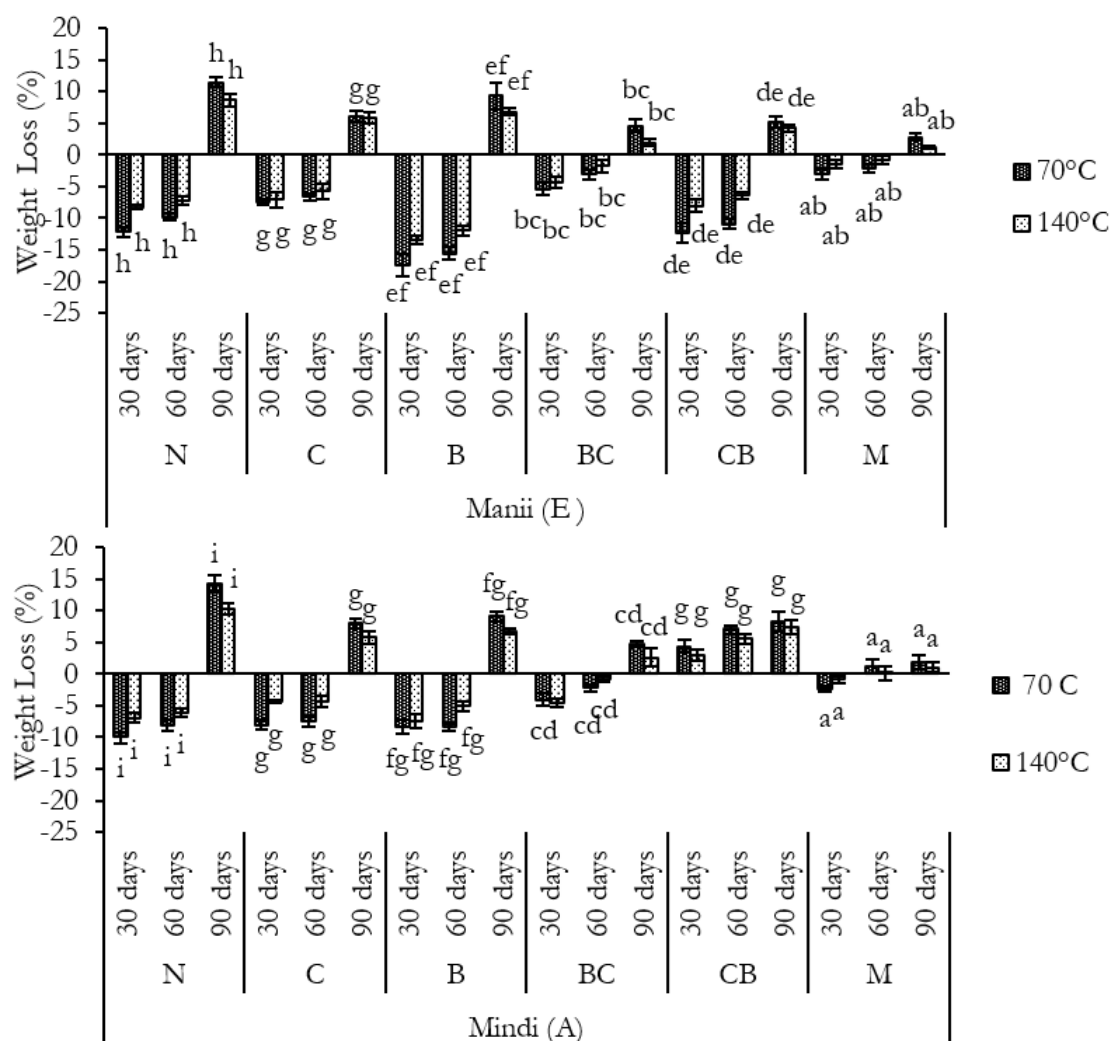


Figure 13. The weight loss after weathering of manii and mindi wood treated without impregnation (N), with boric acid (B), chitosan (C), boric acid-chitosan (BC), chitosan-boric acid (CB), mixture combination boric acid +chitosan (M), and heating temperatures (70 °C and 140 °C). Values that are not substantially different in Duncan's test are shown by the same letters (a, b, c, etc.).

The increase in wood weight during high rainfall periods is attributed to moisture uptake, while the subsequent decrease results from drying under lower rainfall conditions, reflecting dynamic moisture exchange during weathering. These environmental fluctuations may also contribute to color changes during weathering through repeated wetting–drying cycles and sunlight exposure (Krisdianto et al., 2018).

The analysis of variance revealed that weight loss was influenced by the interaction between wood species and impregnation treatment after 90 days of weathering ($F(5,96) = 10.01, p < 0.001$).

The weight loss values of M140 and BC140 were significantly lower than those of the untreated samples (N70). This reduction suggests that boric acid and chitosan acted synergistically to improve the resistance of wood to weathering and moisture-related deterioration. After 6 months of weathering, pine wood impregnated with 4% boric acid showed a weight loss of 17.67%, which was lower than that of the untreated samples (Can & Sivrikaya, 2019). In that study, the weight loss reduction was attributed to excess boron crystals remaining on the surface of the treated pine wood. Chitosan

exhibits antifungal activity due to its ability to interact with fungal cell membranes and its positively charged amino groups ($-NH_2$), which can disrupt microbial growth (Oldertroen et al., 2016). Heat treatment modifies the wood structure into a more hydrophobic form, thereby limiting water absorption and reducing biological susceptibility.

The improved performance observed in boron–chitosan heat-treated ($140\text{ }^{\circ}\text{C}$) samples compared to the control and boron-only treatments indicates enhanced protective effectiveness. Boric acid provides antifungal activity by reducing fungal-induced weight loss, while chitosan further strengthens protection through its antimicrobial properties. Heat treatment further enhances protection by increasing hydrophobicity and reducing moisture availability.

IV. CONCLUSION

Boric acid, chitosan, and heat treatments generally improved the physical properties and weathering resistance of manii (*Maesopsis eminii* Engl.) and mindi (*Melia azedarach* Linn.) woods. Chitosan treatment significantly reduced leaching, water absorption, and weight loss due to weathering compared with boric acid treatment in manii and mindi woods. Chitosan and heat treatments effectively reduced the leaching of the boron preservative, especially with the combined boric acid–chitosan mixture and $140\text{ }^{\circ}\text{C}$ heating (M140). The combination of boric acid and chitosan treatments successfully enhanced the wood's resistance to weathering more effectively than boric acid treatment. A higher concentration of boric acid was also observed in manii and mindi wood using the boric acid–chitosan mixture.

Therefore, the recommended modification treatment for manii and mindi wood is impregnation with a boric acid–chitosan mixture followed by heating at $140\text{ }^{\circ}\text{C}$ (M140). This treatment was generally better than other treatments in reducing leaching, increasing density, and significantly improving weathering resistance compared to untreated samples

of manii and mindi wood. These findings highlight the potential of boric acid–chitosan impregnation combined with heat treatment as a promising wood modification approach for fast-growing wood species and provide a basis for sustainable wood modification.

REFERENCES

- [ASTM] American Society for Testing and Materials. (1976). Standard Test Method of Testing Wood Preservatives by Laboratory Soilblock Cultures. Philadelphia (USA): American Society for Testing and Materials.
- [BMKG] Meteorology, Climatology, and Geophysical Agency. (2022) Bogor Regency Daily Climate Report for June–August (in Bahasa Indonesia). Jakarta (ID): Meteorology, Climatology, and Geophysical Agency.
- [BS] British Standard. (1957). BS 373-1957: Methods of Testing Small Clear Specimens of Timber by Royal Charter. London (UK): British Standards Institution.
- [BSN] Badan Standardisasi Nasional. (1999). Indonesian National Standard Number 01-5010.1 1999. Wood Preservation for Housing and Buildings (in Bahasa Indonesia). Jakarta (ID): National Standardization Agency.
- Barcik, S., Gasparik, M., & Razumov, E. (2015). Effect of temperature on the color changes of wood during thermal modification. *Cellulose Chemistry and Technology*, 49(9): 789–798.
- Cahyono, T., D., Lestari, M., D., & Priadi, T. (2022). Mechanical properties of Samama wood (*Anthocephalus macrophyllus*) after boron and castor bean oil impregnation and heat treatment. *International Wood Products Journal*, 13(3): 203–208. doi://10.1080/20426445.2022.2084590.
- Can, A., & Sivrikaya, H. (2019). Surface characterization of wood treated with boron compounds combined with water repellents. *Color Research & Application*, 44(3): 462–472. doi://10.1002/col.22357.
- Cao, S., Cai, J., Wu, M., Zhou, N., Huang, Z., Cai, L., & Zhang, Y. (2021). Surface properties of poplar wood after heat treatment, resin impregnation, or both modifications. *Bioresources*, 16: 7562–7577.
- Cho, W., Shields, J.R., Dubrulle, L., Wakeman, K., Bhattarai, A., Zammarano, M., Fox, D.M. (2022) Ion complexed chitosan formulations

- as effective fire-retardant coatings for wood substrates. *Polym. Degrad. Stab.* 197: 109870.
- Darmawan, W., Nandika, D., Noviyanti, E., Alipraja, I., Lumongga, D., Gardner, D., & Philippe, G. (2017). Wettability and bonding quality of exterior coating on Jabon and Sengon wood surfaces. *Journal of Coating Technology and Research*, 15: 95-104. doi://10.1007/s11998-017 9954-1.
- Demirel, G. K., Temiz, A., Jebrane, M., Terziev, N., & Gezer, E. D. (2018). Micro-distribution, water absorption, and dimensional stability of wood treated with epoxidized plant oils. *BioResources*, 13(3): 5124–5138. doi://10.15376/biores.13.3.5124-5138.
- Fauziyyah, S., Wimmer, R., Halmschlager, E., & Brischke, C. (2023). Unlocking the potential of fast-growing species from Indonesia: durability and sorption aspects. *Bois et Forêts des Tropiques*, 358: 39-52. doi://10.19182/bft2023.358.a37275.
- Fidan, M. S., & Adanur, H. (2019). Physical and mechanical properties of wood impregnated with equebracho and boron compounds. *Forestist*, 69(1): 68-80. doi://10.26650/forestist.2019.041645.
- Gokhan, G., & Denis, A. (2019). Some physical properties of heat-treated hornbeam (*Carpinus betulus* L.) wood. *Drying Technology*, 27(5): 714-720. doi://10.1080/07373930902827700.
- Hamii, N., Kędzierska, M., Wrońska, N., Katir, N., Dhainaut, J., Royer, S., Lisowska, K., Bryszewska, Milowska, K., El Kadib, A. (2023). Boron nitride embedded in chitosan hydrogel as a hydrophobic, promising metal-free, sustainable antibacterial material. *Material Advances*, 21(4): 5191-5199. doi://10.1039/d3ma00445g
- Haryanto, A., Hidayat, W., Hasanudin, U., Iryani, D. A., Kim, S., Lee, S., & Yoo, J. (2021). Valorization of Indonesian wood wastes through pyrolysis: a review. *Energies*, 14(5): 1407. doi://10.3390/en14051407.
- Herawati, E., Hartono, R., & Sinaga, H.M. (2021). Physical and mechanical properties of four wood species from community forests in Binjai Regency, North Sumatra. *IOP Conf. Series: Earth and Environmental Sciences*, 912(1): 1-6. doi://10.1088/1755-1315/912/1/012024.
- Hidayat, W., Qi, Y., Jang, J.H., Park, B.H., Banuwa, I.S., Febrianto, F., & Kim, N.H. (2017). Color change and consumer preferences towards color of heat-treated *Korean white pine* and *Royal paulownia* woods. *Journal of Korean Science Wood Technology*, 45(2): 213-222.
- Hill, C., Altgen, M., Rautkari L. (2021). Thermal modification of wood-a review: chemical changes and hygroscopicity. *Journal Material Science*, 56: 6581–6614. https://doi.org/10.1007/s10853-020-05722-z
- Istriana, N. (2024). Efektivitas Kombinasi Perlakuan Asam Borat, Kitosan, dan Pemanasan dalam Peningkatan Mutu Kayu Cepat Tumbuh. [Tesis]. Bogor (ID): Institut Pertanian Bogor.
- Istriana, N., & Priadi, T. (2021, November). The resistance of modified manii wood with boric acid and chitosan/glycerol and heating against fungi and termites. In *IOP Conference Series: Earth and Environmental Science*, 891(1):012010. IOP Publishing. doi://10.1088/1755 1315/891/1/012010.
- Kaur, G., Kainth, S., Kumar, R., Sharma, P., Pandey OP. (2021). Reaction kinetics during non-isothermal solid-state synthesis of boron trioxide via boric acid dehydration. *Reaction Kinetics, Mechanisme and Catalysis*, 134:347-359. doi://10.1007/s11144-021-02084-8
- Kim, Y., K., Kwon, G., J., Kim, A., R., Lee, H., S., Purusatama, B., Lee, S., H., Kang, C., W., & Kim N., H. (2018). Effects of heat treatment on the characteristics of royal paulownia (*Paulownia tomentosa* (Thunb.) Steud.) wood grown in Korea. *Journal of the Korean Wood Science and Technology*, 46(5): 511-526. doi://10.5658/WOOD.2018.46.5.511.
- Kim, Y.S., Kim, J.S., & Lee, K.H. (2016). Weathering characteristics of bamboo (*Phyllostachys pubescens*) exposed outdoors for one year. *Journal of Wood Science*, 10 (1): 1007-1086. doi://10.1007/s10086-016-1562-7.
- Kol, H., Ş., Keskin, S., A., & Vaydoğan, K., G. (2017). Effect of heat treatment on the mechanical properties and dimensional stability of beech wood. *Journal of Advanced Technology Sciences*, 6(3): 820-830. doi://10.5658/WOOD.2018.46.5.511.
- Krisdianto, Satiti, E.R., & Supriadi, A. (2018). Discoloration and finishing layer of five wood species due to weathering (in Bahasa Indonesia). *Jurnal Penelitian Hasil Hutan*, 36(3):205-218.
- Lestari, M. D. (2020). Sifat Fisis dan Mekanis Kayu Jabon Merah Termodifikasi Senyawa Boron dan Minyak Jarak Kepyar serta Pemanasan. [Skripsi]. Bogor(ID): Institut Pertanian Bogor.

- Muslich, M., & Rulliaty, S. (2016). Resistance of 45 types of Indonesian wood to dry-wood termites and subterranean termites (in Bahasa Indonesia). *Jurnal Penelitian Hasil Hutan*, 34(1): 51-59.
- Nowrouzi, Z., Mohebbi, B., & Younesi, H. (2014). Influences of nano-chitosan treatment on physical, mechanical properties, and bio-resistance of wood. *Journal Indian Academy Wood Science*, 11(2): 174-181.
- Oldertroen K, H-Kittikun A, Aam BB, Larnoy E. 2016a. Resistance of rubber wood (*Hevea brasiliensis*) treated with chitosan or silane against surface molds. *European Journal of Wood and Wood Products*, 75(1): 101-112. DOI: 10.1007/s00107-016-1071-9.
- Papadopoulos, A., Foti, D., & Kyzas, G. (2020). Sorption behavior of water vapor of wood treated by chitosan polymer. *European Journal of Wood and Wood Products*, 78(3): 483-491. doi://10.1007/s00107-020-01528-7.
- Patel, A.K., Michaud, P., Petit, E., de Baynast, H., Gre'diac, M., & Mathias, J.D. (2013). Development of a chitosan-based adhesive application to wood bonding. *Journal of Applied Polymer Science*, 127: 5014-5021. doi://10.1002/app.38097.
- Percin, O., Sofuoglu, S.D., Uzun, O. (2015). Effect on boron impregnation and heat treatment on mechanical properties of oak (*Quercus petraea* Liebl.) wood. *BioResource*, 10(3): 3963-3978. doi://10.15376/biores.10(3): 3963-3978.
- Priadi T, Kistia J, Khanifah I, Agustin T. 2022. The color changes in and termite and fungal resistance of modified *Maesopsis eminii* Engl. wood with boric acid and seed oil. *Forests*, 13(12):1-12. 10.3390/f13121998.
- Priadi, T., Sholihah, M., & Karlinasari, L. (2019). Water absorption and dimensional stability of heat-treated fast-growing hardwoods. *Jurnal of Korean Wood Science and Technology*, 47(5): 567-578. doi://10.5658/WOOD.2019.47.5.567.
- Sadiyo, S., Susanto, D., Pratiwi, N.E.S. (2017). Nilai kekuatan tumpu baut pada empat jenis kayu rakyat Indonesia. *Jurnal Teknik Sipil*, 24: 153-158.
- Suri, I. F., Purusatama, B. D., Lee, S. H., Kim, N. H., Hidayat, W., Ma'ruf, S. D., & Febrianto, F. (2021a). Characteristic features of the oil-heat-treated woods from tropical fast-growing wood species. *Wood Research*, 66(3): 365-378. doi://10.37763/wr.1336-4561/66.3.365378.
- Susdiyanti, T., Meiganati, K. B., Lidiawati, I., & Abiksak, A. (2023). Struktur anatomi dan sifat fisik kayu jati (*Tectona grandis* L.f.) unggul Nusantara trubusan pada umur 8 tahun. *Jurnal Hutan Lestari*, 11(1): 28-38.
- Syahrial S, Sribudiani E, Somadona S. 2022. Efektivitas pengawetan sengon menggunakan ekstrak biji mahoni dengan metode rendaman dingin terhadap serangan rayap tanah. *Journal of Forest Science Avicennia*, 5(2):159-167. 10.22219/avicennia.v5i2.21622.
- Todaro, L., Rita, A., Negro, F., Moretti, N., Saracino, A., & Zanuttini, R. (2015). Behavior of pubescent oak (*Quercus pubescens* Willd.) wood to different thermal treatments. *Forest Biogeosciences and Forestry*, 8: 748-755. doi://10.3832/for1348-007.
- Turkoglu, T., Baysal, E., Toker, H. (2015). The effect of natural weathering on color stability of impregnated and varnished wood materials. *Material Science and Engineering*, 2015: 1-9. doi://10.1155/2015/526570.
- Vachlepi, A., Suwardin, D., & Hanifarianty, S. (2015). Pengawetan kayu karet menggunakan bahan organik dengan teknik perendaman panas. *Jurnal Penelitian Karet*, 33(1): 57-64.
- Verly, L., D. J., Barnes, H. M., D.S., & Bobadilha, G. (2020). Influence of heat treatment and tannin impregnation on boron depletion and wood durability. *Forests*, 11(2): 201. doi://10.3390/f11020201.
- Vybohova, E., Kucerova, V., Andor, T., Balazova, Z., Velkova, V. (2018). The effect of heat treatment on the chemical composition of ash wood. *BioResources*, 13(4):8394-8408. DOI: 10.15376/biores.13.4.8394-8408.
- Walsh-Korb, Z., Stelzner, I., Dos Santos Gabriel, J., Eggert, G., Avérous, L. (2022). Morphological study of bio-based polymers in the consolidation of waterlogged wooden objects. *Materials*. 15: 681.
- Wei, Y., Wang, M., Zhang, P., Chen, Y., Gao, J., & Fan, Y. (2017). The role of phenolic extractives in color changes of locust wood (*Robinia pseudoacacia*) during heat treatment. *BioResources*, 12(4): 7401-7055. doi://10.15376/biores.12.4. 7041-7055.
- Winarto, F. (2014). Pengaruh Lama Pengempaan dan Konsentrasi Bahan Perikat Alami Serbuk Cangkang Kepiting Terhadap

- Sifat Papan Partikel Mahoni. [Skripsi]. Yogyakarta(ID): Universitas Gadjah Mada.
- Woźniak, M., Gromadzka, K., Kwaśniewska-Sip, P., Cofta, G., Ratajczak, I. (2022) Chitosan–caffeine formulation as an ecological preservative in wood protection. *Wood ScienceTechnology*, 56: 1851–1867.
- Yang, L., & Liu, H. (2020). Effect of a combination of moderate temperature heat treatment and subsequent wax impregnation on wood hygroscopicity, dimensional stability, and mechanical properties. *Forests*, 11:1-9. doi://10.3390/f11090920.
- Zivonic, S., Davis, R.H., & Golden, D.A. (2015). Chitosan as an antimicrobial in food products. Handbook of Natural Antimicrobials for Food Safety and Quality. Cambridge (UK): Woodhead Publishing.

REGRESSION MODEL ANALYSIS FOR DETERMINATION OF *Amyda Cartilaginea* MAXIMUM BREEDING AGE

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REGRESSION MODEL ANALYSIS FOR DETERMINATION OF *Amyda Cartilaginea* MAXIMUM BREEDING AGE. Harvest quota of Asiatic softshell turtle (*Amyda cartilaginea*) in Indonesia is the largest in the world. This has an impact on the decline in wildlife populations, given the lack of ex-situ conservation efforts and the fact that exporters prefer to take from nature. Information on the reproductive biology of the turtles is very important as a basis for conservation by estimating the speed of reproduction in order to maintain their population in nature. The purpose of this study was to determine the relationship between body weight and number of eggs on morphometric variations of the Asiatic softshell turtle (*A. cartilaginea*) as the basis for determining the maximum reproductive age. The method used is observational by measuring morphometric with Curved Carapace Length (CCL), Curved Carapace Width (CCW), Plastron Length (PL) and Plastron Width (PW) techniques. The results showed that the weight of the female ranged from 3 to 7.3 kg, CCL 20-48.4 cm, CCW 17.3-31.6 cm, PL 19.6-35.8 cm, and PW 17-34.5 cm. Weight (Y) is positively correlated with CCL (X) with the equation $Y = 4.031X + 4.1885$. The number of eggs (Y) can be estimated from Body Weight (X) with the allometric formula $Y = 0.0117 X + 2.9424$. These results indicate that the strongest correlation to the number of eggs is CCL. The age structure that produces the most eggs with good quality is from the adult age structure (CCL 35-40 cm) so that it can be recommended as a superior female for captivity.

Keywords: Asiatic softshell turtle, captive, maximum breeding age, model, regression.

ANALISIS MODEL REGRESI UNTUK PENENTUAN USIA REPRODUKTIF MAKSIMUM *Amyda Cartilaginea*. Kuota panen labi-labi (*Amyda cartilaginea*) di Indonesia merupakan yang terbesar di dunia. Hal ini berdampak pada penurunan populasi satwa liar, mengingat minimnya upaya konservasi ex-situ dan fakta bahwa eksportir lebih memilih mengambilnya dari alam. Informasi mengenai biologi reproduksi labi-labi sangat penting sebagai dasar konservasi dengan memperkirakan laju reproduksi guna menjaga kelestarian populasinya di alam. Penelitian ini bertujuan untuk mengetahui hubungan antara berat tubuh dan jumlah telur terhadap variasi morfometrik labi-labi (*A. cartilaginea*) sebagai dasar penentuan usia reproduktif optimal. Metode yang digunakan adalah observasional dengan pengukuran morfometrik menggunakan teknik Panjang Lingkar Karapas (Curved Carapace Length/CCL), Lebar Lingkar Karapas (Curved Carapace Width/CCW), Panjang Plastron (PL), dan Lebar Plastron (PW). Hasil penelitian menunjukkan bahwa berat tubuh betina berkisar antara 3 hingga 7,3 kg, dengan ukuran CCL 20–48,4 cm, CCW 17,3–31,6 cm, PL 19,6–35,8 cm, dan PW 17–34,5 cm. Berat tubuh (Y) berkorelasi positif dengan CCL (X) dengan persamaan $Y = 4,031X + 4,1885$. Jumlah telur (Y) dapat diperkirakan berdasarkan berat tubuh (X) menggunakan rumus alometrik $Y = 0,0117 X + 2,9424$. Hasil ini menunjukkan bahwa CCL memiliki korelasi terkuat dengan jumlah telur. Kelompok umur yang menghasilkan telur terbanyak dengan kualitas baik adalah kelompok umur dewasa (CCL 35–40 cm), sehingga dapat direkomendasikan sebagai induk betina unggul untuk penangkaran.

Kata kunci: *Amyda cartilaginea*, penangkaran, maximum breeding age, model, regresi

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I. INTRODUCTION

Individual growth rate and age at sexual maturity are important variables for understanding the population dynamics of a species. Currently, there is very little information and research on determining the maximum reproductive age, especially for soft-shell turtle species such as *Amyda cartilaginea*, even though this species is most widely used and traded. *A. cartilaginea* is a species of reptile that is vulnerable to illegal harvesting activities due to high demand; this can be the biggest threat to this species (Böhm et al., 2013; Lukošūtė et al., 2021). One effort that can be made to preserve animals is captive breeding. To obtain basic information about genetic quality so that the success of *A. cartilaginea* hatchlings and chicks produced is good, it can be seen from the morphometric characteristics and the number of good-quality eggs produced (Lukošiūtė et al., 2021).

Morphometrics is a study related to variations and changes in body size and is useful for knowing and describing the potential of livestock quantitatively (Takandjandji & Sawitri, 2015). Morphometric characteristics can be measured through: body weight, carapace circumference length (CCL), carapace circumference width (CCW), plastron length (PL), and plastron width (PW). According to the growth chart, the achievement of CCL is one of the main indicators of achieving optimal quality egg production when in a certain growth phase (Horvath et al., 2020). However, individual responses to feed and different environmental carrying capacities during the growth phase lead to large variations in body weight at sexual maturity.

Morphometric characteristics have a positive correlation with body weight as body measurements increase, followed by an increase in body weight (Trisnawanto et al., 2012). Likewise with reproductive success, parents with certain morphometric characteristics will produce eggs of optimum quality (Trisnawanto et al., 2012; Lukošūtė et al., 2021). The

increasing age of the mother is followed by an increase in the ovulation rate, which causes productivity to reach optimal levels and will gradually decrease as the soft shell turtle gets older (Hong, 2022). Therefore, it is necessary to know the maximum breeding age for female spiders so that it can be used as a reference to determine good reproductive quality. Maximum reproductive age is the ideal age range in which an animal can produce the most optimal offspring. Therefore, it is important to know the ideal age range for reproduction. The fertility of female turtles will decrease with age. Females who have good reproductive quality are expected to have a high percentage of egg hatching success as well. So far, the predictors for knowing the reproductive age of turtles are body weight, length of carapace circumference, and width of carapace circumference (Hanscom et al., 2020 ; Hong et al., 2022), but this information still does not answer the question of the maximum reproductive age of turtles. The growth rate of freshwater turtles is characterized by juvenile growth, which can be seen from their morphometric increase (CCL, CCW, PL, and PW). Morphometric variations can affect body weight, which also affects the maximum breeding age in soft-shell freshwater turtles (Congdon et al., 1993; Naimi, 2012).

The reproductive quality of soft-shelled freshwater turtles can be seen based on how many egg follicles are produced in one female brood (Kayani et al., 2015). Morphometrics affect body weight and the number of eggs produced by the ovum. Body weight can affect the size of the CCL, and the size of the CCL will affect the quality and quantity of eggs produced. Good egg quality and quantity are characteristics of animals that have good reproductive quality. Good reproduction will affect the growth rate, which is the basis for determining demographic parameters (Hanscom et al., 2020). One of the factors that affects the maximum breeding age is the number of eggs produced by female sires. The number of turtle eggs is related to the number of oocytes produced in the ovaries. In this

process, the quality of egg cells is determined by a group of cells called follicular cells, whose development is stimulated by follicle stimulating hormone (FSH). FSH will affect the number of eggs because the greater the number of follicular cells, the better the quantity and quality of eggs (Toelihere, 1985). Longer CCL and heavier turtle weights have more FSH, resulting in more follicles (Dinkelacker et al., 2014). Therefore, it is necessary to know body weight and CCL in relation to the number of follicles so that it can be used as one of the determining characteristics of good reproductive quality.

II. MATERIALS AND METHODS

A. Time and Location of The Study

The research has been done from November 2021 until April 2022 at the Asiatic softshell turtle collector, CV. Mutiara Sunyi Pamanukan, Subang, West Java. Besides the collector, the research is also done in its natural habitat which is Mandrapaja, Subang, and Cisaat, Sukabumi, West Java. Mandrapaja and Cisaat tributary was located in at suburban area with calm flow river and sandy mud bottom water, shallow, and

there are also rocks underneath. The location of research is shown in Figure 1.

B. Material and Devices

The object used for maximum breeding age stipulation here is 10 individuals young adult and adult Asiatic softshell turtles with CCL size 20-24.9 cm (5 individuals) and CCL > 25 cm (5 individuals). Materials and equipment used in this research are hanging scales with 50 kg maximum capacity and 1 g accuracy, digital analytic scales with 5 kg maximum capacity and 0.1 g accuracy, a sack to make the scaling process easier, measurement tape with 0.1 cm accuracy, caliper and a set of minor surgical tools, namely a scalpel and scissors. The software used in data analysis is Minitab 17.0

C. Research Method

Morphometric parameters measurement was done with the curve line method, which measure by following the curvature of the body part measured (Kusrini et al., 2014). Morphometric measured includes carapace arch length (Figure 2A), carapace arch wide (Figure 2B), plastron length (Figure 2C), plastron wide (Figure

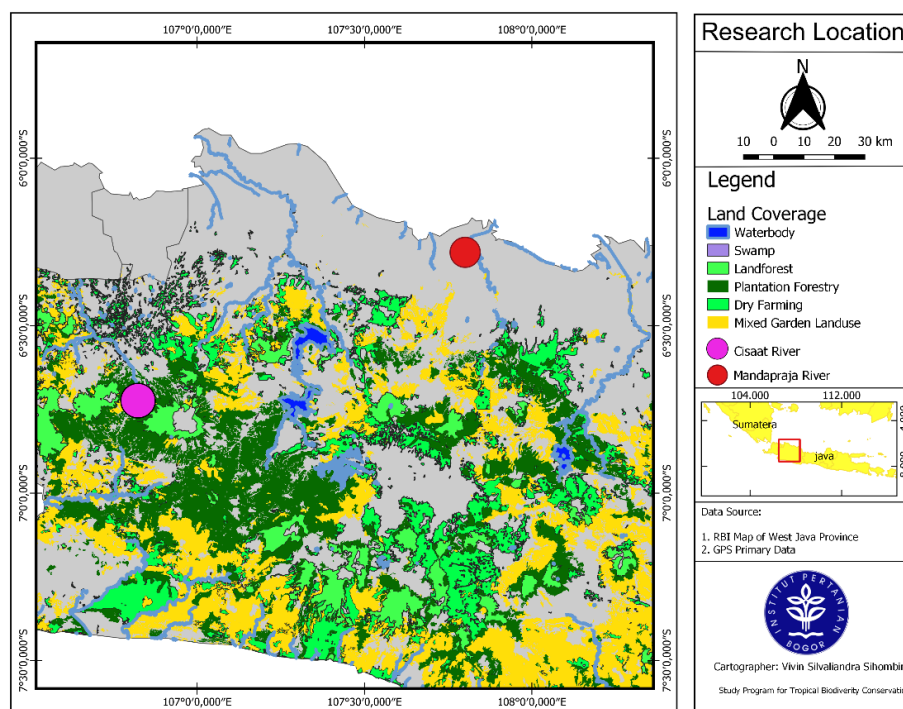


Figure 1. Map of Mandapraja and Cisaat River

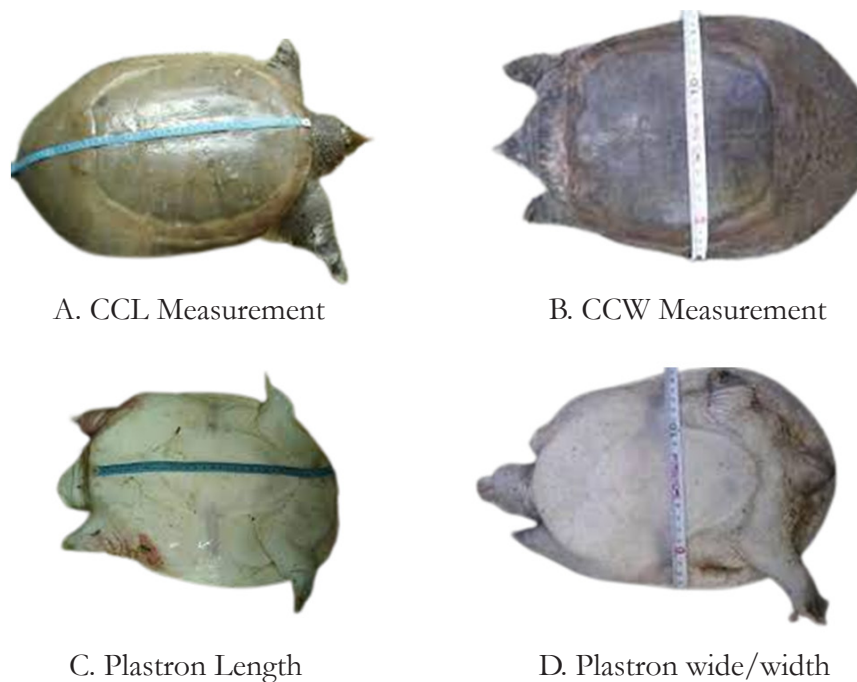


Figure 2. Morphometric parameters measurement of Asiatic softshell turtle

2D), and body weight. The Asiatic softshell turtle body mass measurement by scaling each individual obtained using a hanging scale.

Observation of the cross-section of adult male and female Asiatic softshell turtle reproductive organs and counting the number of eggs is carried out by performing surgery on young adult Asiatic softshell turtle individuals size CCL 20-24.9 cm and adult size CCL >25 cm (Kusrini et al., 2009). The Asiatic softshell turtle cut on the abdomen from anterior to posterior. The cut part is then split to open the abdomen and the eggs are counted. The eggs were grouped according to their diameter.

D. Data Analysis

Data The data that has been collected is grouped based on its age structure. Furthermore, it was analyzed according to Ghazali (2016), namely using the average difference test (t-test) to test the research hypothesis regarding the effect of each independent variable (X_1 = CCL, X_2 =CCW, X_3 = PL, and X_4 : PW) individually. partial to the dependent variable (Y: body weight). The regression test results were obtained with a 95% confidence level

and a significance level of 5% ($= 0.05$). If the significance value of the t test is 0.05, then H_0 is rejected and H_a is accepted. That is, there is an influence between body weight on CCL, CCW, PL, and PW and the number of eggs. Body weight distribution was analyzed using Minitab 17.0 software by inputting CCL and CCW data and the number of eggs in the distribution chart. The steps taken in determining the frequency distribution of CCL size and turtle body weight are to determine the maximum and minimum values of all CCL, CCW, and turtle body weight data; determine CCL and CCW from class intervals; determine the frequency class; and enter the frequency of each class of each variable. Linear regression analysis was conducted to examine the relationship between turtle body weight (independent variable) and the number of eggs laid (dependent variable).

III. RESULTS AND DISCUSSIONS

A. Adult Asiatic Softshell Turtle Morphology

Adult female Asiatic softshell turtle has longer, curvier, and wider carapace (Figure 3A)

and shorter tail (Figure 3C) rather than male adult Asiatic softshell turtle. Male adult Asiatic softshell turtle is shorter, smaller, more flat, and longer tail which protruding from the carapace (Figure 3D). The color of female carapace is blackish brown (Figure 3A), and the cloaca hole is grey (Figure 3C). Male carapace has light brown colour (Figure 3B), with pink tail base and cloaca hole is white (Figure 3D). Figure 3B, with pink tail base and cloaca hole is white (Figure 3D).

B. The Asiatic Softshell Turtle Reproduction Biology

Softshell turtle sexually reproduces and need internal fertilization (Xinping et al., 2015). After doing surgery on the male Asiatic softshell turtle which has 3kg body weight and size CCL 29.4 cm and CCW 25 cm, the reproduction consists of a couple of testicles in a round shape, smooth surface, and yellow color which means it is mature for its gender. Testicles in male Asiatic softshell turtle located on the middle wall of

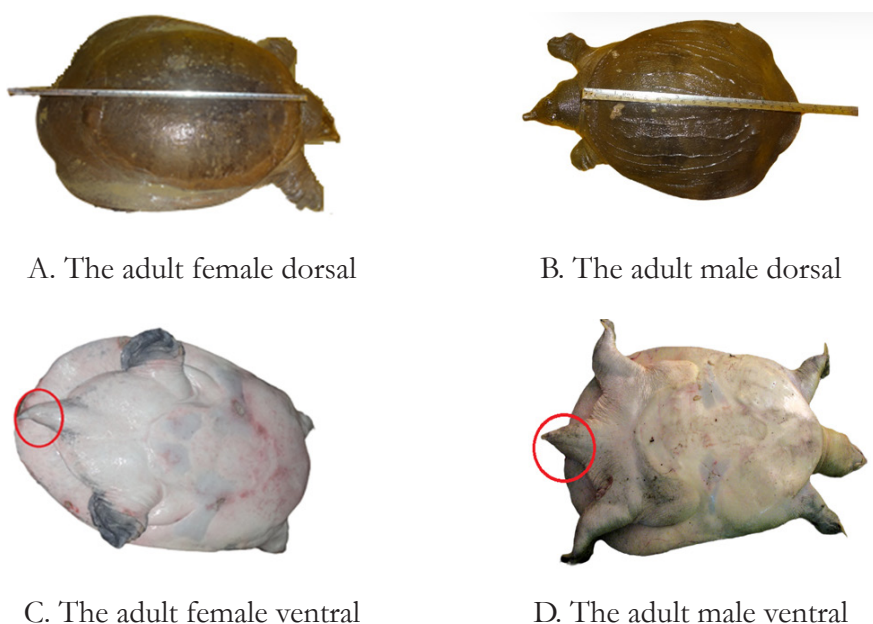


Figure 3. Asiatic softshell turtle morphology

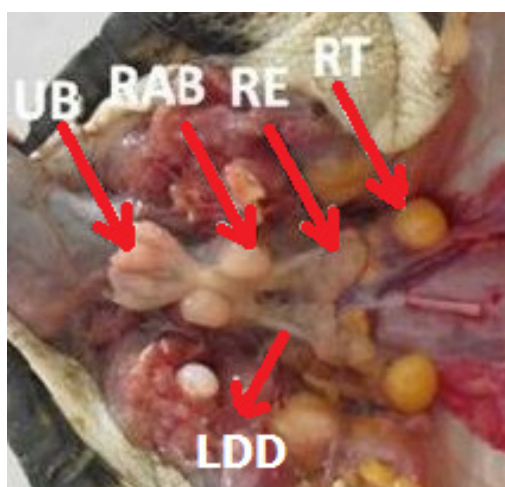


Figure 4. Male adult Asiatic softshell turtle reproduction organs. Notes: UB = urinary bladder, RAB = right accessory urinary, RE = right epididymis, RT = right testicles, LDD = left ductus deferens

the abdominal cavity (abdomen) and attached strongly. Weight for both testicles reaches 3% of the mass which is 90 g. Other than a couple of testicles, male reproduction could be seen in Figure 4. On an adult male Asiatic softshell turtle, there are a couple of ductus deferens that work to carry sperm to the penis. Testicles function to produce spermatozoa that would stream to the sperm tract to the urogenital hole. The urogenital hole is a hole where the gender and urine tract disembody, so through this urogenital hole spermatozoa would be taken out. The reproduction activity of the Asiatic softshell turtle happened by way of cloaca which also functioned to take out feces and urine. As stated by Olsson and Madsen (2006), most reptiles such as snakes and turtles have copulatory, that is the penis that is commonly pulled or inverted and put inside the body or the tail base.

Male reproduction organs and other organs that exist in the abdominal cavity of *A. cartilaginea* are covered by thick fat tissue and placed directly under the abdominal wall muscles. This fat tissue is also taken and heated up to turn into castor oil that believed could cure any disease. After the fat was taken, the male Asiatic softshell turtle's reproduction organs could be seen clearly in the abdominal cavity (Figure 8). For information, all procedures in this study were carried out by veterinarians with

attention to animal welfare and minimizing risks and discomfort, in accordance with applicable ethical guidelines and regulations.

After surgery on female adult Asiatic softshell turtle that weight 7 kg with size CCL 48.4 cm and CCW 31.6 cm, adult female Asiatic softshell turtle consists of uterus, ovarium, longitudinal formed oviduct, infundibulum, and follicle with various diameters (Figure 5). Follicles are liquid bags that contains mature oocyte to form egg cells. The sign of mature gender female Asiatic softshell turtle is follicles with diameter > 3 cm (Mumpuni & Riswanto, 2010). From the result of a research, the total eggs weight of Asiatic softshell turtle after scaling 3.150 g (45% from the Asiatic softshell turtle weight). Determination whether adult female an Asiatic softshell turtle has proper ovarium or not depends on the weight of antral follicles. If total follicles reach >40% from body weight it could be considered normal because the amount and supply of proper eggs to reproduce (Zhu et al., 2013).

Asiatic softshell turtle's ovarium is placed close to the intestines, filling two per three abdominal cavities or nearly covering organs inside the body. Ovarium functioned to produce egg cells or ovum (Kitayama et al., 2021). Furthermore, according to Lubian et al. (2025) ovum is taken out from the ovarium to the oviduct (eggs tract) which later goes to

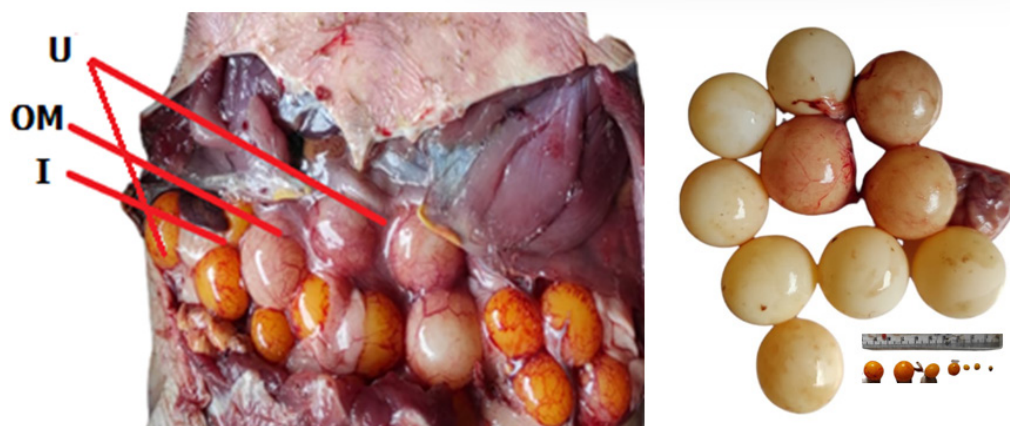


Figure 5. Adult female reproduction organs and various sizes of follicles. Notes: U = uterus, OM = ovum, I= isthmus

the infundibulum. When the ovum is mature enough, it will be collected by infundibulum, then to the oviduct, and if it is ready to fertilize it would go out through the cloaca. As the male, feces and urine are also thrown out through the cloaca

C. Morphometric Size of Asiatic Softshell Turtle

The results of morphometric data measurements on 10 individual turtles, including carapace circumference length (CCL), carapace circumference width (CCW), plastron length (PL), plastron width (PW), and body weight (BB), are presented (Table 1).

The results of morphometric data and body weight according to Kusrini et al. (2009) classified into two age categories: young adult (3.9–5 years old with 20-24.9 cm CCL) and adult (> 5 years old with >25 cm CCL). Data grouped according to weight and morphometric data to test the results of the regression equation that could determine which variables that mostly related. The result of Olukole (2014) research, for African side-neck turtle (*Pelusios castaneus*), it is considered an adult if it is have 15-25 cm CCL (1,1 – 2 years old) and the CCL is >30 cm (>3 years old).

D. Correlation Between Body Weight with Morphometric Data Asiatic Softshell Turtle

Understanding the correlation between body weight with morphometric has several important functions, including: assessing health and physical condition, this correlation can be used as an indicator of softshell turtle health. For example, if a turtle's weight does not match its carapace circumference, it could indicate a health problem or nutritional deficiency. In conservation or captive breeding programs, understanding this relationship helps determine growth standards, determine age, and identify healthy turtles optimal for reproduction. Based on this relationship, breeders and researchers can make more accurate decisions regarding food, environment, and care that support optimal turtle growth.

The results of the CCL analysis with body weight obtained positive allometric values as presented in Figure 6 and Table 2. Based on the graph, the following equation is obtained: $Y = -1.18 + 0.103X_1 + 0.112X_2$; This means that for every 1 cm increase in the length of the carapace circumference, it will increase the turtle body weight by 0.103 kg, and if there is an increase of 1 cm in the carapace circumference,

Table 1. Morphometric size of *A. cartilaginea*

No	CCL (X_1) (cm)	CCW (X_2) (cm)	PL (X_3) (cm)	PW (X_4) (cm)	BB (Y) (kg)
1	48.4	31.6	35.8	34.5	7.3
2	40.2	31.0	33.5	33.2	6.7
3	36.0	30.8	33.0	30.0	5.8
4	34.0	30.0	30.8	29.0	5.5
5	30.0	28.0	28.0	27.4	5.0
6	28.0	26.0	27.3	26.0	4.6
7	26.0	25.0	24.5	22.5	4.5
8	25.0	20.4	22.0	20.3	3.4
9	23.0	18.8	20.7	19.7	3.2
10	20.0	17.3	19.6	17.0	3.0
Average	31.06	25.9	27.52	25.96	4.9
SD	8.23	5.09	5.42	5.62	1.38

it will increase the turtle body weight by 0.112 kg. This gives an indication that the potential of aquatic resources (rivers), which are the natural habitat of the turtles, including their carrying capacity, feasibility, habitat suitability, and feed availability, is still lacking. This has implications for the condition of the turtles caught in the Mandrapaja River, which are generally rather thin when compared to the turtles in East Kalimantan. The physical condition of the turtles caught in West Java tends to be emaciated as a result of the small intake of feed required

for their feasibility to grow and develop. Other factors that make the morphology of the spiders in West Java smaller than those caught in Kalimantan are the relatively fast currents, the influx of household waste, and the heavy metal content. These factors make the waters in West Java not optimal for the optimal development and growth of turtles. The value of the correlation between body weight and morphometric data can be seen in Table 2. For graphical images of the correlation of body weight and CCL, see Figure 6.

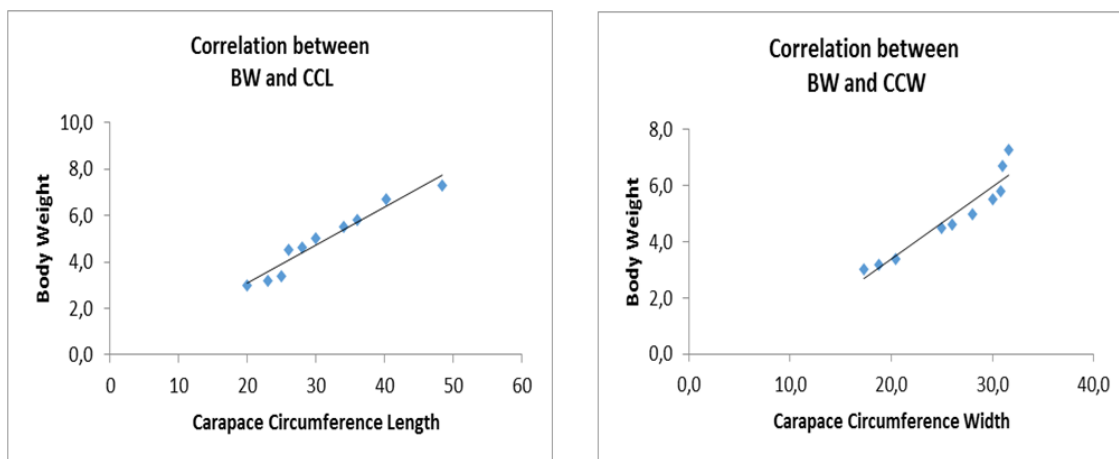


Figure 6. Weight correlation between CCL and CCW

Table 2 . The relationship between the length of the carapace circle and the width of the carapace circle on the turtle body weight

Regression Statistics				
Multiple R				0.992196284
R Square				0.984453465
Adjusted R Square				0.980011598
Standard Error				0.206391632
Observations				10

	Coefficients	Standard Error	t Stat	P-value
Intercept	-1.184851522	0.352235259	-3.363807256	0.0120216
CCL (X_1)	0.102905688	0.016805269	6.12341825	0.0004799
CCW (X_2)	0.111572068	0.027168458	4.106676546	0.0045348

Based on the results of the analysis, a multiple correlation value of 0.99 was obtained, this stated that the relationship between the length of the carapace circumference and the width of the carapace circumference on the turtle body weight was very strong (Table 2).

Based on results, P-values of 0.0005 for CCL and 0.0045 for CCW. This indicates that both variables have a statistically significant effect on the softshell turtle's body weight at the 0.05 significance level. Furthermore, since the P-value for shell circumference (X1) is lower, it can be concluded that shell circumference is the most significant predictor of the turtle's body weight. Therefore, the CCL can be used to predict the weight of a softshell turtle without the hassle of weighing the heavy turtle. Simply measuring the CCL allows us to predict the weight of a softshell turtle.

E. Correlation Between Body Weight and Eggs Number

Data on body weight and number of eggs are presented in Table 3. The relationship between body weight and the total number of turtle eggs ranged from 130 to 340 eggs per brood. Based on the results of the analysis, a correlation value of 0.8995 was obtained, which means that the correlation between turtle body weight and the number of eggs is high. The relationship between the body weight of

the turtles and the number of eggs tends to be linear (Figure 7). By using analysis of variance, the value of $P = 0.047 \pm 0.05$ was obtained, so it can be concluded that the body weight of the turtles has a significant effect on the number of eggs; it also means that the correlation between turtle body weight and the number of eggs is significant.

Based on the data above, it can be seen that those that produce the best eggs are in the CCL of 30-36 cm, which in the CCL has the most number of eggs among the others, namely as many as 288, 300, and 340 eggs.

Table 3. Correlation between Body Weight and Eggs Number

Body wight (kg)	Egg number
7.3	280
6.7	277
5.8	340
5.5	300
5.0	288
4.6	230
4.5	279
3.4	244
3.2	267
3.0	130

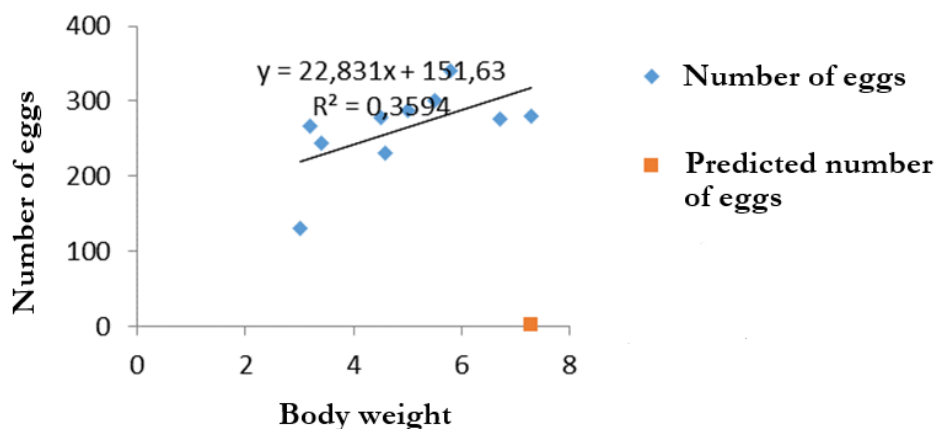


Figure 7. Correlation of body weight with number of eggs

Based on the results above, it can be concluded that the regression equation is $Y = 151.63 + 22.83X$, which states that every 1 kg increase in turtle body weight will increase the number of eggs by 23 eggs. According to the results of Olukole's (2014) research, every 1 kg increase in body weight of the African sideneck turtle (*Pelusios castaneus*) will increase the number of eggs by 15 eggs. One that affects the number of eggs is the feed. According to Swarth et al. (2013), the number of softshell turtle eggs that are fed fish and molluscs can reach 250-350 eggs per parent.

F. Correlation Between CCL Size and Asiatic Softshell Turtle Reproduction

As many as 10 females with the longest CCL were used to see how many immature eggs (eggs with <3 mm follicles), mature eggs (mature eggs that have >3 mm and have corpora lutea) such as shown in Figure 8A, and maturing eggs (eggs that have size >5 mm but clear, aqueous with defective/damaged/no egg yolk) such as shown Figure 8B. The average reproduction range and parameters of adult female Asiatic softshell turtle could be seen in (Table 4).

Relationship between morphometric parameters and average reproduction range of female adult Asiatic softshell turtle used 10 individuals with biggest CCL which i.e. range 40 - 48.4 cm could be seen in Table 4 and Figure 9. The result of CCL research affected egg production, quality, and hatching

success rate. It is because CCL is related closely to the age and gender maturing of the Asiatic softshell turtle mother. The longer the distance between the oviduct and the cloaca, the bigger and the more advance the mature egg to come out. The result of this research is in accordance with Iverson and Moler (1997) whom it stated that the increase of carapace circumference on Florida softshell turtle (*Apalone ferox*) would give a significant change to the clutch egg rate, production, eggs eight, and hatching weight.

Table 4. Female adult *A. cartilaginea* reproduction range and parameters average

Variable	N	Mean $\pm$ SD	R a n g e (scope)
CEL (mm)	10	24.65 $\pm$ 2.26	21-28.2
CEW (mm)	10	24.4 $\pm$ 2.34	21.4-27.8
CS (jumlah)	10	17.3 $\pm$ 4.93	12-27
RCS (%)	10	2.91 $\pm$ 0.49	2-3.97
EM (g)	10	0.19 $\pm$ 0.04	0.16-0.28
REM (%)	10	0.033 $\pm$ 0.003	0.03-0.04
CM (gr)	10	270.41 $\pm$ 13.98	2.8-5.6
RCM (%)	10	0.78 $\pm$ 0.091	0.65-0.92

Notes: Clutch Egg Length, CEW = Clutch Egg Width, CS = Clutch Size, RCS = Relative Clutch Size (CS/BB), EM = Egg Mass, REM = Relative Egg Mass (REM = EM/BB), CM = Clutch Mass, RCM = Relative Clutch Mass (CM/BB)

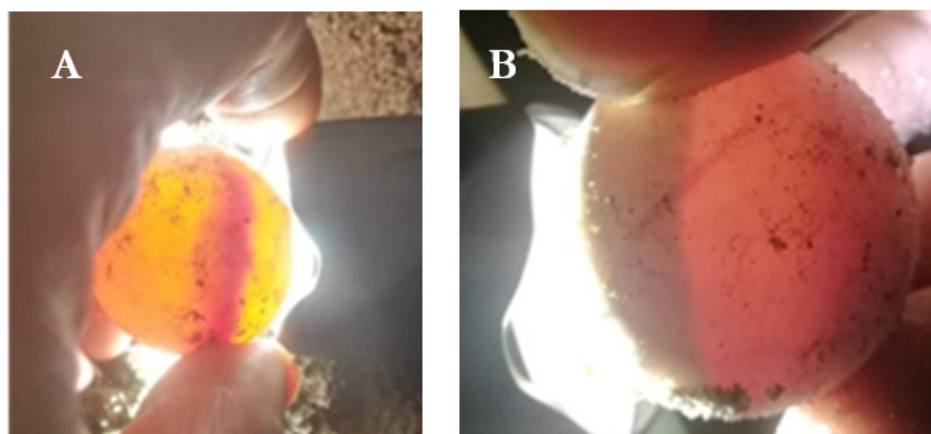


Figure 8. Mature (A) and immature egg (B) of female asiatic shoftshell turtle

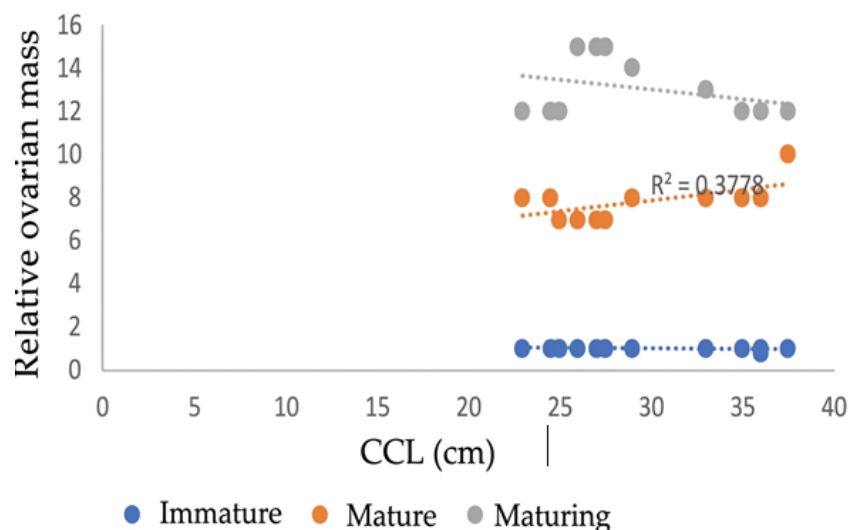


Figure 9. The relation between CCL and ovarium mass

Mature eggs' regression coefficient value is 0.377. Each addition 0.005% of maturing eggs, then mature eggs decreased by 0.377. Generally, the determination value from this equation is 74.3% which means mature eggs number are influenced by the 74.3% CCL variable, and the rest of it is affected by other variable factors such as CCW, PL, and PW ($r = 0.96$; $P < 0.0001$). Based on the result of Olukole et al. (2014) research, the number of *Pelusios castaneus* eggs could be seen from CCL, the bigger the carapace circumference, the more eggs produced.

Based on the results of the analysis above, a correlation value of -0.58 was obtained, indicating that the relationship between turtle body weight and immature egg quality was moderate and had a negative direction. Based on the results of the analysis above, a correlation value of 0.46 was obtained, indicating that the relationship between turtle body weight and mature egg quality was moderate and had a positive direction. Based on the results of the analysis above, a correlation value of 0.57 was obtained, indicating that the relationship between turtle body weight and maturing egg quality was moderate and had a positive direction. This means that the increasing weight of the turtles is followed by the decreasing number of immature eggs.

Research shows that softshell turtles can reproduce between the ages of 5 and 8 years and reach peak reproductive productivity at a specific age, usually at full maturity and maximum breeding age (around 8 to 12 years). During this age range, turtles typically exhibit optimal reproductive performance, including maximum egg production and good reproductive quality. Before reaching adulthood, egg production tends to decrease, and after a certain age, egg production can decline due to aging.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

From the result of the research for young adult and adult group Asiatic softshell turtle obtained average value, standard deviation, Asiatic softshell turtle population growth pattern coefficient analysis is positive allometric for the relation between carapace circumference length with body weight. This condition gave meaning that growth pattern length development is more dominant than biomass growth. It indicates that water resource potential especially the compatibility of habitat and the availability of food resource in the natural habitat Mandrapraja river relatively less so it implicates on the Asiatic softshell turtle

morphometric condition that generally a bit skinny. For carapace width growth pattern with body weight is also positive allometric which means the addition of body weight is faster than body width.

For correlation between CCL and egg number, it could be concluded that the size of the carapace of the Asiatic softshell turtle could be used to determine the reproductive level of the Asiatic softshell turtle. The bigger CCL the number of eggs are produced. But, the egg quality that is healthy and could be hatched well needs a mother who has 20-40 cm CCL to be a superior female Asiatic softshell turtle because on that CCL size of Asiatic softshell turtle are experiencing peak reproductive period. >40 cm CCL and weighted >7 kg produced many immature eggs which are not good for the success of hatching eggs but are in demand for consumption because of the larger egg size. According to the research result, CCL could be used as a benchmark to determine the maximum reproductive age for an Asiatic softshell turtle. Asiatic softshell turtle reproductive age based on the research result is 9-12 years old range.

B. Recommendations

The high demand for reptiles, especially freshwater turtles such as *Amyda cartilaginea* makes the Asiatic softshell turtle prone to overuse. Entrepreneurs often relied on harvests from nature to export raw materials. Harvesting has to be accompanied by preservation so that its availability in nature is not disturbed. Not all of the reproduction efforts in Asiatic softshell turtle captivity succeed, a lot of obstacles appeared and not working. To improve egg hatching success rate, the result of this research recommends using superior females with 9-12 years old age range and 3.5-6 kg weight also ideal CCL (20-40 cm). This paper could be a recommendation for entrepreneurs or trade managers in carrying out captive business as well as a guide on how to select healthy brooders that could reproduce well to save costs.

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REFERENCES

- Böhm, M., Collen, B., Baillie, J. E. M., Bowles, P., Chanson, J., Cox, N., Hammerson, G., Hoffmann, M., Livingstone, S. R., Ram, M., Rhodin, A. G. J., Stuart, S. N., van Dijk, P. P., Young, B. E., Afuang, L. E., Aghasyan, A., García, A., Aguilar, C., Ajtic, R., & Zug, G. (2013). The conservation status of the world's reptiles. *Biological Conservation*, 157, 372-385. doi:10.1016/j.biocon.2012.07.015.
- Congdon, J. D., Dunham, A. E., & van Loben Sels, R.C. (1993). Delayed sexual maturity and demographics of Blanding's turtles (*Emydoidea blandingii*): Implications for conservation and management of long-lived organisms. *Conservation Biology*, 7, 826-833. doi:10.1046/j.1523-1739.1993.740826.x
- Dinkelacker, S. A., & Hilzinger, N. L. (2014). Demographic and reproductive traits of western chicken turtles, *Deirochelys reticularia miaria*, in central Arkansas. *Journal of Herpetology*, 44, 439-444.
- Ghozali, I. (2016). *Aplikasi Analisis Multivariate Dengan Program IBM SPSS 23* (Edisi 8). Cetakan ke VIII. Semarang : Badan Penerbit Universitas Diponegoro.
- Hanscom, R. J., Dinkelacker, S. A., McCall, A., & Parlin, A. F. (2020). Demographic traits of freshwater turtles in a maritime forest habitat. *Herpetologica*, 76, 12 - 21.
- Hong, X., Zhang, X., Liu, X., Wang, Y., Yu, L., Li, W., Chen, F., & Zhu, X. (2022). Status and analysis of artificial breeding and management of

- aquatic turtles in China. *Biology*. 11: 1368. doi:10.3390/biology11091368.
- Horvath, E., Danko, S., Havaš, P., Schindler, M., Šebela, M., Halpern, B., Csibrany, B., Farkas, B., Kanuch, P., & Uhrin, M. (2020). Variation in shell morphology of the European pond turtle, *Emys orbicularis*, in fragmented central European populations. *Biol J Linn Soc.* 20: 1–14 doi:10.1093/biolinnean/blaa184/6008088
- Iverson, J. B., & Moler, P. E. (1997). The female reproductive cycle of the Florida softshell turtle (*Apalone ferox*). *Journal of Herpetology*, 31(3), 399–409. doi:10.2307/1565669.
- Kayani, B. S., Anwar, M., & Ashfaq, M. (2015). Morphometric studies of the fresh water turtles from Rawalpindi Islambabad Region of Pakistan. *Journal of Biodiversity and Environmental Sciences*, 6(5), 228–233.
- Kitayama, C., Tomiyasu, J., Bochimoto, H., Kondo, S., Tokuda, K., Ogawa, R., Okubo, S., & Kondoh, D. (2021). Histological findings of sperm storage in green turtle (*Chelonia mydas*) oviduct. *Scientific Report, Nature*, 11 (19416). doi:10.1038/s41598-021-98917-6
- Koch, A., Ives, I., Arida, E., & Iskandar, D. T. (2008). On the occurrence of the Asiatic softshell turtle, *Amyda cartilaginea* (Boddaert, 1770), on Sulawesi, Indonesia. *Hamadryad*, 33, 121 – 127.
- [KSDAE] *Buku Kuota Pengambilan Tumbuhan Alam dan Penangkapan Satwa Liar Periode Tahun 2020. 2021.* Jakarta: Kementerian Lingkungan Hidup dan Kehutanan. Annual Report.
- Kusrini, M. D., Mardiasuti, A., Mumpuni, Awal, R., Ginting, S. M., & Badiah. (2014). Asiatic soft-shell turtle *Amyda cartilaginea* in Indonesia: A review of its natural history and harvest. *Journal of Indonesian Natural History*, 2(1), 26–34.
- Kusrini, M.D., Mardiasuti, A., Darmawan, B., Mediyansyah & Muin, A. (2009). *Survey on harvest and trade of Asiatic softshell turtle Amyda cartilaginea in East Kalimantan, Indonesia.* Nata Samastha Foundation. Bogor.
- Lubian, E., Palloti, G., Dillani, F., & Vetere, A. (2025). Disorders of the female reproductive tract in Chelonians. A Review. *Animals*, 15(1275): 1-26.
- Lukošiūtė, K., Brimaitė, M., Pikūnienė, A., Krugelis, R., & Paulauskas, A. (2021). Morphometric measurements of the European pond turtle (*Emys orbicularis*) (L., 1758) in Lithuania. *Biologija*. 67(2). P. 114–121
- Lutz, D. (2005). *Tuatara: A Living Fossil*, Salem. Oregon (US): DIMI Pr.
- Mumpuni, & Riyanto A. (2010). *Harvest, Population and Natural History of SoftShell Turtle (Amyda cartilaginea) in South Sumatera, Jambi and Riau Provinces, Indonesia.* Research Center for Biology. The Indonesian Institute of Sciences (LIPI).
- Naimi, M., Znari, M., Lovich, J.E., Feddadi, Y., & Baamrane, M. A. A. (2012). Clutch and egg allometry of the turtle *Mauremys leprosa* (Chelonia: Geoemydidae) from a polluted peri-urban river in west-central Morocco. *Herpetological Journal*, 22, 43 – 49.
- Olsson, M., & Madsen, T. (2006). Sexual selection and sperm competition in reptiles. Book Chapter. Sperm Competition and Sexual Selection. Academic Press. ISBN 0-12-100543-7.
- Olukole, S. G., Matthew, O., Oyeyemi, & Bankole, O. O. (2014). Biometrical and histometrical observations on the testis and epididymis of the African sideneck turtle (*Pelusios castaneus*). *European Journal of Anatomy*. 18 (2): 102-108.
- Sihombing, V. S., Kwatrina, T. K., & Santosa, Y. (2021). Dynamics of the global trade Asiatic Softshell Turtle (*Amyda cartilaginea* Boddaert 1770): Shifting trends in commerce and consequences for sustainability. IOP Conf. Ser.: Earth Environ. Sci. 914 012003. doi:10.1088/1755-1315/914/1/012003.
- Swarth, C. W. (2004). Natural history and reproductive biology of the redbellied turtle (*Pseudemys rubriventris*). Pp. 73–83 in Conservation and Ecology of Turtles of the Mid-Atlantic Region: A Symposium (C.W.Swarth, W.M. Roosenburg, and E. Kiviat, eds.). Bibliomania, USA.
- Takandjandji, M., Gunawan, H., & Sihombing, V. S. (2018). Rapid assessment method for population estimation of softshell turtle (*Amyda cartilaginea* Boddaert, 1770) and reticulated python (*Python reticulatus* Schneider, 1801). *Biodiversitas*, 19, 265–271. doi: 10.13057/biodiv/d190136.
- Trisnawanto, R., Adiwinarti, R., & Dilaga, W. S. (2012). Hubungan antara ukuran-ukuran tubuh dengan bobot badan dombos jantan. *Anim Agric*, J 1(1): 653-668. van Dijk, P.P., Saumure, R.A., Buhlmann, K.A., Iverson, J.B., Mittermeier, R.A. (2014). Conservation biology of freshwater turtles and tortoises: A compilation project of the IUCN/SSC tortoise and freshwater turtle specialist group.

- Chelonian Research Monographs* 5(7),329–479.
doi:10.3854/crm.5.000.checklist.v7.2014.
- Xinping, Z., Xiaoyou, H., Jian, Z., Jianhua, L., & Zicheng, F. (2015). Reproduction of captive Asian giant softshell turtles, *Pelochelys cantorii*. *Chelonian Conservation and Biology*, 14(2), 143-147. doi:10.2744/CCB-1139.1.
- Zhu, A. L., Shi, Y., Zhu, X. P., Wei, C. Q., Li, W., & Duan, A. L. (2013). Effects of different temperature on embryonic de-velopment, hatchling traits and hatchling moving of *Trionyx sinensis*. *Genomics and Applied Biology*, 32, 303–307.

NATURAL RESOURCES MANAGEMENT IN INDONESIA: THEORY AND IMPLEMENTATION

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NATURAL RESOURCES MANAGEMENT IN INDONESIA: THEORY AND IMPLEMENTATION. Indonesia has abundant and valuable natural resources. Most are non-renewable, so their use should be managed sustainably. Resource use is not free from the political intervention, for example, during the national general elections, natural resources become important for financing the political activities of politicians competing in the elections. This paper reviews the political dimensions of natural resource management, particularly how natural resources function as political capital. Natural resource management (NRM) is shaped by collusion, corruption, and nepotism. As a result, natural resource wealth is not a blessing but a resource curse. Natural resource management faces a paradox, particularly in the forestry, mining, and plantation sectors. For example, in the mining sector, nickel products are exported illegally, and investors are predominantly from China. To address this situation, the government should reform its NRM laws and policies based on people prosperity approach. The three ministries (Ministry of Environment and Forestry, Ministry of Energy and Mineral Resources, and Ministry of Agriculture) related to NRM should develop best policies and regulations for the benefit and prosperity of all Indonesian people. Future research would focus on political engagement between the government official and business people, and the nepotism of appointed commissioners in state-owned companies in NRM business.

Keywords: Politics, natural resources, corruption, resource curse, prosperity.

PENGELOLAAN SUMBER DAYA ALAM DI INDONESIA: TEORI DAN IMPLEMENTASI. Indonesia memiliki kekayaan dan sumber daya alam yang berharga. Sebagian besar merupakan sumber daya tak terbarukan, oleh karena itu, pemanfaatan sumber daya tersebut harus dikelola secara berkelanjutan. Pemanfaatan sumber daya tersebut tidak lepas dari intervensi politik, misalnya, selama pemilihan umum nasional, sumber daya alam menjadi sumber daya penting untuk membiayai kegiatan politik para politisi yang berkompetisi dalam pemilihan umum. Tulisan ini bertujuan untuk meninjau aspek politik sumber daya alam sebagai modal alam utama bagi karier politik mereka. Pengelolaan sumber daya alam (SDA) diwarnai oleh kolusi, korupsi, dan nepotisme. Pengelolaan SDA juga telah mendapatkan kutukan sumber daya alam dan produk pertambangan diekspor secara ilegal. Industri pertambangan nikel didominasi oleh investor Tiongkok. Terdapat fenomena paradoks di sektor kehutanan, pertambangan, dan perkebunan. Untuk mengatasi kondisi ini, pemerintah harus merumuskan kembali undang-undang dan kebijakan SDA berdasarkan pendekatan kesejahteraan rakyat. Tiga kementerian (Kementerian Lingkungan Hidup dan Kehutanan, Kementerian Energi dan Sumber Daya Mineral, dan Kementerian Pertanian) yang terkait dengan SDA harus membuat kebijakan dan peraturan terbaik untuk kepentingan dan kesejahteraan seluruh rakyat Indonesia. Penelitian ke depan lebih difokuskan pada keterikatan secara politik antara pejabat pemerintah dan pelaku bisnis dan nepotisme dalam penunjukan komisaris BUMN di bidang pengelolaan SDA.

Kata kunci : Politik, sumberdaya alam, korupsi, kutukan sumberdaya alam, kemakmuran.

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I. INTRODUCTION

Natural resources are a major form of capital for developed and developing countries alike. However, most developing countries with abundant natural resources have poorer populations (Peluso, 1992). Various studies have shown that countries rich in natural resources are vulnerable to the resource curse. A condition where resource wealth does not directly correlate with community well-being (Auty, 2002; Murdiyarso, 2024). This phenomenon occurs because heavy dependence on natural resources is often linked to slower economic growth, limited economic diversification, corruption, and poor institutional quality (Alssadek & Benhin, 2023; Badeeb, Lean, & Clark, 2017). Furthermore, poverty in resource-rich regions is also influenced by several factors, such as conflicts over natural resources use (Murdiyarso, 2024), weak regulation and law enforcement, poor natural resource governance, and practices of corruption, collusion, and nepotism (Rahma, Fauzi, Juanda, & Widjojanto, 2021). Consequently, natural resources, which should be an instrument of development, actually trigger conflict, inequality, and environmental damage.

The existence and utilization of natural resources have caused conflicts worldwide, particularly in developing countries. Many actors are involved in the resource conflicts with different interests and power to use the resources. In Africa, such conflict tends to escalate due to competing economic and political interests (Gausset, Whyte, & Birch-Thomsen, 2005). Meanwhile, in Asia, conflicts in forestry sector have long persisted because actors have differing interests in managing scarce natural resources (Yasmi, Kelley, & Enters, 2010). This situation shows that resource conflicts are influenced not only by the diversity of actors but also by resource limitations and unclear management rights, which give rise to conflicts such as ownership conflicts, benefits distribution conflicts, and land control conflicts (Fisher, Kim, Latifah, & Mukarom,

2017; Ginsburg & Keene, 2020). When these resources are limited or management rights are unclear, tensions between actors increase and can escalate into conflict in various forms. The Agrarian Reform Consortium (KPA) reported that total agrarian conflict in Indonesia in 2023 was 241 cases in various regions, covering a total area of 638.188 hectares, located in 346 villages and involving of 135,608 households. This number of conflicts increased 12 percent compared to the number of conflict in 2022. This indicates that the implementation of agrarian reform set in 10 years has not run well (KPA, 2024).

Indonesia is known for its abundant natural resources, including marine resources, forests, oil and gas, gold, coal, silver, copper and nickel (Rahma et al., 2021; Rahman, 2016). This condition makes Indonesia a destination country for foreign capital investment, particularly in mining and forestry sectors and water resource management (Rahman, 2016). This natural resource wealth should be able to achieve public welfare, as mandated by Article 33, section (3) stated that "Earth, water and natural wealth containing in its inner part is 'owned' by the state and used it for the biggest people prosperity". The concept of "owned by the state" has been clearly defined by the decree of Constitutional Court as ownership and the mandate to regulate, manage, and oversee their use for the welfare of the people (Mawuntu, 2012; Rahman, 2016).

Essentially, the government has full authority to manage natural resources. However, natural resource governance is still weak. The issue of natural resource governance in Indonesia is also reflected in the rampant corruption and illegal exploitation in the mining and forestry sectors. Several major cases include the illegal control of forest by PT Duta Palma Group at Indragiri Hulu District, Riau Province (Yusuf, Saputro, & Kusumaningtias, 2025). Another example is the illegal exploitation and trading of nickel ore in the PT Antam concession area in the Mandiodo Block, North Konawe, Southeast Sulawesi. The case involved PT Lawu Agung

Mining and resulted in criminal convictions for corruption related to the illegal extraction and sale of nickel ore. Windu Aji Sutanto, the ultimate beneficial owner of PT Lawu Agung Mining, was ordered to pay IDR 135.84 billion in restitution (Mahkamah Agung Republik Indonesia, 2024). The case also illustrates the broader environmental and governance challenges associated with illegal nickel mining in Southeast Sulawesi, particularly in terms of regulatory oversight and enforcement. The last corruption is tin commodity trade commerce at the mining business are PT Timah Tbk in 2015-2022 in Bangka Belitung Province. (Nadefanti & Kusumawati, 2025). These cases not only cause significant state losses but also revealed weak oversight and law enforcement in natural resource management. This case also demonstrates the close relationship between economic and political interests and control of natural resources.

Beyond governance issues, political interests also shape natural resource management in Indonesia. Indonesia's natural resources are vulnerable to being used as instruments of political funding through the granting of mining and plantation permits, as well as land concessions to certain business groups. This is because natural resources are often used to fund elections and gain political power. This encourages the exploitation of natural resources oriented towards short term economic gain. These patronage relationships between political elites and business actors create conflicts of interest and weaken law enforcement. Politicians and business actors often form mutually beneficial relationships through mining and plantation permits, creating conflicts of interests, weak law enforcement, and environmental exploitation. As a result, they often overlook natural resource management goals in favor of community well-being and environmental sustainability.

Although numerous studies have examined natural resource conflicts and mining governance in Indonesia, most research focuses on legal, economic, or environmental aspects

in isolation. Research specifically analysing natural resource management through the lens of natural resource politics and its relationship to orientations toward community well-being remains relatively limited. Yet, the political dimension plays a crucial role in shaping policy direction, access distribution, and power relations in natural resource management.

Therefore, this paper would describe how do the politics of natural resource management in Indonesia influence natural resource governance and its orientation toward community well-being. This paper aims to: (i) explain the definition of politics and natural resource; (ii) identify the main principles in NRM; (iii) analyse the reality of NRM politic; and (iv) formulate a recommendation for the NRM politic based people prosperity

II. THEORY

Politics has been defined from various angles and perspectives. The *Kamus Besar Bahasa Indonesia* (KBBI) defines politic as (i) knowledge on constitutional or statehood (including governmental system and government principles); (ii) all affairs and actions (policy, strategy, and etc) concerning state government or toward other countries; (iii) a way of acting in addressing or dealing with a problem and a wisdom (KBBI IV Daring, 2016). Politics is fundamentally concerned with the distribution of power, decision-making, and resource allocation within society. Lasswell (2018) defines politics as "who gets what, when, and how," showing that politics is inseparable from the struggle over access to economic resources and political power. In the context of political economy, political decisions are always influenced by economic interests and the distribution of power among actors in society (Frieden & Lake, 2002; Leftwich, 2015). Thus, politics is not merely a normative process, but also an arena for competing interests (Leftwich, 2015).

In the context of natural resource management, politics shapes how the state,

market, and society interact to control, distribute, and utilize natural resources. Thus, natural resource management (NRM) is a political arena that brings together numerous interests and power relations (Bryant & Bailey, 1997). Recent studies further demonstrate that natural resource governance is characterized by contestation among state institutions, business actors, and local communities, particularly in resource-rich regions where competing claims over land and natural resources are prevalent (Lerip & Jauhar, 2026; Noor, Kosandi, Rahman, Emilia Yustiningrum, & Nasution, 2025; Williams & Le Billon, 2017). Although the state possesses formal authority to regulate natural resources through regulations and public policies, in practice, these policies are often influenced by specific economic and political interests (Frieden & Lake, 2002; Hidayat, Tambunan, & Haning, 2025; Meckelburg & Wardana, 2024). Therefore, natural resource management must be understood through a political economy approach, which positions natural resources as objects of competition among actors seeking access to, control over, and benefits from these resources (Frieden & Lake, 2002; Leftwich, 2015). From a political economy perspective, natural resources are viewed not only as economic assets but also as sources of strategic power that can be used to maintain political power and accumulate economic capital (Leftwich, 2015; Ross, 2013). Consequently, natural resource management often leads to unequal access, agrarian conflicts, environmental exploitation, and political rent-seeking practices (Bryant & Bailey, 1997; Peluso, 2023; Ross, 2013). Therefore, the primary problem in natural resource management lies not in resource scarcity, but rather in governance and the distribution of power over these resources (Peluso, 1992).

The political economy perspective views the control of natural resources as shaped by the interaction between political power and economic interests in the policy-making process (Frieden & Lake, 2002). In practice, these relations form state-business alliances

that enable the distribution of rights to manage natural resources through licensing mechanisms, land concessions and exploitation contracts (Asrinaldi, 2025; Hidayat et al., 2025; Meckelburg & Wardana, 2024). Ross (2013) explains that countries rich in natural resources tend to experience a concentration of economic and political power concentrated among certain elite groups. This dynamic shifts natural resource management policies toward short-term economic interests than public welfare and environmental sustainability.

This aligns with Resource Curse Theory, which argues that an abundance of natural resources does not automatically lead to prosperity or sustainable development. On the contrary, natural resource wealth often exacerbates governance issues, particularly when political institutions cannot distribute benefits in an accountable and inclusive manner. Auty (2002), the originator of the resource curse concept and Ross (2013) show that natural resource abundance often creates various challenges such as corruption, economic dependency, and weak institutions. This occurs because natural resources create rent-seeking incentives that reinforce political-economic oligarchies and reduce economic diversification. Furthermore, Collier & Hoeffler (2004) also show that dependence on natural resources can increase the risk of conflict, especially when access to resources becomes the object of competition between actors.

The Resource Curse Theory perspective suggests that the impact of natural resource abundance is heavily influenced by the quality of the institutions that manage them. Within the Institutional Theory framework, institutions are the "rules of the game" that govern how political and economic actors interact in the decision-making process and the management of natural resources (Dau, Chacar, Lyles, & Li, 2022; Hodgson, 2015; North, 1990). Therefore, the quality of these institutions determines whether natural resource wealth can be managed to generate well-being or, conversely, give rise to various governance issues. Weak institutions are

characterized by inconsistent regulations, and weak law enforcement creates opportunities for corruption, collusion, and illegal exploitation of natural resources (Robinson & Acemoglu, 2012). Conversely, strong institutions are capable of managing natural resources in a more transparent, and accountable manner, with a focus on public welfare and sustainable development. Institutional weaknesses result in the exploitation of natural resources being as a tool to maintain power, leading to an unequal distribution of the benefits derived from these resources, while social conflicts, environmental degradation, and economic inequality continue to increase (Karl, 1997). Thus, natural resource governance from an institutional perspective is also determined by the capacity of institutions to regulate the distribution of access, benefits, and accountability regarding the use of these resources.

Numerous studies have shown that resource-rich countries often experience the resource curse, a condition in which an abundance of natural resources is associated with rising corruption, dependence on the extractive sector, poor institutional quality, and poor economic and social development performance (Auty, 2002; Ross, 2013). Recent studies also indicate that the quality of institutions, governance, and state capacity are key factors determining whether natural resource wealth becomes a driver of development or, conversely, reinforces the resource curse (Ahmad, Peng, Awan, & Ahmed, 2023; Chen, Khurshid, Rauf, Yang, & Calin, 2023; Chung & Jin, 2025; Narh, 2025). Empirical evidence from various regions shows that weaknesses in governance can lead to different consequences. In Africa, for example, the exploitation of mineral and oil resources often triggers armed conflict and political power struggles due to the high economic value of natural resources (Collier & Hoeffler, 2004). In Asia, conflicts over forest and land management arise from competing interests between the state, corporations, and local communities (Yurdi Yasmi, Guernier, & Colfer, 2009). This phenomenon demonstrates

that natural resources management is an arena of political contestation influenced by distribution of power, the quality of institutions, and governance mechanisms. However, the “resource curse” is not an inevitable condition. Norway is an example of a country considered successful in managing its oil resources through strong institutions, transparent governance, and a distribution of benefits oriented towards public welfare (Mehlum, Moene, & Torvik, 2006). This comparison underscores that differences in the outcomes of natural resource management are not primarily determined by the size of resource reserves, but rather by the quality of the institutions and governance structures that regulate the relationship among the state, the market, and society.

In Indonesia, natural resource management still faces structural problems related to the quality of governance and the distribution of power. A number of studies indicate that Indonesia’s natural resources sector remains characterized by strong ties between political elites and business actors, as reflected in patronage practices and the formation of oligarchic networks in public policy decision-making (Aspinall & Berenschot, 2019; Hadiz, 2004; Robison & Hadiz, 2004). These conditions create opportunities for corruption, the misuse of permits, and the illegal and unsustainable control of natural resources, particularly in the mining and forestry sectors. Furthermore, agrarian conflicts and land disputes remain recurring issues in various regions, and particularly concerning local communities’ access to and control over natural resources (Peluso, 2023; Ribot & Peluso, 2003). Numerous cases of mining corruption and illegal land acquisition clearly illustrate that natural resource management is fraught with political and economic interests. This situation indicates that natural resource governance in Indonesia has not been fully managed for the purposes of public welfare and environmental sustainability (Hadiz, 2004).

Natural resource management can be understood as the result of the interaction

between economic and political structures, the quality of institutions, and power relations in the struggle for access to, control over, and the distribution of the benefits of natural resources. The political economy perspective emphasizes that public policy is not neutral but is influenced by power relations and interests that form alliances between political elites and business actors, which in many cases lead to patronage and oligarchy (Frieden & Lake, 2002; Hadiz, 2004; Leftwich, 2015; Robison & Hadiz, 2004). These relationships drive rent-seeking, which contributes to the “resource curse”—a condition in which an abundance of natural resources does not necessarily improve well-being but is instead associated with corruption, conflict, and weak institutions (Auty, 1993; Ross, 2013), where the impact is largely determined by the quality of institutions as mechanisms regulating resource distribution (Chen et al., 2023; Chung & Jin, 2025; Mehlum et al., 2006; North, 1990; Robinson & Acemoglu, 2012). Empirically, this situation is reflected in various cases of resource conflicts in Africa and Asia resulting from struggles over access and control (Collier & Hoeffler, 2004; Yurdi Yasmi et al., 2009), as well as in the Indonesian context through the dominance of patronage networks, oligarchies, and agrarian conflicts between the state, corporations, and local communities (Aspinall & Berenschot, 2019; Peluso, 1992; Ribot & Peluso, 2003). This shows that outcomes in natural resource management depend largely on power configurations and institutional capacity to regulate access, control, and the distribution of resource benefits.

This research argues that the main problems in natural resource management are not caused solely by the existence of natural resources themselves, but by the interaction between political power, business interests, and the quality of state institutions. Ineffective governance of natural resources can contribute to conflict, corruption, and inequality (Auty, 2002). In this context, the relationship between political elites and business actors often results

in policies biased toward certain economic interests (Frieden & Lake, 2002). Meanwhile, the quality of institutions and law enforcement are determining factors in creating transparent and equitable natural resource governance (North, 1990). This article views the politics of natural resource management as being influenced by three main factors: political power relations, the economic interests of business actors, and the quality of state institutions and governance. These factors influence the orientation of natural resource management policies and determine the extent to which natural resources can be utilized for public welfare.

In general, politic can be understood as the study of relations among citizens, between citizens and state, and among state and state or state relationship. General definition of politic is various activities in a political system including process determines objectives of the system and implementation those objectives (Budiardjo, 2013). The political activities consist of decision making, public policy, power, and authority implementation for developing collaboration and prevent or manage conflicts (Sakti, 2020). Standard definition of politic is about who get what, when, and how (Lasswell, 1963). Politic is an establishment process in community in form of decision-making process particularly in the State. This definition provides not only to a positive in the context of political solution (compromise and non-violence or descript as art of governance science), but also a negative connotation (Leftwich, 2015).

Meanwhile, Kusnendi (2014) pointed out that economists divide resources into natural resources, human resources, and man-made resources. Natural resources consist of sunshine, air, water, soil, mineral, and forest. (Chitadze, 2023) stated that general definition of natural resource is something that is available inside and outside of earth. It is still potential in nature and has not involved in production process to increase the availability of goods and services in economy. Natural resource goods in contrast, refer to natural resources that have

been extracted from within or from the surface of earth and ready to be used to meet human needs.

The use of natural resources depends mainly on the benefits of natural resource to human life. Chitadze (2023) underlined that several benefits of natural resources are (i) vegetable natural resources as materials for food, clothing, wood products, and medicines; (ii) animal natural resources as food material sources including fishery, farm, and other farming systems; and (iii) energy natural resources as energy sources for various human activities, such as electricity and fuel for vehicles, natural gas for cooking, and other daily activities. Therefore, the value of natural resources is determined by its use value for human being. For example, fertile agriculture lands can be potential agriculture areas.

Natural resources can be classified based on its origin, sustainability, and usage. Based on its origin, natural resources are divided into organic (biotic) and an-organic (abiotic) natural resources. Organic natural resources come from living materials such as coal and crude oil. An-organic natural resources are from non-living materials such tin, bauxite, iron, and natural gases. Based on its sustainability, natural resources can be divided into renewable and non-renewable resources. Renewable resource are natural resources that can be replenished naturally over time, meaning that their availability can be maintained or restored when

properly manage. Examples include air, wind, waterfall power, sunshine, flora, and fauna. Non-renewable resources are finite resources that cannot be replenished within a human time scale once they have been depleted. Examples include tin, bauxite, iron, coal and crude oil. Based on its usage, natural resources are divided into space, material, energy and biodiversity. Natural resources space are the space needed for human life (Chitadze, 2023; Kusnendi, 2014; Team Careers360, 2022).

Natural resources grouped on the basis of its use and utilization are divided into common pool resources (CPRs)/common goods and public goods. The public goods are often used for non-limited and non-rivalry goods and impossible to prevent people from using them. For example, public goods in relation to natural resources are clean air, clean and health environment. The use of CPRs is competitive related to the benefit and access toward the natural resources. The term of CPRs is introduced by Ostrom & Ostrom (1977) stating that natural resources have two characteristics, (1) jointness of use or consumption meaning that every consumption or harvesting by someone on natural resources would reduce the capacity or allotment of other persons to use (subtractable) the natural resources such a coal, oil and gases; (2) there is a cost occurring (Price) for limiting access of resources to other parties (exclusion) as shown in Table 1.

Table 1. Type of goods (Source: Ostrom & Ostrom, 1977)

		Jointness of Use or Consumption	
		Alternative	Joint
Exclusion	Feasible	Private good: bread, shoes, automobiles, haircuts, books, etc,	Toll good: theatre, nightclub. telephone service, toll road, cable TV, electric power
	Infeasible	Common pool resource: water pump from a ground water basin, fish taken from the ocean, crude oil extracted from an oil field	Public good: peace and security, national defence, mosquito abatement, fire protection, weather forecasts and “public” TV

The NRM can be reviewed based on several regulatory regimes. Based on property regime, it involves (1) property rights over natural resources consist of several forms, i.e. (i) State property where the legal claim is held by the government, such as the forest ownership and others; (ii) Private property where the legal claim is held by individual or corporation; (iii) communal property where a group of people have claimed legally on natural resources. This communal property guarantees all members of the group have the same access to the natural resources, meanwhile the other properties have different access.

In fact, common property of natural resources would disappear and diminish the local and traditional community role in natural resources ownership and management in developing countries. One of characteristics is the occurrence of natural resource ownership transformation from the customary people to the state ownership or through privatization program (private companies) by the state. However, since 2012 the Constitutional Court Decision No. 35/PUU-X/2012, the government of Indonesia has returned the customary natural resources to customary people (Subarudi, 2014)

III. METHOD

This research uses a qualitative policy analysis approach to examine the political dynamics of natural resource management in Indonesia. This approach was chosen because it explains the relationship between political actors, institutions, and governance practices in natural resource management (Creswell & Poth, 2016). The research focuses on how political interests, institutional arrangements, and the roles of business actors influence natural resource management and its impact on community welfare. The unit of analysis in this study includes state policies and governance practices related to the mining, forestry, and land management sectors.

This research utilizes secondary data obtained through a literature review. The literature study method was used to collect and analyse various documents and data relevant to the research topic (Johnston, 2014). The data sources used include: (1) laws and government regulations related to natural resource management; (2) official reports from state institutions and anti-corruption agencies; (3) reports on agrarian conflicts; (4) publication statistics; (5) scientific journal articles and books; and (6) documentation of corruption and illegal theft cases published by authorized institutions. To ensure data validity and reliability, this study prioritized credible sources, such as peer-reviewed academic publications, official government documents, court decisions, and reports from trusted institutions (Yin, 2018).

In the analysis process, this study employed content analysis techniques to explain the substance of laws, regulations, and policy documents related to natural resource governance. Content analysis was conducted to identify how state policies regulate access to, control over, and distribution of natural resources, as well as the positions of political and economic actors within these governance structures (Bungin, 2001; Krippendorff, 2018). Furthermore, this study employed a qualitative case study approach to examine several cases of corruption and natural resource conflicts in Indonesia. The case study approach was chosen because it provides a deeper understanding of complex governance phenomena within their real-life political and institutional contexts (Yin, 2018).

The analysis phase involved data collection, data classification, content interpretation, and thematic analysis. The primary focus of the analysis was on identifying patterns of political influence, institutional weaknesses, and various governance issues in natural resource management. This research does not aim to make broad causal generalizations about structural corruption or political financing;

rather, it analytically examines indications of political-economic relationships reflected in policy implementation, licensing practices, and various corruption cases in the natural resource sector.

In the final stage, the research findings are interpreted descriptively and analytically using Resource Curse Theory, Political Economy Theory, and Institutional Theory. These three theoretical approaches are used to explain the relationship between political power, institutional quality, business interests, and natural resource governance in Indonesia (Auty, 2002; North, 1990; Ross, 2013)

IV. RESULT AND DISCUSSION

In recent decades, concerns about human rights, environmental sustainability, democracy, and social justice have influenced approaches to NRM. Accordingly, the perspectives of governmental and non-governmental organization in both developed and developing countries regarding natural resource and environment management has also changed. NRM is no longer viewed solely as an economic instrument, but as part of governance related to environmental protection, social welfare, and democratic accountability (Nurjaya, 2022).

Sustainable natural resource governance is based on three principles: justice, democracy and sustainability. Principle of justice refers to the policy on NRM has to be planned, implemented, monitored and evaluated in a sustainable way, not only to safeguard the sustainability and continuity of natural resource and environmental functions, but also to ensure the interests of present and future generations, intergenerational and intragenerational equity, and gender equality. However, in practice, unequal access to land, forests, and mining concessions often benefits political and economic elites and marginalizes local communities.

The principle of democracy in natural resource management are based on transparency, public participation, decentralization, accountability,

and the recognition and protection of community rights (Ribot & Larson, 2005). Democratic principles imply that natural resource and environmental management policies must accommodate the management authorities between central and local, ensure community access to information on NRM, multi-stakeholder participation, transparency, non-discrimination, public accountability, coordination and integrated among sectors, wisely conflict resolution, and protection of human rights and acknowledgement of legal pluralism in NRM. However, in many developing countries, including Indonesia, natural resource governance is often centralized and dominated by state and business interests, while limiting public participation.

The principle of sustainability in NRM must ensure sustainable function and benefits, both for state and community benefits in a balance and proportional way and for present and next generation benefits in sustainable way. The principle of sustainability requires that natural resource utilization balance economic benefits with long-term ecological and environmental protection (Brundtland, 1987). Therefore, sustainable governance requires institutional capacity, environmental oversight, and effective law enforcement.

In order to confirm with the three main principles, Corruption Eradication Commission (KPK) initiated the National Rescue Movement of Natural Resources (Gerakan Penyelamatan Nasional Sumber Daya Alam-GNPSDA), which was implemented over five years. The focus development of the movement is to expand the definition and meaning of corruption in the more contextual, particularly corruption in natural resource sector. In the long run, corruption problem in natural resource sector can be understood not merely as the problems of corrupt actors, but also as a governance problem involving the failure to implement regulations, weak law enforcement, and the ineffective of the state's role. Corruption is frequently understood as the use of public resources for private interests or

personal enrichment through various means. It does not work of state role, weak law order and enforcement, so that this has detrimental to state interest (KPK, 2018). This perspective argues that weak institutions and poor governance structures create opportunities for rent-seeking and corrupt behaviour (North, 1990).

Reality of NRM Politic

Politic of NRM as written in national constitution (UUD 1945) is really different with its implementation in the field. This would be summarized as shown in Table 2.

Table 2. Reality of NRM politics, causing factors and its chosen strategies

No.	Reality of NRM Politics	Causing Factors	Strategies to Cope It	Evidences
1.	NRM is dominated by resource-extraction orientation, with limited attention to conservation and sustainability. More attention on resources use-orientation and ignores the interests of conservation and sustainability of its resource function. It neglects access and interests of potential customary and local community economy	Dominance of extractive-growth paradigm; weak integration of ecological and social consideration; marginalization of local and customary communities. NRM is an instrument to increase national economic growth, state revenue and foreign exchange to attract a big capital orientation. NRM is implemented as a state-based resource management with centralistic orientation and sectoral approach.	NRM implementation should be integrated with ecology system and community based NRM	Syamsiyah, Sadeli, Saidah, Noor, & Widiyanesti (2025). "Community Participation in the Development of Sustainable, Environmentally Conscious Villages in the Cirasea Sub-Watershed, Indonesia." <i>Sustainability</i> , 17(11), 4871; Natan, Tetelepta, Pattikawa, & Ongkers (2021). "Incorporating Ecological, Socio-economic and Institutional Frameworks for Sustainable Mud Crab Fishery Management in Indonesia." <i>Environment and Natural Resources Journal</i> , 19(3), 207–219; "A Review on Sustainability of Watershed Management in Indonesia." <i>Sustainability</i> , 13(19), 11125.
2.	NRM is implemented by the free perception of state bureaucrats	Lack of law politic on natural resource utilization. Law politic of NRM is incompatible with national constitution.	Strengthening constitutional review mechanisms and the role of the Constitutional Court; The constitutional court (Mahkamah Konstitusi-MK) is to guard constitution (Mahfud MD, 2010). MK is giving (final) interpretation toward constitution (Redi, 2015).	Mahfud (2009). <i>Konstitusi dan Hukum dalam Kontroversi Isu</i> . Jakarta: Rajawali Press; (Asshiddiqie, 2021). <i>Konstitusi dan Konstitusionalisme Indonesia</i> . Jakarta: Sinar Grafika; (Rahman, 2016). "Politik Hukum Sumber Daya Alam Pasca Putusan Mahkamah Konstitusi." <i>Jurnal Konstitusi</i> , 13(3), 455–478

No.	Reality of NRM Politics	Causing Factors	Strategies to Cope It	Evidences
			MK Decisions related to NRM become law politics and a guidance for the law makers (Rahman, 2016).	
3.	Weak law instrument of natural resources has impacted toward: (i) natural resource curse; (ii) strong relationship between natural resource exploitation and general or local head election; and (iii) paradoxical NRM.	Lack of good governance on NRM implementation so that it creates natural resource curse The economic growth depends mainly on extractive economy	Strengthening good governance and transparency; The good government should be applied to prevent the natural resource curse and corruption in natural resource trading.	Rosser (2007). "Escaping the Resource Curse: The Case of Indonesia." <i>Journal of Contemporary Asia</i> , 37(1), 38–58; McCarthy (2007). "Shifting Resource Entitlements and Governance Reform During the Agrarian Transition in Sumatra." <i>The Journal of Legal Pluralism</i> , 55, 95–121; EITI Indonesia Reports, Ministry of Energy and Mineral Resources.
4	There is a strong relationship between natural resource exploitation and political year and general or local head elections. For example, when time approaching to political year, many licenses of NRM is clearance sold.	High cost of politics; Monetization of resource licenses; Patronage-based politics; This is caused by high political cost in Indonesia and many efforts would be realized to obtain the cost. For examples the cost to be head of district or province is ranging Rp. 20-100 billion (KPK, 2015) and to be central parliament members is around Rp 6 billion (KPK, 2015). The easiest way to get the cost from the giving licenses and exploitation of natural resources abundantly.	Reforming political financing and improving licensing transparency; Government of Indonesia (GoI) should give a political budget to political parties. The existing political budget from GoI should be increased proportionally The community should be well educated for avoiding money politic during the election period	Setiawan & Widyana (2022) High-cost democracy: stimulus ijon politik dalam pemilu lokal di region kaya sumber daya alam; Balboni, Burgess, Heil, Old, & Olken (2021) Cycles of Fire? Politics and Forest Burning in Indonesia.. "Mahalnya Ongkos Politik Pilkada." (KPK, 2015)
5.	Resource-rich sectors show paradoxical outcomes: high resource endowment but low economic contribution. Paradoxical NRM occurs in forestry, mining, and crop estate sectors. For example,	An incompetent policy on NRM. An inefficient wood industry A corruption in NRM is still unsolved and tend to increase.	Policy reform and anti-corruption enforcement in natural resource sectors; Implementation of policies on NRM should focus on the greatest prosperity	Antaranews (2022) GDP contribution of forestry only 0.66%: minister. Delfirman & Dzaki (2025). Shifts in the control of natural resources: An analysis of the resource curse in Tin-Rich Bangka Belitung

No.	Reality of NRM Politics	Causing Factors	Strategies to Cope It	Evidences
	according to the Finance Minister statement that the contribution from forestry sector to the GDP is less than 1 percent, it only reached Rp 112 trillion (AntaraneWS, 2022). In Bangka Belitung, mining activities have led to environmental degradation (Delfirman & Dzaki, 2025), while in Jambi the expansion of monoculture plantation crops become one of the factors causing deforestation (Rustiadi et al., 2018).		of Indonesia people. Corruption eradication should be main priority for the new government. Sasongko, Mizuno, Utomo, & Koestoer (2024), highlight that the Environmental Impact Assessment is potential to help the corruption cases investigation, and the government needs to reformulate the law enforcement with this approach.	Rustiadi et al.. (2018). Land use and spatial policy conflicts in a rich-biodiversity rain forest region: The case of Jambi Province. Sasongko et al., (2024). EIA in Strengthening Law Enforcement and Penalties: A Case of Corruption in Natural Resource Sector
6.	Illegal mining and oil palm plantation frequently occur within forest areas At present, the palm oil estate in forest area of 3.3 million ha would be legally solved through a whitening.	Overlapping regulations; weak enforcement; institutional fragmentation; The forest area become location for illegal business practices of crop estate (8.4 million ha) and mining (8.7 million ha) with state loss of thousand trillion rupiah (Tempo.co, 2021).	Cross-ministerial policy harmonization and stronger law enforcement; The best solution for the whitening of palm oil estate is the same perspective of whitening between the MoEF and the Ministry Coordination of Marine and Investment.	Tempo.co (2021). “8,4 Juta Hektare Kebun Sawit di Kawasan Hutan”; Mardela et al., (2023), “Penyelesaian Sawit dalam Kawasan Hutan”; (Tuk-Indonesia, 2023) “Sinkronisasi Kebijakan Pemutihan Sawit.
7.	Delayed implementation of mineral downstream has generated economic efficiencies; Resistance to conduct mining downstream one year after its issuance of the Law No. 4/2009. After 15 years, the government is eager to implement mining downstream again with high economic loss during 15 years cancelation.	Weak law enforcement on implementation of mining downstream. Audit Board of Indonesia (BPK) has not calculated the loss yet	Law enforcement strengthening in implementation of mining downstream; BPK should calculate the loss properly	Law No. 4/2009 on Mineral and Coal Mining; reports from Badan Pemeriksa Keuangan (BPK); Haryadi, H. (2021). “Hilirisasi Mineral dan Tantangannya di Indonesia.” <i>Jurnal Ekonomi dan Kebijakan Publik</i> , 12(1), 45–60.
8.	Mining policy reforms generate social conflict and criminalization of local resistance;	Pro-investor regulatory bias; elite dominance in policymaking;	Judicial review and stronger civil society participation;	WALHI (2025) Siaran Pers WALHI. Revisi UU Minerba: Langkah Mundur Pengelolaan

No.	Reality of NRM Politics	Causing Factors	Strategies to Cope It	Evidences
	The new mining law (No. 1/2019) is more liberal than the Law No. 4/2009, The new regulation will proceed communities refusing the mining license into the court as criminals	Most of parliament members are the businessmen. The businessmen think the community protest is disturbance of their mining business	The civil society should conduct the judicial review of Law No. 1/2019 to MK	Sektor Pertambangan di Indonesia; Dewi (2025) Juridical Analysis of the Effectiveness of Law Enforcement in Handling Nickel Mining Violations in North Maluku: Dispute Cases Between Companies and Affected Communities; Natsir, Ilahi, & Adnas (2024) Political and legal developments in mineral and coal mining laws: A critical review ; Syeirazi (2021) Resentralisasi Negara: Catatan Kritis atas UU No. 3/2020 tentang Minerba
9.	There is a disparity between the economic benefits promised through nickel downstreaming and the distribution of benefits received by local communities. While investment and industrialization generate value-added and profits for industry players, local communities instead face the loss of livelihoods, land dispossession, and the burden of environmental pollution. (Yusman, Ikhsan, & Papuling, 2024).	The dominance of Chinese investment in nickel mining has led to both hopeful and reactions among Indonesians, and it concerns about economic sovereignty and dependency (Riyanto et al., 2025) Weak monitoring and evaluation system of nickel export activities Resource dependency; Foreign capital dominance	Strengthening export monitoring and regulatory oversight; The domination of China in nickel should be reduced by new policy Applying the good monitoring and evaluation system	Riyanto et al. (2025)“Various visions of the industrialized future: anxiety, aspiration, and Chinese nickel investment in Indonesia”. Yusman et al. (2024). “Karut Marut Investasi Nikel Tiongkok di Sulawesi Tengah dalam Konteks Perburuhan“
10.	Large-scale corruption cases occur in the mining sector (e.g., PT Timah case) The totals state loss is Rp 300 trillion from PT Timah consisting of Rp 271 trillion (environmental destruction loss) and of Rp 29,499 trillion (excessive payment of smelter rental cost	Weak governance; Elite capture; Illegal mining network; The massive corruption scandal involving the tin trade, valued at IDR 300 trillion, exemplifies a form of natural resource management that constitutes a fundamental violation of Pancasila values and	Establishment of a Task Force for illegal mining. Law enforcement strengthening in good mining governance and corruption prevention.	Ricky Fairuz Julio & Sri Isnani Setyaningsih, (2025) “Mega Korupsi Tata Niaga Timah Rp 300 Triliun: Analisis Pelanggaran Prinsip Pancasila Dan Etika Tata Kelola Dalam Pengelolaan Sumber Daya Alam”

No.	Reality of NRM Politics	Causing Factors	Strategies to Cope It	Evidences
	and payment of illegal tin ore to its business partnerships).	the principles of good governance (Julio & Setyaningsih, 2025).		
11.	Mining policy revisions granting licenses to mass organizations raise governance concerns; Newest issue of mining policy is the revision of government regulation (PP) No. 96 Year 2021 into PP No 25 Year 2024 that offers specific mining business license to religious mass organizations. However, this policy is not equipped with principles of justice, democracy, participation, and transparency in natural resource and environment management in Indonesia (Nurjaya, 2022).	Rent-seeking politics; Weak transparency; Policy populism; The main reason for new policy is for increasing community prosperity. This policy also triggers social conflict in its field implementation due to incapability of religious organization	Policy review and strengthening governance principles (Transparency, Participatory, accountability); This new policy should be reviewed totally. In fact, there is internal conflict in Nahdlatul Ulama (NU) Management due to the no transparency of money received from its mining business.	Nurjaya (2022). <i>Politik Hukum Pengelolaan SDA dan Lingkungan Hidup</i> ; Government Regulation No. 25/2024; reports on internal conflict within Nahdlatul Ulama (NU) regarding mining revenues.
12.	Oil palm expansion contributes to deforestation and land conflicts Paradox in estate sector especially palm oil estates area increased significantly for the last ten years with rate of 1 million ha per year as recorded and remarked in the Ministry of Agriculture (MoA).	Weak land governance; Illegal land occupation; Regulatory failure; Recent policy changes address illegal occupation by replacing criminal sanctions with administrative penalties, aiming to legalize unlicensed plantations and improve compliance and environmental responsibility (Maskun, Violetta, Mukhlis, Normiati, & Tajudin, 2025)	Strong enforcement and protection of forest zones; The Ministry of Forestry must keep its forest area intensively. The GoI should fine or conduct a law process the illegal oil palm plantations fairly.	Ministry of Agriculture statistics on oil palm expansion; (Maskun et al. (2025), “The Dilemma of Administrative Sanctions in Legalizing Palm Oil Plantations in Indonesian Forest Areas”
13.	NRM remains fragmented across ecological, social, and economic dimensions	Sectoral governance approach; Lack of policy integration;	Integrated sustainable NRM and stronger state-research collaboration;	Natan et al. (2021; Syamsiyah et al.. (2025)

No.	Reality of NRM Politics	Causing Factors	Strategies to Cope It	Evidences
	In practice, efforts to support sustainable NRM has many dimensions and perspectives that is not only to discuss the technical aspects of exploitation or production and ecology, but also socio-economic aspects.	Lack of policy integration; Indonesia has not posed the integrated evolution system (management, technical and socio-economic dimensions) for sustainable NRM.	The GoI should implement sustainable NRM practices effectively. It also needs good collaboration between GoI and researchers for developing the technical management and environmental sound operation aspects to achieve the sustainable NRM.	

Table 2 indicated the political realities of NRM in Indonesia. The research findings identify various governance issues, such as corrupt practices, weak law enforcement, overlapping regulations, ineffective oversight, political intervention and suboptimal policy implementation on the ground. These issues indicate that natural resource governance remains oriented toward extractive economic growth rather than ecological sustainability and social welfare. Therefore, these issues must be understood not merely as administrative failures, but as a reflection of structural weaknesses in Indonesia's natural resource management system.

Based on the Resource Curse Theory, these findings indicate that Indonesia continues to experience the natural resource curse, a situation in which an abundance of natural resources fails to contribute to the people's well-being due to weak governing institutions (Auty, 2002; Ross, 2013). Weak governance creates opportunities for political and economic actors to control resource rents through patronage, rent-seeking, and elite capture. As a result, natural resource wealth becomes closely linked to increased corruption, environmental degradation, social conflict, and unequal distribution of resource benefits. This interpretation is supported by the finding of Rahma et al. (2021) who pointed out that phenomenon of natural resource curse in the

area development in Indonesia as follows: (i) the higher local revenues from mining do not guarantee the realization of massive sustainable development; (ii) local government did natural resource extraction is vulnerable to natural resource curse; (iii) local government depend mainly on oil and gasses is more vulnerable to the natural resource than the local producing mineral and coal; and (iv) Scoring of local with high sustainability score tends to low or far away from natural resource curse phenomena. Five provinces with abundant natural resources have highest NRC scores, namely as East Kalimantan (16.6), West Papua (15.2), Papua (13.6), Riau (12.0) and Aceh (11.4)-have the highest NRC scores, indicating that reliance on natural resources alone cannot generate prosperity without the support of strong institutions.

The research findings support Institutional Theory, which asserts that institutions determine how political and economic actors interact through a set of rules (North, 1990). When regulatory institution is weak, law enforcement becomes inconsistent, accountability declines, and likelihood of elite capture and rent-seeking increase. Thus, governance failure serves as a primary mechanism linking the abundance of natural resources to corruption, unequal distribution benefits, and poor-quality development. Consequently, corruption in the natural resources sector cannot be viewed merely as

individual misconduct but rather as a form of systematic institutional failure. The biggest mining corruption case involving PT Timah – which is still under legal proceedings and has resulted in a total state loss of Rp 300 trillion. However, the biggest estate corruption in PT Duta Palma Group with the illegal area of 23,692 ha. The owner was charged by 15 years in prison and pay a replacement money of Rp 2.23 billion and a state financial loss of Rp 39.7 billion. However, in cassation level the Supreme Court add 1 year in prison, but he pays only replacement money (Rp 2.23 billion) and the state financial loss (Rp 39.7 billion) is eliminated (Yusuf et al., 2025).

Corruption in the mining, forestry, and plantation sectors provides clear evidence that governance issues are structural. The corruption cases at PT Timah and the illegal plantation at PT Duta Palma illustrate how business actors exploit regulatory loopholes and political connections for economic gain. These cases represent systemic corruption involving political, economic, and bureaucratic actors (KPK, 2018). Institutional weaknesses create opportunities for regulatory manipulation, illegal licensing, and environmental crimes (North, 1990; Robinson & Acemoglu, 2012). Weak oversight systems, overlapping regulations, and inconsistent law enforcement reduce the state's capacity to effectively control exploitation activities. As a result, natural resource governance is vulnerable to elite domination and corruption.

Clear evidence of institutional weakness is evident in nickel mining governance. Despite downstream industrialization policies, Indonesia continues to face illegal exports, weak oversight, and foreign domination in the downstream industry. This demonstrates that strong institutional capacity and transparent governance must align with downstream industrial policies.

According to the KPK (2018), the corruption in natural resource sector can be indicated by a small actor group (private or organization) through alternative institution

(pseudo legal) supported by extensive networks and strong control over social, economy and politic. Through these networks, actors are able to obtain various benefits (economy – politic) in systemically ways. This type of corruption is closer to the structural corruption definition than the institutional corruption type. This corruption can be understood as a network offering or transaction among individuals running systematically, with the involvement of trust, betrayal, cheating, subordination for certain interest, confidentiality, several parties' engagement, and symbiotic mutualism for the actors. Corruption, of course, does not happen due to mal-function of state agency implementing regulations as legal institution. However, it is due to the existing of alternative institution focusing on private/group interests that compete with legal institution for gaining legitimation and trust from various actors both in state agencies and wider communities.

Ineffective NRM policy implementation is indicated by involving the religious mass organization to hold mining license. The revision of regulations and the issuance of policies to grant mining concessions to mass religious organizations illustrate the ways in which politics influences resource governance. Murdiyarso (2024) pointed out that this new policy creates controversy in community due to technical reason and lack of capacity for mining concession receiver. The revision of regulations and the issuance of policies to grant mining concessions to mass religious organizations illustrate the ways in which politics influences resource governance. This situation is worsened by the difficulty level of mining business and its impacts produced, and is also prone to conflict of interest. The main problem of the religious organization has not a business unit and lack of human resource capacity and capital. This policy is similar to HPH mini (local community has been given 100 ha of concession area), where the community has only obtained a fee commission from the logging company and has not recorded how much trees harvested by the contractors. In addition, the small-scale units of mining

have serious problems with the environment destruction and many children died due to swimming in the mine holes that are not covered after mining exploitation. These conditions increase the risk of elite control, environmental damage, and conflicts of interest.

This study demonstrates the close relationship between political interests, business actors, and natural resource exploitation. Natural resource licenses are often used as political and economic tools in elections. Mining, plantation, and forestry concessions are also frequently linked to political financing and patronage networks between politicians and business actors. This suggests that state policy is often shaped by the interaction of political power and economic interests (Frieden & Lake, 2015). In Indonesia, high electoral costs encourage political actors to seek financial support from resource-based businesses. As a result, the licensing process in the mining and plantation sectors is vulnerable to corruption, rent-seeking, and regulatory control.

In the renewable resource sector, governance issues are closely linked to land conversion, illegal occupation of forest areas, and agrarian conflicts. The expansion of oil palm plantations drives deforestation and land disputes involving corporations, local communities, and indigenous peoples. The government's efforts to address illegal plantations through legalization policies and land settlements tend to be unbalanced. The government tends to prioritize economics over environmental sustainability and social justice. As a result, law enforcement in natural resource management is weak, and recognition of community-based resource management is limited. This situation demonstrates that environmental degradation in developing countries is closely linked to unequal power relations and resource control (Bryant & Bailey, 1997).

In the non-renewable natural resource sector, governance issues are closely linked to economic dependence on extractives, corruption, and weak oversight systems. Downstream mining policies have not provided economic justice for

local communities. Instead, economic profits tend to be concentrated among large companies and political-business networks. Illegal mining activities, smuggling, environmental destruction, and weak post-mining rehabilitation reflect the failure of governance in the extractive sector. This demonstrates the extractive resource curse, which often weakens institutional accountability and encourages rent-seeking behaviour (Karl, 1997; Ross, 2013).

Overall, this study shows that natural resource governance in Indonesia still exhibits various characteristics of the 'resource curse'. The findings of this study confirm that governance failures are the primary mechanism linking political interests, rent-seeking by elites, and the unsustainable exploitation of natural resources. Therefore, sustainable natural resource management requires effective regulatory and governance reform. Effective governance depends heavily on strengthening institutions, increasing transparency, public participation, and integrating ecological and socio-economic considerations into policy implementation. An integrated evaluation system for NRM is really required to support the achievement of sustainable NRM. This evaluation involves monitoring of technical, ecological, and also socio-economical aspects. This kind of evaluation would detect very early the mistake or wrong practices in NRM operation in the field. This evaluation should be designed and put in the framework of regulations.

V. CONCLUSION

This study finds that natural resource management (NRM) in Indonesia continues to be constrained by governance failures, including corruption, weak law enforcement, regulatory inconsistency, political patronage, illegal resource exploitation, and unequal access to natural resources. Although the constitution mandates that the natural resources be managed for the greatest prosperity of the people, in fact, the businessmen have gained more benefits than the local community. It has been proved

by its high contribution to environmental degradation, social conflict, and marginalization of indigenous and local communities. The findings demonstrate that Indonesia exhibits key characteristics of the resource curse, where abundant natural resources coexist with weak institutions, elite capture and rent-seeking rather than equitable and sustainable development. This confirms that lower governance quality, rather than resource abundance itself, determines development outcomes.

To address this systemic failure and paradox in NRM implementation, several actions are required, such as: (i) applying the principle of “legal pluralism,” which integrates customary law into the national legal framework; (ii) strengthening the rule of law and its implementation; (iii) encouraging the active participation of various stakeholders and aligning policies with the principles of democracy and social justice; (iv) dismantling collusive power structures and minimizing land conflicts and (v) eliminating money politics, high political cost, and oligarchy domination. Ultimately, true reform depends on improving institutional systems. This ensures that natural resources are managed not merely as commodities for the elite but as sustainable assets entrusted to current and future generations.

In order to cope the paradox phenomena in forestry, mining and plantation sectors, the GoI should reformulate its NRM laws and policies based on people prosperity approach and free from corruption. The three ministries (MoEF, MoEMR, and MoA) related to NRM should develop effective policies and regulations for the benefit and prosperity of all Indonesian people and for achieving sustainable NRM. The future research would focus on the political engagement between the government official with the business actors and the nepotism of appointed commissioners of state-owned companies in NRM business.

REFERENCES

- Ahmad, M., Peng, T., Awan, A., & Ahmed, Z. (2023). Policy framework considering resource curse, renewable energy transition, and institutional issues: Fostering sustainable development and sustainable natural resource consumption practices. *Resources Policy*, 86, 104173. <https://doi.org/10.1016/j.resourpol.2023.104173>
- Allsadek, M., & Benhin, J. (2023). Natural resource curse: A literature survey and comparative assessment of regional groupings of oil-rich countries. *Resources Policy*, 84, 103741. <https://doi.org/10.1016/j.resourpol.2023.103741>
- Antaranews. (2022, June 28). *GDP contribution of forestry only 0.66%: minister*. Retrieved from <https://en.antaranews.com/news/236617/gdp-contribution-of-forestry-only-066-minister>
- Aspinall, E., & Berenschot, W. (2019). *Democracy for sale: Elections, clientelism, and the state in Indonesia*. Cornell University Press.
- Asrinaldi, A. (2025). Government domination in policy making in the House of Representatives during the President Jokowi era. *Asian Journal of Comparative Politics*, 10(3), 272–285. <https://doi.org/10.1177/20578911251326136>
- Asshiddiqie, J. (2021). *Konstitusi dan konstitusionalisme Indonesia*. Sinar Grafika.
- Auty, R. (2002). *Sustaining development in mineral economies: The resource curse thesis*. Routledge.
- Badeeb, R. A., Lean, H. H., & Clark, J. (2017). The evolution of the natural resource curse thesis: A critical literature survey. *Resources Policy*, 51, 123–134. <https://doi.org/10.1016/j.resourpol.2016.10.015>
- Balboni, C., Burgess, R., Heil, A., Old, J., & Olken, B. A. (2021). Cycles of Fire? Politics and Forest Burning in Indonesia. *AEA Papers and Proceedings*, 111, 415–419. <https://doi.org/10.1257/pandp.20211005>
- Brundtland, G. H. (1987). Our common future—Call for action. *Environmental Conservation*, 14(4), 291–294.
- Bryant, R. L., & Bailey, S. (1997). *Third world political ecology*. Psychology Press.
- Budiardjo, M. (2013). *Dasar-dasar Ilmu Politik*. Jakarta: PT Gramedia Pustaka Umum.
- Bungin, B. (2001). *Metodologi Penelitian Kualitatif: Aktualisasi Metodologis Ke Arab Ragam Varian Kontemporer*. Jakarta: PT. Raja Grafindo Perkasa.

- Chen, Y., Khurshid, A., Rauf, A., Yang, H., & Calin, A. C. (2023). Natural resource endowment and human development: Contemporary role of governance. *Resources Policy*, 81, 103334. <https://doi.org/10.1016/j.resourpol.2023.103334>
- Chitadze, N. (2023). World Natural Resources and Their Impact on the Environmental Conditions of Our Planet. In V. Yilanci (Ed.), *Perspectives on Ecological Degradation and Technological Progress* (pp. 42–78). IGI Global Scientific Publishing. <https://doi.org/10.4018/978-1-6684-6727-5.ch003>
- Chung, C., & Jin, T. (2025). Revealing the role of institutional quality and geopolitical risk in natural resources curse hypothesis. *Resources Policy*, 100, 105457. <https://doi.org/10.1016/j.resourpol.2024.105457>
- Collier, P., & Hoeffler, A. (2004). Greed and grievance in civil war. *Oxford Economic Papers*, 56(4), 563–595.
- Creswell, J. W., & Poth, C. N. (2016). *Qualitative inquiry and research design: Choosing among five approaches*. Sage publications.
- Dau, L. A., Chacar, A. S., Lyles, M. A., & Li, J. (2022). Informal institutions and international business: Toward an integrative research agenda. *Journal of International Business Studies*, 53(6), 985–1010. <https://doi.org/10.1057/s41267-022-00527-5>
- Delfirman, & Dzaki, H. M. (2025). Shifts in the control of natural resources: An analysis of the resource curse in Tin-Rich Bangka Belitung, Indonesia. *Extractive Industries and Society*, 23. <https://doi.org/10.1016/j.exis.2025.101682>
- Dewi, N. K. A. P. (2025). Juridical Analysis of the Effectiveness of Law Enforcement in Handling Nickel Mining Violations in North Maluku: Dispute Cases Between Companies and Affected Communities. *Indonesian Journal of Law and Justice*, 2(3), 12. <https://doi.org/10.47134/ijlj.v2i3.3541>
- Fisher, L. A., Kim, Y.-S., Latifah, S., & Mukarom, M. (2017). Managing Forest Conflicts: Perspectives of Indonesia's Forest Management Unit Directors. *Forest and Society*, 1(1), 8. <https://doi.org/10.24259/fs.v1i1.772>
- Frieden, J. A., & Lake, D. A. (2002). *International political economy: perspectives on global power and wealth*. Routledge.
- Frieden, J. A., & Lake, D. A. (2015). *World politics: Interests, interactions, institutions: Third international student edition*. WW Norton & Company.
- Gausset, Q., Whyte, M. A., & Birch-Thomsen, T. (2005). *Beyond Territory and Scarcity: Conflict Over Natural Resource Management*. Nordiska Afrika Institutet.
- Ginsburg, C., & Keene, S. (2020). At a crossroads: consequential trends in recognition of community-based forest tenure from 2002–2017. *China Economic Journal*, 13(2), 223–248. <https://doi.org/10.1080/17538963.2020.1755129>
- Hadiz, V. R. (2004). Decentralization and democracy in Indonesia: A critique of neo-institutionalist perspectives. *Development and Change*, 35(4), 697–718.
- Hidayat, S., Tambunan, D., & Haning, Y. (2025). Unjust by default: The political economy of Indonesia's local government policy on infrastructure development. *Asian Journal of Comparative Politics*, 10(2), 152–170. <https://doi.org/10.1177/20578911241260442>
- Hodgson, G. M. (2015). On defining institutions: rules versus equilibria. *Journal of Institutional Economics*, 11(3), 497–505. <https://doi.org/10.1017/S1744137415000028>
- Johnston, M. P. (2014). Secondary data analysis: A method of which the time has come. *Qualitative and Quantitative Methods in Libraries*, 3(3), 619–626.
- Julio, R. F., & Setyaningsih, S. I. (2025). Mega Korupsi Tata Niaga Timah Rp 300 Triliun: Analisis Pelanggaran Prinsip Pancasila dan Etika Tata Kelola Dalam Pengelolaan Sumber Daya Alam. *Desentralisasi: Jurnal Hukum, Kebijakan Publik, Dan Pemerintahan*, 2(4), 113–129. <https://doi.org/10.62383/desentralisasi.v2i4.1238>
- Karl, T. L. (1997). *The paradox of plenty: Oil booms and petro-states* (Vol. 26). Univ of California Press.
- KBBI IV Daring. (2016). Politik. Badan Pengembangan dan Pembinaan Bahasa, Kementerian Pendidikan Dasar dan Menengah Republik Indonesia. Retrieved March 2, 2026, from <https://kbbi.kemendikdasmen.go.id/entri/politik>
- KPA. (2024). *Laporan Tahunan Agraria 2023: Dekade Krisis Agraria*. Jakarta: Konsorsium Pembaruan Agraria.
- KPK. (2015). *Laporan Studi Potensi Benturan Kepentingan Dalam Pendanaan Pilkada*. Retrieved from <https://www.kpk.go.id/storage/5475/Laporan-Pendanaan-Pilkada.pdf>
- KPK. (2018). *Nota Sintesis: Evaluasi Gerakan Nasional Penyelamatan Sumber Daya Alam (GNP-SDA)*. Jakarta: Komisi Pemberantasan Korupsi.
- Krippendorff, K. (2018). *Content analysis: An introduction to its methodology*. Sage publications.

- Kusnendi. (2014). *Modul 1: Pengertian dan Konsep Dasar Sumber Daya*. Retrieved from <https://pustaka.ut.ac.id/lib/wp-content/uploads/pdfmk/PKOP4419-M1.pdf>
- Lasswell, H. D. (1963). *Politics: Who Gets What, When, How*. World Publishing Company.
- Lasswell, H. D. (2018). *Politics: Who gets what, when, how*. Papamoa Press.
- Leftwich, A. (2015). *What is Politics?: The Activity and Its Study*. John Wiley & Sons.
- Lerip, Y., & Jauhar, B. (2026). Political Discourse of Natural Resources and Actor Relations in Environmental Contestation in Mahakam Ulu: Diskursus Politik Sumber Daya Alam dan Relasi Aktor dalam Kontestasi Lingkungan di Mahakam Ulu. *Jurnal Pemerintahan Dan Politik*, 11(2), 454–471.
- Mahfud, M. D. (2009). *Konstitusi dan hukum dalam kontroversi isu*. Rajawali Pers.
- Mahfud MD, M. (2010). *Perdebatan Hukum Tata Negara Pasca Amendemen Konstitusi*. Jakarta: Rajawali Pers.
- Mahkamah Agung Republik Indonesia. (2024). *Putusan Mahkamah Agung Republik Indonesia Nomor 7918 K/PID.SUS/2024*.
- Mahkamah Agung Republik Indonesia. (2024). *Putusan Pengadilan Tinggi DKI Jakarta Nomor 32/PID.SUS-TPK/2024/PT DKI*.
- Mardela, H. A., Apriza, K. N., Naufal, M. R., & Almira, S. I. (2023). Analisis Dilema Pengambilan Keputusan Pada Regulasi Pemutihan Lahan Sawit Dalam Undang-Undang Cipta Kerja. *Kultura: Jurnal Ilmu Hukum, Sosial Dan Humaniora*, 1(2), 155–163. <https://doi.org/https://jurnal.kolibi.org/index.php/kultura/article/view/292/283>
- Maskun, Violetta, K. V., Mukhlis, M. M., Normiati, & Tajudin, M. S. (2025). The Dilemma of Administrative Sanctions in Legalizing Palm Oil Plantations in Indonesian Forest Areas. *Volksgeist Jurnal Ilmu Hukum Dan Konstitusi*, 8(1), 171–190. <https://doi.org/10.24090/volksgeist.v8i1.13114>
- Mawuntu, J. R. (2012). Konsep penguasaan negara berdasarkan pasal 33 UUD 1945 dan putusan mahkamah konstitusi. *Jurnal Hukum Unsrat*, 20(3), 11–21.
- McCarthy, J. (2007). Shifting resource entitlements and governance reform during the agrarian transition in Sumatra, Indonesia. *The Journal of Legal Pluralism and Unofficial Law*, 39(55), 95–121.
- Meckelburg, R., & Wardana, A. (2024). The political economy of land acquisition for development in the public interest: The case of Indonesia. *Land Use Policy*, 137, 107017. <https://doi.org/10.1016/j.landusepol.2023.107017>
- Mehlum, H., Moene, K., & Torvik, R. (2006). Institutions and the resource curse. *The Economic Journal*, 116(508), 1–20.
- Murdiyarso, D. (2024, June 8). *Kutukan Sumber Daya Alam Makin Dekat*. Retrieved from <https://www.kompas.id/baca/opini/2024/06/07/kutukan-sumber-daya-alam-makin-dekat>
- Nadefanti, S. R., & Kusumawati, A. (2025). Urgensi Pengesahan “Rancangan Undang-Undang Perampasan Aset” Menurut Teori Pemulihan Aset Negara: Studi Kasus Korupsi PT.Timah Tbk. *Jurnal Ilmu Multidisiplin*, 4(5), 3110–3121. <https://doi.org/10.38035/jim.v4i5.1513>
- Narh, J. (2025). The resource curse and the role of institutions revisited. *Environment, Development and Sustainability*, 27(4), 8187–8207. <https://doi.org/10.1007/s10668-023-04279-6>
- Natan, Y., Tetelepta, J. M. S., Pattikawa, J. A., & Ongkers, O. T. S. (2021). Incorporating the Ecological, Socio-economic and Institutional Conceptual Model Framework for Sustainable Management of Small-scale Mud Crab (*Scylla serrata*) Fishery in Western Seram Regency, Indonesia: 10.32526/ennrj/19/2020189. *Environment and Natural Resources Journal*, 19(3), 207–219.
- Natsir, M., Ilahi, A. H. A., & Adnas, T. P. (2024). Political and legal developments in mineral and coal mining laws: A critical review. *Diponegoro Law Review*, 9(2), 186–203. <https://doi.org/10.14710/dilrev.9.2.2024.186-203>
- Noor, F., Kosandi, M., Rahman, A. R., Emilia Yustiningrum, R. R., & Nasution, A. M. (2025). Natural Resources Governance in Indonesia from a Political Perspective: The Marine, Fisheries, and Forestry Cases. In *Approaching Natural Resources for Sustainable Development in Indonesia: Confronting the Socio-Ecological Crisis* (pp. 27–36).
- North, D. C. (1990). *Institutions, institutional change and economic performance*. Cambridge university press.
- Nurjaya, I. N. (2022). *Prinsip-Prinsip Dasar Pengelolaan Sumber Daya Alam yang Berkeadilan, Demokratis, dan Berkelanjutan*. IAHN-TP Palangkaraya.
- Ostrom, V., & Ostrom, E. (1977). *Public Goods and Public Choices*. Indiana University, Workshop in Political Theory and Policy Analysis.

- Retrieved from <https://books.google.co.id/books?id=nSypXwAACAAJ>
- Pengadilan Tindak Pidana Korupsi pada Pengadilan Negeri Jakarta Pusat. (2024). *Putusan Nomor 116/Pid.Sus-TPK/2023/PN Jkt.Pst*.
- Peluso, N. L. (1992). Rich forests, poor people: Resource control and resistance in Java. In *Rich Forests, Poor People: Resource Control and Resistance in Java*. Berkeley and Los Angeles, California: University of California Press.
- Peluso, N. L. (2023). *Rich Forests, Poor People Resource Control and Resistance in Java*. University of California Press. <https://doi.org/10.1525/california/9780520073777.001.000>
- Rahma, H., Fauzi, A., Juanda, B., & Widjojanto, B. (2021). Fenomena Natural Resource Curse dalam Pembangunan Wilayah di Indonesia. *Jurnal Ekonomi Dan Pembangunan Indonesia*, 21(2). <https://doi.org/10.21002/jepi.2021.10>
- Rahman, I. N. (2016). Politik Hukum Pengelolaan Sumber Daya Alam Menurut Pasal 33 UUD 1945. *Jurnal Konstitusi*, 13(1).
- Redi, A. (2015). Dinamika konsepsi penguasaan negara atas sumber daya alam. *Jurnal Konstitusi*, 12(2), 401–421.
- Ribot, J. C., & Larson, A. M. (2005). *Democratic decentralization through a natural resource lense*. Psychology Press.
- Ribot, J. C., & Peluso, N. L. (2003). A theory of access. *Rural Sociology*, 68(2), 153–181.
- Riyanto, G., Yeremia, A. E., Astuti, R., Zuada, L. H., Hidayat, A., & Rakhmani, I. (2025). Various visions of the industrialized future: anxiety, aspiration, and Chinese nickel investment in Indonesia. *Asia Europe Journal*, 23(2–3), 369–391. <https://doi.org/10.1007/s10308-025-00727-2>
- Robinson, J. A., & Acemoglu, D. (2012). *Why nations fail: The origins of power, prosperity and poverty*. Profile London.
- Robison, R., & Hadiz, V. R. (2004). *Reorganising power in Indonesia: The politics of oligarchy in an age of markets*. Routledge.
- Ross, M. L. (2013). *The oil curse: How petroleum wealth shapes the development of nations*. Princeton University Press.
- Rosser, A. (2007). Escaping the resource curse: The case of Indonesia. *Journal of Contemporary Asia*, 37(1), 38–58.
- Rustiadi, E., Barus, B., Iman, L. S., Mulya, S. P., Pravitasari, A. E., & Antony, D. (2018). Land use and spatial policy conflicts in a rich-biodiversity rain forest region: The case of Jambi Province, Indonesia. In *Springer Geography*. https://doi.org/10.1007/978-981-10-5927-8_15
- Sakti, F. T. (2020). *Pengantar Ilmu Politik*. Bandung: UIN Sunan Gunung Djati.
- Sasongko, M. A., Mizuno, K., Utomo, S. W., & Koestoer, R. H. (2024). EIA in Strengthening Law Enforcement and Penalties: A Case of Corruption in Natural Resource Sector. *Hasanuddin Law Review*, 10(3), 292–303. <https://doi.org/10.20956/halrev.v10i3.5167>
- Setiawan, H., & Widyana, M. R. (2022). High-Cost Democracy: Stimulus Ijon Politik dalam Pemilu Lokal di Region Kaya Sumber Daya Alam. *Jurnal Adhyasta Pemilu*, 5(1), 1–18. <https://doi.org/10.55108/jap.v5i1.90>
- Subarudi. (2014). Kebijakan Pengelolaan Hutan Adat Pasca Putusan Mahkamah Konstitusi No. 35/PUU-X/2012: Suatu Tinjauan Kritis. *Jurnal Analisis Kebijakan Kebutuhan*, 11(3), 207–224. <https://doi.org/10.20886/jakk.2014.11.3.207-224>
- Syamsiyah, N., Sadeli, A. H., Saidah, Z., Noor, T. I., & Widiyanesti, S. (2025). Community Participation in the Development of Sustainable, Environmentally Conscious Villages in the Cirasea Sub-Watershed, Indonesia. *Sustainability*, 17(11), 4871.
- Syeirazi, M. K. (2021). Resentralisasi Negara: Catatan Kritis atas UU No. 3/2020 tentang Minerba. In A. K. Umam (Ed.), *Kuasa Oligarki atas Minerba Indonesia* (pp. 138–157). Jakarta: Universitas Paramadina.
- Team Careers360. (2022). *Resources - Definition, Examples, Types of Natural Resources, FAQs*. Team Careers360. Retrieved from <https://school.careers360.com/chemistry/natural-resources-topic-pge>
- Tempo.co. (2021, January 20). Anggota DPR Catat Ada 8,7 Juta Ha Pertambangan Ilegal di Hutan Indonesia. *Tempo*. Retrieved from <https://nasional.tempo.co/read/1424919/anggota-dpr-catat-ada-87-juta-ha-pertambangan-ilegal-di-hutan-indonesia>
- Tuk-Indonesia. (2023). *Fakta di Balik Pemutihan Sawit Ilegal dalam Kawasan Hutan*. Hasil Penelitian Bersama Antara TUK Indonesia, Greenpeace dan Pantau Gambut. Retrieved from <https://www.tuk.or.id/wp-content/uploads/Fakta-di-Balik-Pemutihan-Sawit-Ilegal-dalam-Kawasan-Hutan-2.pdf>
- WALHI. (2025). *Siaran Pers WALHI. Revisi UU Minerba: Langkah Mundur Pengelolaan Sektor Pertambangan di Indonesia*. WALHI. Retrieved from <https://www.walhi.or.id/revisi-uu>

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- Williams, A., & Le Billon, P. (Eds.). (2017). *Corruption, natural resources and development: From resource curse to political ecology*. Edward Elgar Publishing.
- Yasmi, Y, Kelley, L., & Enters, T. (2010). *Conflict Over Forests and Land in Asia: Impacts, Causes, and Management*. Bangkok: RECOFTC.
- Yasmi, Yurdi, Guernier, J., & Colfer, C. J. P. (2009). Positive and negative aspects of forestry conflict: lessons from a decentralized forest management in Indonesia. *International Forestry Review*, 11(1), 98–110.
- Yin, R. K. (2018). *Case study research and applications* (Vol. 6). Sage Thousand Oaks, CA.
- Yusman, W., Ikhsan, M., & Papuling, S. R. (2024). Karut Marut Investasi Nikel Tiongkok (Studi Kasus Perburuhan, Konflik Agraria dan Dampak PLTU Captive di Kawasan IMIP. In *IHIP dan SEI*. Retrieved from <https://walhisulteng.org/wp-content/uploads/2024/10/Karut-Marut-Investasi-Nikel-Tiongkok.pdf>
- Yusuf, M. A., Saputro, C. B., & Kusumaningtias, R. (2025). Di Balik Daun Sawit: Korupsi Terstruktur Dan Tata Kelola Yang Terluka. *Jurnal Ekonomi Revolusioner*, 8(6), 56–62. <https://doi.org/ISSN:24410685>

VULNERABILITY ASSESSMENT OF OVERUTILISED FABACEAE MEMBERS OF KATSINA STATE, NORTHERN NIGERIA

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VULNERABILITY ASSESSMENT OF OVERUTILISED FABACEAE MEMBERS OF KATSINA STATE, NORTHERN NIGERIA. Fabaceae, a globally diverse and economically important group of plants, faces increasing susceptibility to both natural and anthropogenic threats, posing significant risks to biodiversity and contributing to the potential extinction of certain species. This study aims to assess the vulnerability of over-utilised members of the Fabaceae in Katsina, utilizing a semi-structured questionnaire to interview 180 respondents about their use of these plants. Vulnerability was evaluated using ethnobotanical indices, including the Relative Frequency of Citation (RFC), Cultural Importance (CI), Relative Importance (RI), and Importance Value (IV). The study identified 32 vulnerable Fabaceae species across 25 genera and 5 subfamilies. Most respondents were male (87%), aged 46-75 (53%), and married (77%), with traditional medicinal practitioners (34%) and farmers (33%) constituting the two largest occupational groups. *Albizia* the most vulnerable genus, with three species. The plant *Parkia biglobosa* had the highest Vulnerability Index (VI) of 3.00. The stem bark (39%) was the most utilised plant part. According to IUCN status, the most vulnerable species were classified as Near Threatened (NT) (13%, 4 species), followed by Least Concern (LC) (78%, 25 species), and Not Evaluated (NE) (9%, 3 species). Key threats identified included deforestation (31%), agricultural expansion (23%), urbanisation (21%), overharvesting (15%), and introduction of the invasive species (10%). Addressing these threats is crucial for the conservation and sustainable use of these important species. The findings could guide conservation efforts, inform sustainable utilization, and inspire further studies on the biodiversity of Fabaceae and ecosystem resilience.

Keywords: Identification, Vulnerable Fabaceae, Plant Overutilization, Plant Conservation, Katsina State.

PENILAIAN KERENTANAN ANGGOTA FABACEAE YANG DIMANFAATKAN SECARA BERLEBIHAN DI NEGARA BAGIAN KATSINA, NIGERIA UTARA. Fabaceae merupakan kelompok tumbuhan yang sangat beragam secara global dan memiliki nilai ekonomi penting, namun semakin rentan terhadap berbagai ancaman alami maupun antropogenik. Kondisi tersebut menimbulkan risiko yang signifikan terhadap keanekaragaman hayati dan dapat berkontribusi terhadap kepunahan beberapa spesies. Penelitian ini bertujuan untuk menilai tingkat kerentanan anggota Fabaceae yang dimanfaatkan secara berlebihan di Katsina dengan menggunakan kuesioner semi-terstruktur untuk mewawancarai 180 responden mengenai pemanfaatan tumbuhan tersebut. Kerentanan dievaluasi menggunakan indeks etnobotani, yaitu Relative Frequency of Citation (RFC), Cultural Importance (CI), Relative Importance (RI), dan Importance Value (IV). Penelitian ini mengidentifikasi 32 spesies Fabaceae yang rentan, yang termasuk ke dalam 25 genus dan 5 subfamili. Sebagian besar responden adalah laki-laki (87%), berusia 46–75 tahun (53%), dan telah menikah (77%), dengan praktisi pengobatan tradisional (34%) dan petani (33%) sebagai dua kelompok pekerjaan terbesar. *Albizia* merupakan genus yang paling rentan, dengan tiga spesies. Tumbuhan *Parkia biglobosa* memiliki nilai Vulnerability Index (VI) tertinggi, yaitu 3,00. Kulit batang (39%) merupakan bagian tumbuhan yang paling banyak dimanfaatkan. Berdasarkan status IUCN, spesies yang rentan diklasifikasikan sebagai Near Threatened (NT) sebesar 13% (4 spesies), Least Concern (LC) sebesar 78% (25 spesies), dan Not Evaluated (NE) sebesar 9% (3 spesies). Ancaman utama yang teridentifikasi meliputi deforestasi (31%), perluasan lahan pertanian (23%), urbanisasi (21%), pemanenan berlebihan (15%), dan introduksi

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spesies invasif (10%). Penanganan terhadap berbagai ancaman tersebut sangat penting untuk mendukung konservasi dan pemanfaatan berkelanjutan spesies-spesies penting tersebut. Hasil penelitian ini dapat menjadi dasar dalam upaya konservasi, mendukung pemanfaatan yang berkelanjutan, serta mendorong penelitian lebih lanjut mengenai keanekaragaman hayati Fabaceae dan ketahanan ekosistem.

Kata kunci: Identifikasi, Fabaceae rentan, Pemanfaatan tumbuhan secara berlebihan, Konservasi tumbuhan, Negara Bagian Katsina

I. INTRODUCTION

Fabaceae, also known as Leguminosae, is considered one of the most economically significant plant families. It ranks as the third-largest plant family globally, comprising approximately 19,500 species across around 735 genera. (Bahuguna, 2024; Putra et al., 2022). The term "legume" originates from this traditional family name. Members of Fabaceae are well recognized for their substantial contributions to agriculture, their adaptability to diverse habitats, and their wide range of life forms (trees, shrubs, herbs, lianas, etc.) (Yahara et al., 2013).

The conservation of Fabaceae is crucial due to its substantial societal and community contributions, particularly as a vital nutritional source in regions with limited access to animal-derived protein. (Henchion et al., 2017). Legumes are rich in essential nutrients and serve multiple purposes, including medicinal, nutritional, fodder, shelter, and ornamental uses. (Joshi et al., 2024; Delgado-Salinas et al., 2021; Sathesh Naik et al., 2020). As such, they play a vital role in ensuring food security. (Joshi et al., 2023).

A vulnerability index is essential for quantitatively assessing the conservation status of plant taxa, thus aiding in their long-term availability. Quantitative ethnobotanical assessments support hypothesis testing, provide statistical evidence, and enable comparative research. These approaches help refine scientific hypotheses by situating them within rigorous research contexts. (Helida et al., 2015; Pacifici et al., 2015). In rural communities, residents depend on plant resources for daily sustenance, drawing on generations of traditional knowledge to utilize and manage

these resources sustainably (Bharadwaj et al., 2021; Mothupi & Shackleton, 2025). However, the overexploitation of plant resources remains a pressing concern. Effective conservation strategies and vulnerability assessments are essential for determining the true status of species in specific study areas to ensure their protection and sustainable management. Species that are most at risk tend to be those that are in high demand, slow-growing, difficult to reproduce, limited in geographic distribution, and native to ecologically fragile environments (Rao & Chellaiah Periyasamy, 2020).

A vulnerability assessment of farmlands in northern Katsina State, Nigeria, has revealed significant ecological degradation due to desertification, which threatens horticultural productivity and biodiversity. Desertification refers to land degradation in arid, semi-arid, and dry sub-humid regions, primarily caused by climatic changes and unsustainable human activities. This results in the loss of vegetation and soil fertility. The findings highlight the urgent need for effective land management strategies, including vegetation restoration, soil rehabilitation, and the expansion of irrigation practices (Yahaya, 2021). Further analysis of vulnerable species in Katsina State has emphasized the severe threat biodiversity faces in the region. Over 100 species have been identified as threatened, with *Xeroderris stuhlmannii* reported to be locally extinct (Bello et al., 2019). Globally, approximately 15,000 medicinal plant species are currently at risk of extinction (Aftab & Hakeem, 2021). The preservation of these species, especially native and indigenous ones, is critical for biodiversity conservation. Achieving this goal requires changes in local living standards and attitudes

toward plant use and conservation. This study aims to evaluate the vulnerability index of species within the *Fabaceae* family in Katsina State to support informed conservation and sustainable management efforts.

II. MATERIAL AND METHOD

A. Study Area

This research was conducted between March and August 2024 in Katsina State, one of the northwestern states of Nigeria (Fig.1). Katsina State has a land area of 23,938 km² and is located between latitudes 11°08'N and 13°22'N and longitudes 6°52'E and 9°20'E (Saulawa et al., 2018). The state is bordered to the north by the Niger Republic, to the east by Jigawa and Kano States, to the south by Kaduna State, and to the west by Zamfara State. Nine (9) local governments were randomly selected as representatives of the total of thirty-four (34) local government areas. The study LGAs were the areas we visited and sampled, selected to serve as representatives of the entire state.

B. Data Collection Methods

Information on *Fabaceae* (Leguminosae) was obtained through semi-structured questionnaires, and purposive sampling was used to select 180 respondents for interviews across nine local government areas in Katsina State, Nigeria. The selected Local Governments included Funtua, Bakori, Kankara, Batagarawa, Katsina, Kaita, Sandamu, Mai'adua, and Zango, which were drawn through stratified sampling. In this process, the local governments were divided into subgroups based on three zones: Katsina, Daura, and Funtua. A sample was then randomly selected from each group to ensure that each zone is equally represented in the final sample. The people interviewed included farmers, traditional medicine herbal practitioners, and others (petty traders, craftsmen, animal husbandry, etc). The interviews were conducted in the respondents' native language, Hausa, allowing them to explain the various natural and artificial factors affecting *Fabaceae* in their communities. The questionnaires comprised two sections:

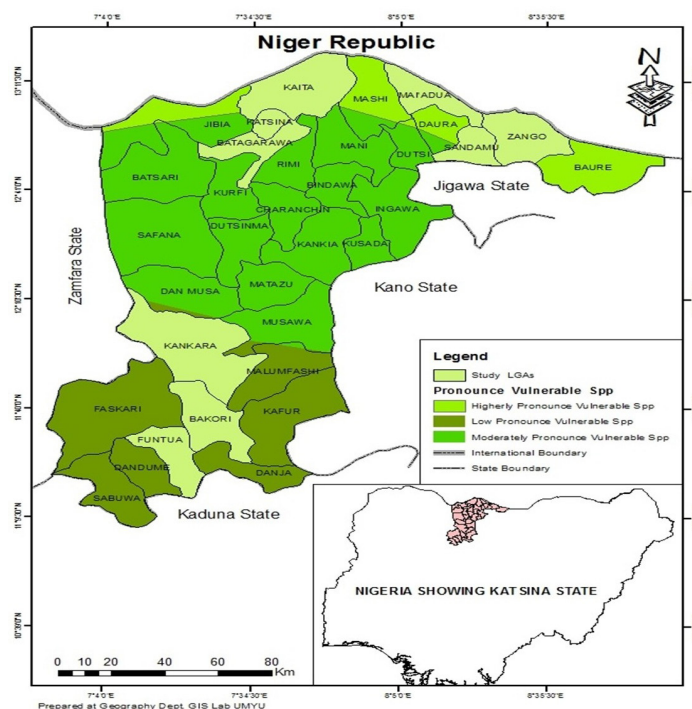


Figure 1. Map of Katsina State showing the study area

Section A focused on the demographics of the respondents (age combined with sex, occupation, and marital status), while Section B gathered information related to the major factors causing the plant's vulnerable, parts of Fabaceae that are utilized (species' local names, organs/parts used, categories of ailments managed by each organ/part, and products made from each species).

C. Collection and Identification of Plant Samples

Numerous trips have been undertaken to document plants in various locations across the state, including home gardens, protected areas, and farmlands. The identification and verification of the collected samples were conducted using the Plants of the World online resource. Furthermore, the samples were deposited at the Umaru Musa Yar'adua University Herbarium in Katsina, Nigeria, for identification and voucher specimen number.

D. Data Analysis

The data gathered here were tabulated in the Microsoft Excel spreadsheets, and descriptive statistics analysis was employed. Demographic characteristics of the respondents are analyzed using percentages.

1. Frequency of Citation (FC)

The total number of respondents mentioned a given species during the surveys. If many respondents mention a certain species, there is a tendency towards overutilization. Where FC is the total number of citations (Shah et al., 2023).

2. Relative Frequency of Citation (RFC)

$$RFC = FC/N \dots\dots\dots(1)$$

Where FC = Frequency of Citation. N = Total number of respondents who participated in the study. This signifies how important species are in a community (Ralte et al., 2024).

3. Number of Use (NU)

This is the expert categories' number of uses for each species.

$$NU = \sum UR_u \dots\dots\dots(2)$$

Where NU = Number of Uses, UR = Category of uses for a taxon, and u = all the categories of uses mentioned in the study (Alemayehu et al., 2023).

4. Use Report (UR)

This is the use report per organ/parts reported by the respondents.

$$UR = \sum UR_{ui} \dots\dots\dots(3)$$

Where UR = Total use reports, UR_{ui} = Report for each category (Tamene et al., 2023).

5. Relative Importance (RI)

This is the summation of the relative frequency of citations and the number used, divided by two.

$$RI = \sum RFC + NU/2 \dots\dots\dots(4)$$

Where RI = Relative Importance, $\sum RFC$ = Total number of mentioned reports, NU = Number of uses (Leonti 2022).

6. Vulnerability Index (VI)

This is the summation of the percentage results obtained from frequency of citation (FC%), number of uses (NU Scalling), and number of organs/parts used (NOU Scalling) (Todou et al., 2023).

$$VI = FC + NU + NOU \dots\dots\dots(5)$$

Where FC indicates the percentage category within frequency of citations (FC) of a species, which is measured in 3 scale scores, NU= represents the number of uses of each species, and NOU= the number of organs used (NOU) (Badjaré et al., 2018; Kankara et al., 2022; Kankara et al., 2024). These were the main concern parameters in identifying the vulnerability index of the species.

E. Frequency of Citation (FC)

In 2022, the International Union for Conservation of Nature (IUCN) published

the Red List of Threatened Species, which classifies the conservation status of plant species into nine categories: Data Deficient (DD), Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR), Extinct in the Wild (EW), Extinct (EX), and Not Evaluated (NE) (IUCN, 2022). In this study, the assessment was done based on the above criteria and status.

III. RESULT AND DISCUSSION

A. Demographic Characteristics of The Respondents

1. Respondents' Age and Gender Reports

In this study, participants were randomly selected and grouped into three age categories: 15–45 years, 46–75 years, and above 75 years to capture generational differences in plant knowledge. This is because younger, middle-aged, and elderly people often hold and transmit ethnobotanical knowledge in distinct ways. The results revealed that individuals in the 46–75 age range made the most significant contributions in this study to documenting the various medicinal and cultural importance of the plants, especially members of the family *Fabaceae* (Table 1). This finding is consistent with previous studies by Abdallah et al. (2020); Mechaala et al. (2022) and Elhasnaoui et al. (2024), which similarly identified this same age group as the key holders of the most extensive ethnobotanical

knowledge. The older age contributions, especially on ethnobotanical studies, suggest a gradual erosion of traditional ecological knowledge among the younger generation, raising concerns over the sustainability of this cultural heritage. Therefore, urgent measures are needed to foster intergenerational knowledge transfer, such as incorporating ethnobotanical knowledge into community-based educational initiatives and engaging youth in conservation practices.

The study also revealed a higher proportion of male participants, reflecting traditional gender roles, in which men (157) were the majority interviewed, compared with females (23), who have limited access to and engagement with natural resources. This could be due to cultural limitations, social and religious constraints, etc. This pattern aligns with the findings of Ngamsou Abdel et al. (2024), who also observed male dominance in ethnobotanical knowledge systems. However, this gender disparity highlights the need for gender-sensitive conservation strategies that actively involve women in biodiversity management and plant resource governance. Recognising and integrating women's knowledge, often transmitted through informal networks and domestic use, can contribute to more inclusive and effective conservation outcomes, ensuring that both ecological and cultural dimensions are preserved.

Table 1. Potential of ecoregional identity for ecotourism development in Aceh Tengah District.

Age	Respondents number	Gender	Number of respondents per gender	Percentage (%)
15-45 years	57	Males	56	31
		Female	01	0.5
46-75 years	95	Males	83	46
		Females	12	6.7
>75 years	28	Males	18	10
		Females	10	5.6

2. Respondents' Marital Status

Table 2 outlines the marital composition of participants. In this study, married men comprised the largest group at 77%, followed by others at 17%, while singles represented the smallest group at 6%. The highest number of married men identified in this study reflects their exploration of various life forms, driven by poverty and limited resources, which is essential for providing for their families. This finding aligns with the work of Kankara et al. (2020) who studied medicinal plants used for complementary and alternative cancer therapy in Katsina State, Northwestern Nigeria, as well as the research by Asigbaase et al. (2024) in their ethnobotanical survey of medicinal tree species used by forest-fringe communities in Southwestern Ghana. Both studies highlighted the dominance of married men among their participants.

3. Respondents' Occupation

Figure 2 displays the representation of the respondents' occupations, revealing that the majority of participants were traditional

medical practitioners (62, 34.4%), slightly higher than farmers (59, 32.8%), and those in other categories (59, 32.8%). The other category included respondents with various occupations, which were merged for this study. The prevalence of traditional herbal practitioners and farmers suggests a consensus among locals and lower-income earners on the use of plants for healing. However, this trend raises significant concerns for biodiversity and increases the vulnerability of species to extinction. Many people cut plants without ensuring proper replacements, which threatens sustainability. Some plants take a long time to grow, are difficult to cultivate and harvest, or are collected from the wild without being replanted. Even small amounts of repeated harvesting can gradually deplete wild populations, particularly for rare or locally endemic species, leading to ecological disruption and potential extinction. Most respondents inherited their knowledge from closely associated persons, a finding that is inconsistent with that of Obakiro et al. (2023) and Owor et al. (2024).

Table 2. Potential of ecoregional identity for ecotourism development in Aceh Tengah District.

Marital status	Number of each category	Percentage (%)
Single	11	6.11
Married	138	76.66
Others	31	17.22

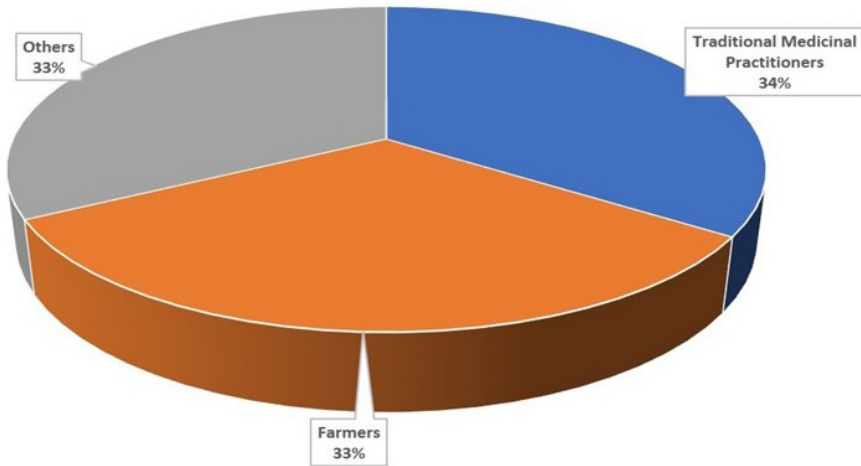


Figure 2. Respondent's Occupation

4. Identification of the vulnerable *Fabaceae* species of Katsina State

Table 3 presents 32 vulnerable species belonging to the *Fabaceae* family in Katsina State. These species span 25 genera and five subfamilies. The genera with the highest number of representatives were *Albizia* (3 species), followed by *Acacia*, *Bauhinia*, *Cassia*, *Detarium*, and *Erythrophleum*, each represented by two species. The remaining genera, such as *Daniellia*, *Dialium*, *Dalbergia*, etc., each contributed only one species.

These species were distributed among five subfamilies: *Caesalpinioideae* (47%), *Mimosoideae* (22%), *Papilionoideae* (19%), *Detarioideae* (9%), and *Cercidoideae*, which had the least representation with (3%) (Figure 3). The documented species are extensively used in the treatment of a wide range of ailments, including gastrointestinal

disorders, diabetes, cancer, asthma, anemia, hemorrhoids, wound healing, and spiritual afflictions (Yaradua, 2015; Bello et al., 2019; Yirgu et al., 2019; Kankara et al., 2022).

However, the overutilisation of *Fabaceae* species for medicinal purposes, along with other uses such as fodder, timber, furniture, wood handles, fuelwood, charcoal, mortar and pestle production, handicrafts, and dyes, raises significant conservation concerns. These pressures are compounded by environmental and anthropogenic factors such as unsustainable agricultural practices, deforestation, desertification, the introduction of invasive species, and rapid urbanisation. Collectively, these dynamics have exacerbated the vulnerability of *Fabaceae* species across the region, particularly in light of Katsina's rapidly changing ecological landscape (Bello et al., 2019; Lawal et al., 2022).

Table 3. Medicinal and Other Uses of Vulnerable Species of *Fabaceae* in Katsina State.

S/N	Species	Subfamily	Voucher's number	Uses
1	<i>Albizia chevalieri</i> Harms	Caesalpinioideae	UMYUH06	Used to treat piles and gastrointestinal disorders in addition to being used as fuel wood, wood handles, and roofing making, also serves as fodder.
2	<i>Albizia lebbeck</i> (L.) Benth	Caesalpinioideae	UMYUH0780	Serves to manage hemorrhoids, diabetes, and aphrodisiacs, and other uses such as seed uses for music entertainments, stems used as fuel wood, mortar and pestle making, handicraft, and charcoal making.
3	<i>Albizia coriaria</i> Welw. ex Oliver	Mimosoideae	UMYUH1992	Used to manage hemorrhoids and for charcoal making and demarcation of a piece of land, fuelwood, handles, and fodder
4	<i>Acacia polyacantha</i> Willd.	Mimosoideae	UMYUH33	Used to treat all cold-related diseases and general body problems, and serves as fodder, fuel wood, and wood handles.
5	<i>Acacia pycnantha</i>	Mimosoideae	UMYUH2373	Used to treat gastrointestinal disorders and for roofing, serves as fodder and fuel wood.
6	<i>Bauhinia reticulatum</i> (Schum.) Milne Redhead	Caesalpinioideae	UMYUH1011	For cancer and anemia treatments, seeds and seed pods are used to enhance the building strength, and the leaves serve as fodder for animals. The stem bark is also used in furniture, handicrafts, and charcoal making.
7	<i>Bauhinia rufescens</i> Lam.	Cercidoiceae	UMYUH1984	Ease labor and spiritual treatments, Fodder for animals, firewood, and used in the making of mortar and pestle.

S/N	Species	Subfamily	Voucher's number	Uses
8	<i>Cassia arereh</i> Delile	Ceasalpinioideae	UMYUH611	For gonorrhea and stomachache treatments, in addition, they have been used to increase lactation in mothers. Other uses were for roofing houses, serving as fodder for animals, furniture, fuel wood, handicrafts, and wood handles.
9	<i>Cassia fistula</i> L.	Ceasalpinioideae	UMYUH1294	Addresses infertility in women and sickling problems. Other uses include fuel wood and fodder for animals.
10	<i>Daniellia oliveri</i> Hutch. & Dalziel	Detarioideae	UMYUH2390	For fever and cancer treatments, also used for Fuel wood and wooden handles.
11	<i>Detarium microcapum</i> Guill. & Perr.	Detarioideae	UMYUH698	Used to treat wounds and toothache, gonorrhea, and cholera also serves as fuel wood, roofing for houses, and furniture.
12	<i>Detarium senegalense</i> J.F. Gmel.	Ceasalpinioideae	UMYUH335	Used to treat fever, asthma, and gastrointestinal disorders, also serves as fuel wood and fodder for animals.
13	<i>Dialium guineense</i> Willd.	Ceasalpinioideae	UMYUH2398	Used to treat stomachache and asthma, also serves as fuel wood, charcoal making, and building of houses.
14	<i>Dalbergia sissoo</i> Roxb.	Papilionioideae	UMYUH2093	Used against spirituals and for roofing houses
15	<i>Delonix regia</i> (Hook.) Raf.	Ceasalpinioideae	UMYUH100	For diabetes and inflammation treatments, the seeds are used for musical entertainment, and the stem bark for fuel wood, mortar, and pestle.
16	<i>Dichrostachys cinerea</i> (L.) Wight & Arn,	Ceasalpinioideae	UMYUH614	For back pain and gastrointestinal disorders, and used for fuel wood, and in building houses
17	<i>Entada Africana</i> Guill. & Perr.	Mimosoideae	UMYUH2117	For stomachache and hemorrhoid treatments and fodder for animals, and fuel wood.
18	<i>Erythrophleum saueolens</i> (Guill. & Perr.) Brenan	Ceasalpinioideae	UMYUH356	For pulmonary disease treatments, and used as fuel wood and charcoal making
19	<i>Erythrophleum africana</i> (Benth.) Harms.	Ceasalpinioideae	UMYUH1670	Used for convulsion treatments in babies, axe and hoe handles, firewood, and fodder
20	<i>Erythrina senegalensis</i> DC.	Papilionioideae	UMYUH356	For the treatment of fever and hemorrhoids, and is also used for fuel wood and furniture.
21	<i>Faidherbia albida</i> (Delile) A. Chev,	Ceasalpinioideae	UMYUH599	Used to treat measles and pneumonia, break spiritual ailments, for animal fodder, used in furniture and mortar and pestle making, axe and hoe handles.
22	<i>Indigofera polyphylla</i> DC.	Papilionioideae	UMYUH210	Serves to break spiritual ailments and for dyeing.
23	<i>Isobertinia doka</i> Craib & Stapf	Detarioideae	UMYUH2389	Used for gastrointestinal disorders treatments and furniture making, fuel wood, and hoe handles.

S/N	Species	Subfamily	Voucher's number	Uses
24	<i>Lonchocarpus sericeus</i> (Poir.) Dc.	Papilionoideae	UMYUH2113	For spiritual treatments, fuel wood, and charcoal.
25	<i>Leucaena leucocephala</i> (Lam.) de Wit	Cesalpinioidae	UMYUH2393	For the treatment of stomachache-related problems in animals and sources for timber, fuelwood, and forage for animals
26	<i>Milletia thonningii</i> (Schumach. & Thorn.) Baker	Papilionoideae	UMYUH345	Used for abdominal pain and helminth treatments and in making fish apparatus, fuelwood, furniture, wood handles, handicrafts, and tables, etc
27	<i>Parkia biglobosa</i> (Jacq.) G.Don	Mimosoideae	UMYUH1274	For the treatment of hemorrhoids, fever, and coccidiosis, its seed is used in soup making, serves as fodder, is used to strengthen the building, and is also used in furniture making and fuelwood.
28	<i>Prosopis africana</i> (Guill. & Perr.) Taub.	Mimosoideae	UMYUH639	Used for pile treatments and in the making of mortar and pestle, roofing of houses, leaves used as fodder, charcoal making, wood handles, furniture, and timber
29	<i>Pterocarpus santalinoides</i> Dc.	Papilionoideae	UMYUH2106	For treatment of hypertension and furniture making, fuel wood, wood handles, and fodder for animals.
30	<i>Senna siamea</i> (Lam.) H.S. Irwin & Barneby	Cesalpinioidae	UMYUH220	For cancer treatments, and use as fodder for animals and fuel wood.
31	<i>Tamarindus indica</i> L.	Cesalpinioidae	UMYUH2219	For gastrointestinal disorders and cancer treatments, it also serves as a blood tonic and is used for fodder, fuel wood, mortar and pestle making, and timber.
32	<i>Vachellia nilotica</i> (L.) P.J.H. Hurter & Mabb.	Mimosoideae	UMYUH600	Used for piles, conjunctivitis, ear, and wound treatment, also for soup making, fodder for animals, and as fuel wood.

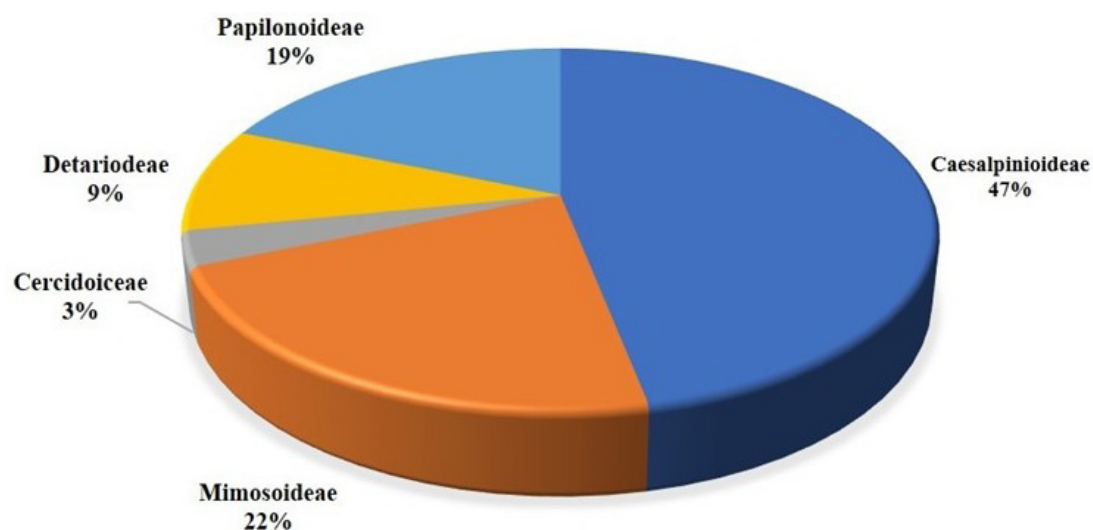


Figure 3. Category of each subfamily representative

5. Vulnerability Index of Fabaceae Species

Table 4 presents the vulnerability status of each documented *Fabaceae* species, alongside the contributing factors responsible for their decline. These factors include the frequency and diversity of uses, specific plant parts exploited, methods of collection, and the growth stage at which the plant parts are harvested (Kankara et al., 2024). Among these, anthropogenic influences were found to be the most critical, particularly in communities facing high poverty rates and limited access to formal healthcare systems, where dependence on plant-based resources is intensified.

In this study, species vulnerability was assessed using a set of ethnobotanical indices: frequency of citation (FC), relative frequency of citation (RFC), number of uses (NU), relative number of uses (RNU), and organ/part used (OU). These were complemented by vulnerability parameters, including the number of organs used (NOU), relative importance (RI), and values derived from core index analyses (FC, NU, and NOU). The resulting composite

measure, the Vulnerability Index (VI), was used to classify species on a scale from 1 to 3, where values approaching 3 indicate higher vulnerability.

Based on this metric, the four most vulnerable species identified were *Parkia biglobosa* (VI = 3.00), followed by *Bauhinia reticulatum*, *Tamarindus indica*, and *Vachellia nilotica* (each with a VI of 2.67). While *Parkia biglobosa* emerged as the most frequently cited species, it is important to note that citation frequency alone does not fully account for vulnerability (Breshears et al., 2021). Notably, the three remaining species identified as highly vulnerable did not rank as the next most cited, highlighting that vulnerability is shaped by multiple interacting factors beyond mere popularity or frequency of use.

Ultimately, it is the cumulative pressure from diverse utilitarian activities ranging from medicinal and domestic applications to timber and fodder extraction that determines a species' vulnerability status. This underscores the importance of integrating multidimensional indices in assessing the conservation priorities of ethnobotanically significant taxa.

Table 4. Basic Indices Used to Identify the Vulnerable Species of Fabaceae in Katsina State.

No.	Species	Basic Indices					VI Parameters					
		FC	RFC	NU	RNU	OU	NOU	RI	FC%	NU Sca	NOU Sca	VI
1	<i>Parkia biglobosa</i> (Jacq.) G.Don	121	0.67	9.00	1.00	RSLD	4	0.84	3.00	3.00	3.00	3.00
2	<i>Bauhinia reticulatum</i> (Schum.) Milne Redhead	78	0.43	6.00	0.67	RSLD	3	0.55	2.00	3.00	3.00	2.67
3	<i>Tamarindus indica</i> L.	67	0.37	8.00	0.89	RSLD	4	0.63	2.00	3.00	3.00	2.67
4	<i>Vachellia nilotica</i> (L.) P.J.H. Hurter & Mabb.	92	0.51	7.00	0.78	RSLD	4	0.65	2.00	3.00	3.00	2.67
5	<i>Albizia chevalieri</i> Harms	88	0.49	6.00	0.67	RS	2	0.58	2.00	3.00	2.00	2.33
6	<i>Albizia lebbeck</i> (L.) Benth.	37	0.20	7.00	0.78	RSL	3	0.49	2.00	3.00	2.00	2.33
7	<i>Albizia coriaria</i> Welw. ex Oliv.	37	0.20	5.00	0.56	RSL	3	0.38	2.00	3.00	2.00	2.33
8	<i>Bauhinia rufescens</i> Lam.	74	0.41	6.00	0.67	RSL	4	0.54	2.00	3.00	2.00	2.33
9	<i>Cassia arereb</i> Delile	97	0.54	7.00	0.78	RSL	3	0.66	2.00	3.00	2.00	2.33
10	<i>Detarium microcarpum</i> Guill. & Perr.	92	0.51	6.00	0.67	RSL	3	0.59	2.00	3.00	2.00	2.33
11	<i>Detarium senegalense</i> J.F.Gmel	96	0.53	5.00	0.56	RSL	3	0.55	2.00	3.00	2.00	2.33
12	<i>Dialium guineense</i> Willd.	67	0.37	5.00	0.56	RSL	3	0.47	2.00	3.00	2.00	2.33
13	<i>Delonix regia</i> (Hook.) Raf.	31	0.17	5.00	0.56	RSLD	4	0.37	1.00	3.00	3.00	2.33

No.	Species	Basic Indices					VI Parameters					
		FC	RFC	NU	RNU	OU	NOU	RI	FC%	NU Sca	NOU Sca	VI
14	<i>Entada africana</i> Guill. & Perr.	85	0.47	4.00	0.44	RSLD	4	0.46	2.00	2.00	3.00	2.33
15	<i>Faidherbia albida</i> (Delile) A. Chev.	98	0.54	8.00	0.89	RSL	3	0.72	2.00	3.00	2.00	2.33
16	<i>Millettia thonningii</i> (Schumach. & Thorn.) Baker	37	0.20	6.00	0.67	RSL	3	0.44	2.00	3.00	2.00	2.33
17	<i>Prosopis africana</i> (Guill. & Perr.) Taub.	83	0.46	7.00	0.78	RSL	3	0.62	2.00	3.00	2.00	2.33
18	<i>Acacia polyacantha</i> Willd.	31	0.17	5.00	0.56	RSL	3	0.37	1.00	3.00	2.00	2.00
19	<i>Acacia pycnantha</i> Benth	48	0.26	4.00	0.44	RSL	3	0.35	2.00	2.00	2.00	2.00
20	<i>Cassia fistula</i> L.	45	0.25	4.00	0.44	RSL	3	0.35	2.00	2.00	2.00	2.00
21	<i>Daniellia oliveri</i> Hutch. & Dalziel	62	0.34	4.00	0.44	RSL	3	0.39	2.00	2.00	2.00	2.00
22	<i>Dichrostachys cinerea</i> (L.) Wight & Arn,	60	0.33	4.00	0.44	RSL	3	0.39	2.00	2.00	2.00	2.00
23	<i>Eythrina senegalensis</i> DC.	58	0.32	4.00	0.44	RSL	3	0.38	2.00	2.00	2.00	2.00
24	<i>Pterocarpus santalinoides</i> Dc.	29	0.16	5.00	0.56	RSL	3	0.36	1.00	3.00	2.00	2.00
25	<i>Senna siamea</i> (Lam.) H.S. Irwin & Barneby	81	0.45	3.00	0.33	RSL	3	0.39	2.00	2.00	2.00	2.00
26	<i>Dalbergia sissoo</i> Roxb.	31	0.17	2.00	0.22	SL	2	0.20	1.00	2.00	2.00	1.66
27	<i>Erythrophloeum sauveolens</i> (Guill. & Perr.) Brenan.	27	0.15	3.00	0.33	RSL	3	0.24	1.00	2.00	2.00	1.66
28	<i>Erythrophloeum africana</i> (Benth.) Harms	33	0.18	4.00	0.44	RSL	3	0.31	1.00	2.00	2.00	1.66
29	<i>Indigofera polyphylla</i> DC.	19	0.10	2.00	0.22	SL	2	0.20	1.00	2.00	2.00	1.66
30	<i>Isobornia doka</i> Craib & Stapf	24	0.13	3.00	0.33	RSL	3	0.23	1.00	2.00	2.00	1.66
31	<i>Lonchocarpus sericeus</i> (Poir.) Dc.	31	0.17	3.00	0.33	RSL	3	0.25	1.00	2.00	2.00	1.66
32	<i>Leucaena leucocephala</i> (Lam.) de Wit	31	0.17	4.00	0.44	RSL	3	0.31	1.00	2.00	2.00	1.66

Remarks: FC= frequency of citations; RFC = relative frequency of citations; NU = number of uses; RNU = relative number of uses; OU = organs used; NOU = number of organs used; RI = relative importance; VI = vulnerability index; L = Leaves; S = Stem; R = Root; D= Seeds, Sca= Scale.

Scoring: FC%: scored 1 if FC = 20%; scored 2 if FC > 20% to 60%; scored 3 if FC > 60%

NUSca: scored 1 if NU < 2; scored 2 if 2 ≤ NU ≤ 4, scored 3 if NU ≥ 5

NOUSca: scored 1 if NOU < 2; scored 2 if 2 ≤ NOU ≤ 3; scored 3 if NOU ≥ 4

6. The Most Utilised Plant Parts of the Vulnerable Species and IUCN Status

Table 5 presents data on the plant parts used from vulnerable species and their corresponding International Union for Conservation of Nature (IUCN) status. The most commonly utilised plant part in this study was stem bark (39%, 32 species), followed by leaves (33%, 27 species)

. Roots were the third most used (22%, 18 species), while seeds were the least utilised (6%, 5 species) (Figure 4). The high reliance on stem bark highlights the socio-economic challenges faced by local communities, as it is frequently used not only for traditional medicinal purposes such as treating gastrointestinal disorders, cancer, hemorrhoids, asthma, fever, gonorrhea,

and diabetes but also as a source of fuelwood. This pattern aligns with findings by Ngamsou Abdel et al. (2024), who also identified the stem bark as the most commonly used plant part in treatments related to COVID-19.

In terms of IUCN conservation status, the majority of species fell under the Least Concern (LC) category (78%, 25 species), followed by Near Threatened (NT) (13%, 4 species), and Not Evaluated (NE) (9%, 3 species) (Figure 5).

Table 5. The Most Utilized Vulnerable Species, Plant Parts Used, and IUCN Status

No.	Species	Part Used	IUCN Status
1	<i>Parkia biglobosa</i> (Jacq.) G.Don	Stem bark, Leaves, Seeds & Roots	LC
2	<i>Bauhinia reticulatum</i> (Schum.) Milne Redhead	Stem bark, Seeds, Leaves & Roots	NE
3	<i>Tamarindus indica</i> L.	Stem bark, Leaves, Seeds & Roots	LC
4	<i>Vachellia nilotica</i> (L.) P.J.H. Hurter & Mabb.	Stem bark, Leaves, Seeds & Roots	LC
5	<i>Albizia chevalieri</i> Harms	Stem bark, Root	LC
6	<i>Albizia lebbbeck</i> (L.) Benth,	Stem bark, Leaves & Roots	LC
7	<i>Albizia coriaria</i> Welw. ex Oliv.	Stem bark, Leaves & Roots	NT
8	<i>Bauhinia rufescens</i> Lam.	Stem bark, Leaves & Roots	LC
9	<i>Cassia arereb</i> Delile	Stem bark, Leaves & Roots	NT
10	<i>Detarium microcarpum</i> Guill. & Perr.	Stem bark, Roots & Leaves	LC
11	<i>Detarium senegalense</i> J.F.Gmel	Stem bark, Leaves & Roots	LC
12	<i>Dialium guineense</i> Willd.	Stem bark, Roots & Leaves	LC
13	<i>Delonix regia</i> (Hook.) Raf.	Stem bark, Leaves, Roots & Seeds	LC
14	<i>Entada africana</i> Guill. & Perr.	Stem bark, Leaves, Seeds & Roots	LC
15	<i>Faidherbia albida</i> (Delile) A. Chev.	Stem bark, Leaves & Roots	LC
16	<i>Milletia thonningii</i> (Schumach. &Thorn.) Baker	Stem bark, Leaves & Roots	LC
17	<i>Prosopis africana</i> (Guill. & Perr.) Taub.	Stem bark, Leaves & Roots	LC
18	<i>Acacia polyacantha</i> Willd.	Stem bark, Leaves & Roots	LC
19	<i>Acacia pycnantha</i> Benth	Stem bark, Leaves & Roots	LC
20	<i>Cassia fistula</i> L.	Stem bark, Leaves & Roots	LC
21	<i>Daniellia oliveri</i> Hutch. & Dalziel	Stem bark, Leaves & Roots	LC
22	<i>Dichrostachys cinerea</i> (L.) Wight & Arn,	Stem bark, Leaves & Roots	LC
23	<i>Erythrina senegalensis</i> D.C.	Stem bark, Roots & Leaves	LC
24	<i>Pterocarpus santalinoides</i> D.C.	Stem bark, Leaves & Roots	NE
25	<i>Senna siamea</i> (Lam.) H.S. Irwin & Barneby	Stem bark, Leaves & Roots	LC
26	<i>Dalbergia sissoo</i> Roxb.	Stem bark & Leaves	NT
27	<i>Erythrophleum saueolens</i> (Guill. & Perr.) Brenan.	Stem bark, Leaves & Roots	NE

No.	Species	Part Used	IUCN Status
28	<i>Erythrophleum africana</i> (Benth.) Harms	Stem bark, Leaves & Roots	LC
29	<i>Indigofera polyphylla</i> DC.	Stem bark & Leaves	NT
30	<i>Isoberlinia doka</i> Craib & Stapf	Stem bark, Leaves & Roots	LC
31	<i>Lonchocarpus sericeus</i> (Poir.) Dc.	Stem bark, Leaves & Roots	LC
32	<i>Leucaena leucocephala</i> (Lam.) de Wit	Stem bark, Leaves & Roots	LC

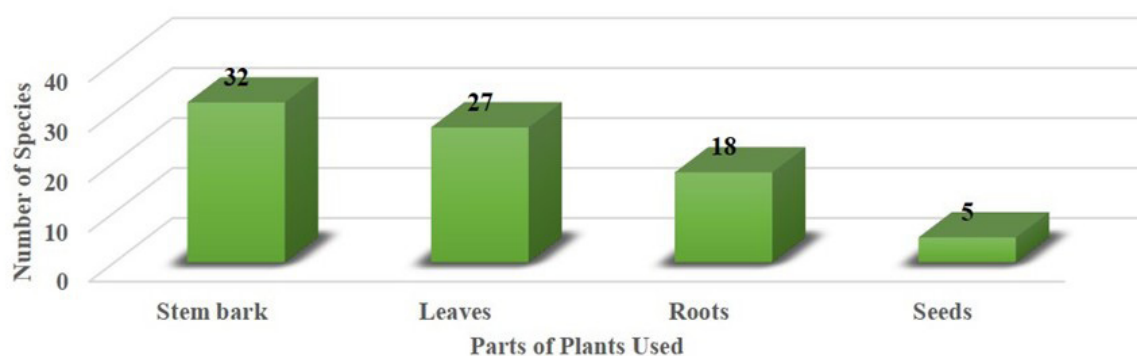


Figure 4. Plant Parts Used

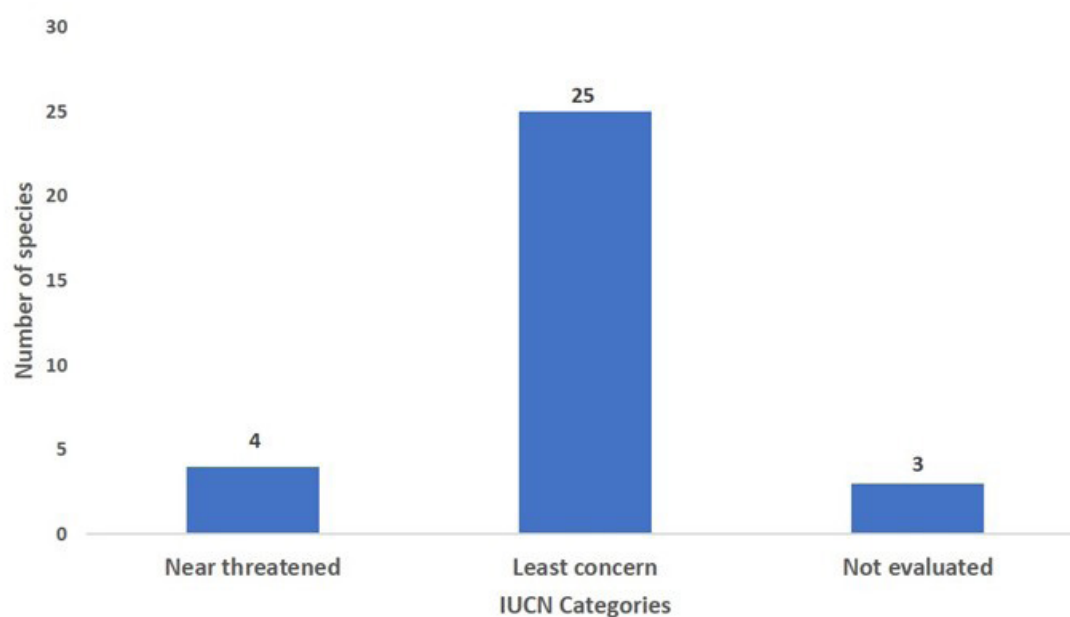


Figure 5. Global IUCN Status of the Overutilized Species Identified Factors Responsible for The Plant's Vulnerability

The overutilisation of plant resources in Katsina State has been attributed to a variety of anthropogenic activities. The major factors identified in this study include the deforestation (57 respondents, 31%) agricultural expansion and related challenges (41 respondents, 23%), urbanisation (38 respondents, 21%), overharvesting (27 respondents, 15%), introduction of invasive species (17 respondents, 10%), (Figure 6). These human-induced pressures have significantly altered natural ecosystems and disrupted biodiversity, thereby threatening ecological stability (Prakash & Verma, 2022).

Among the threats, deforestation was reported by respondents as the most pressing concern. If left unmitigated, it poses the risk of widespread ecosystem degradation. These findings are consistent with those of Bello et al., 2019 and Dueñas et al., 2018, who similarly reported that a majority of threatened plant species in their studies were adversely affected by anthropogenic drivers such as overutilisation, deforestation, unsustainable harvesting practices, and agricultural encroachment.

Anthropogenic activities have significantly altered ecosystems and continue to pose substantial threats to species' survival within the study area. In this study, thirty-two (32) highly vulnerable plant species were identified. Of these, 26(81%) were reported to be

exploited for fuelwood, 15(47%) for fodder, 11(34%) for timber, 9(28%) for the production of wooden items such as handles, doors, and windows, 5(16%) for charcoal, 4(13%) each for mortar, pestle, and handicrafts, and 1(3%) for dyes (Figure 7). These findings illustrate the extent of human reliance on plant resources for a variety of utilitarian purposes, despite the potential ecological consequences.

This pattern of overutilisation is consistent with previous studies by Gasperini & Artuso (2022); Poudyal et al. (2023); Charmakar et al. (2024), who emphasized that unsustainable exploitation of natural resources, particularly for fuelwood, timber, and related uses, plays a critical role in accelerating biodiversity loss. These findings reinforce the pressing need for sustainable resource management and conservation strategies targeting vulnerable species.

7. The influence of human activities on the species vulnerability

Anthropogenic activities have significantly altered ecosystems and continue to pose substantial threats to plant species' survival within the study area. In this study, 32 highly vulnerable plant species were identified. Of these, 26 (81%) species were reported to be exploited for fuelwood, 15 (47%) for fodder, 11(34%) for timber, 9 (28%) for the production

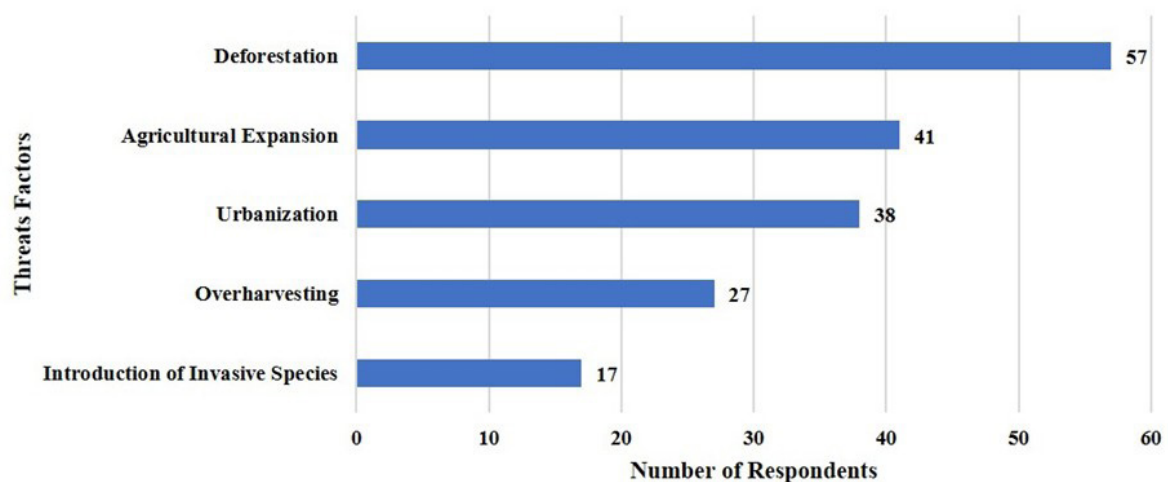


Figure 6. Threat factor causing plant species vulnerability in the study area

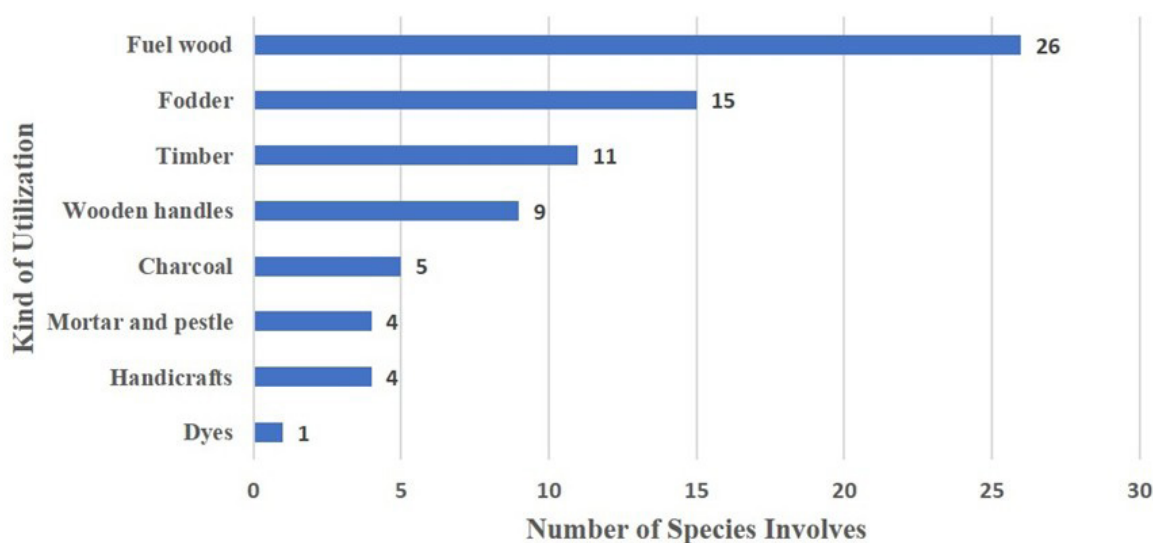


Figure 7. The utilization of the threatened Species

of wooden items such as handles, doors, and windows, 5(16%) for charcoal, 4 (13%) each for mortar, pestle, and handicrafts, and 1(3%) for dyes (Figure 7). These findings illustrate the extent of human reliance on plant resources for a variety of utilitarian purposes, despite the potential ecological consequences.

This pattern of overutilisation is consistent with previous studies by Gasperini & Artuso (2022); Poudyal et al. (2023; Charmakar et al. (2024), who emphasized that unsustainable exploitation of natural resources, particularly for fuelwood, timber, and related uses, plays a critical role in accelerating biodiversity loss. These findings reinforce the pressing need for sustainable resource management and conservation strategies targeting vulnerable species.

IV. CONCLUSION

This study highlights the alarming vulnerability of plant species in Katsina State, particularly in Sandamu, Zango, and Maiadua, Local Government Areas. The threat factors identified include deforestation (31%), agricultural expansion (23%), urbanisation (21%), overharvesting (15%), and the introduction of invasive species (10%). The

findings reveal a high dependence on plant resources for fuelwood, timber, fodder, and traditional medicine practice, while vital to local livelihoods, are contributing to the rapid decline of several ecologically and culturally significant species.

The study identified 32 vulnerable *Fabaceae* species across 25 genera and 5 subfamilies. *Albizia* emerged as the most vulnerable genus, with three species, while *Acacia*, *Bauhinia*, *Cassia*, *Detarium*, and *Erythrophleum* each contained two vulnerable species. Most respondents were male (87%), aged 46-75 (53%), and married (77%), with traditional medical practitioners (34%) being the dominant occupations. Among the 32 vulnerable species identified, four species, *Parkia biglobosa* (Vulnerability Index/VI of 3.00), *Tamarindus indica*, *Bauhinia reticulatum*, and *Vachellia nilotica*, each with a VI of 2.67 were found to be the most at risk due to intensive human use. The stem bark (39%) was the most utilised plant part.

Although only four species, namely *Albizia coriaria*, *Cassia arereh*, *Dalbergia sissoo* and *Indigofera polyphylla* are currently listed as Near Threatened under IUCN criteria, region-specific pressures suggest that the global conservation status may underestimate local threats. Therefore,

establishing a regional plant assessment framework is critical for providing timely data and supporting effective conservation planning. Immediate, context-sensitive conservation strategies, including community engagement, sustainable harvesting practices, reforestation efforts, and policy implementation, are essential to mitigate the ongoing loss of biodiversity. Without such intervention, the degradation of plant resources will not only threaten ecological balance but also compromise the socio-economic resilience of the communities that depend on them.

REFERENCES

- Abdallah, M. S., Mustafa, M., Nallappan, M. A., Go, R., & Go, R. (2020). Ethnobotanical Knowledge of the Most Commonly Used Plants in the Management of Gastrointestinal Ailments in Yobe State, Nigeria. *African Journal of Traditional, Complementary and Alternative Medicines*, 17(1), 21–32. <https://doi.org/10.21010/ajtcam.v17i1.3>
- Aftab, T., & Hakeem, K. R. (2021). Medicinal and aromatic plants: Healthcare and industrial applications. In *Medicinal and Aromatic Plants: Healthcare and Industrial Applications*. Springer International Publishing. <https://doi.org/10.1007/978-3-030-58975-2>
- Alemayehu, E., Asfaw, Z., & Woldu, Z. (2023). Ethnobotanical study on medicinal plant knowledge among three ethnic groups in peri-urban areas of south-central Ethiopia. *Journal of Ethnobiology and Ethnomedicine*, 19(1), 10. <https://doi.org/10.1186/s13002-023-00629-w>
- Asigbaase, M., Adusu, D., Musah, A. A., Anaba, L., Nsor, C. A., Abugre, S., & Derkyi, M. (2024). Ethnobotanical and ethnopharmacological survey of medicinal tree species used in the treatment of diseases by forest-fringe communities of Southwestern Ghana. *Heliyon*, 10(1), e23645. <https://doi.org/10.1016/j.heliyon.2023.e23645>
- Badjaré, B., Kokou, K., Bigou-lare, N., Koumantiga, D., Akpakouma, A., Adjayi, M. B., & Abbey, G. A. (2018). Étude ethnobotanique d'espèces ligneuses des savanes sèches au Nord-Togo : diversité, usages, importance et vulnérabilité. *BASE*, 152–171. <https://doi.org/10.25518/1780-4507.16487>
- Bahuguna, K. (2024). Review of Some Important Plant Families. *Certified Journal | Babuguna. World Journal of Pharmaceutical Research*, 13, 1305. <https://doi.org/10.20959/wjpr202415-33443>
- Bello, A., Jamaladdeen, S., Elder, M. T., Yaradua, S. S., Kankara, S. S., Wagini, N. H., Stirton, C. H., & Muasya, M. (2019). *Bothalia-African Biodiversity & Conservation*. <https://doi.org/10.4102/abc.v49i1.2325>
- Bharadwaj, B., Pullar, D., To, L. S., & Leary, J. (2021). Why firewood? Exploring the co-benefits, socio-ecological interactions, and indigenous knowledge surrounding cooking practice in rural Nepal. *Energy Research and Social Science*, 75. <https://doi.org/10.1016/j.erss.2021.101932>
- Breshears, D. D., Fontaine, J. B., Ruthrof, K. X., Field, J. P., Feng, X., Burger, J. R., ... & Hardy, G. E. S. J. (2021). Underappreciated plant vulnerabilities to heat waves. *New Phytologist*, 231(1), 32–39. <https://doi.org/10.1111/nph.17348>
- Byg, A., & Balslev, H. (2001). Diversity and use of palms in Zahamena, eastern Madagascar. In *Biodiversity and Conservation* (Vol. 10).
- Charmakar, S., Kimengsi, J., & Giessen, L. (2024). Linking institutional change mechanisms with forest management outcomes: evidence from community forestry in Nepal. *Ecology and Society*, 29(3), art1. <https://doi.org/10.5751/ES-15085-290301>
- Delgado-Salinas, A., Torres-Colín, L., Luna-Cavazos, M., & Bye, R. (2021). Diversity of Useful Mexican Legumes: Analyses of Herbarium Specimen Records. *Diversity*, 13, 267. <https://doi.org/10.3390/D13060267>
- Dueñas, M. A., Ruffhead, H. J., Wakefield, N. H., Roberts, P. D., Hemming, D. J., & Diaz-Soltero, H. (2018). The role played by invasive species in interactions with endangered and threatened species in the United States: a systematic review. *Biodiversity and Conservation*, 27(12), 3171–3183. <https://doi.org/10.1007/s10531-018-1595-x>
- Elhasnaoui, A., Janah, I., El bouny, H., Amssayef, A., Haidani, A., & Lahrach, N. (2024). Medicinal plants used in the treatment of urogenital disorders in the Drâa-Tafilalet region of Southeastern Morocco: An ethnobotanical survey. *Scientific African*, 26, e02464. <https://doi.org/10.1016/j.sciaf.2024.e02464>
- Noreen, F., Tamoor, M., Adil, M., Mushtaq, U., & Nisa, Q. (2018). Data of ethnomedicinal plants in Wazirabad, District Gujranwala,

- Punjab. *Pak. J. Pharmacol. Care Health Syst*, 5, 2376-0419. <https://doi.org/10.4172/2376-0419.1000194>
- Gasparini, A., & Artuso, S. (2022). How to Improve Biodiversity-Related Information. In *Extinction Governance, Finance and Accounting* (pp. 318–347). Routledge. <https://doi.org/10.4324/9781003045557-19>
- Helida, A., Zuhud, E. A. M., Hardjanto, Purwanto, & Hikmat, A. (2015). Index of cultural significance as a potential tool for conservation of plant diversity by communities in the Kerinci Seblat National Park. *Jurnal Manajemen Hutan Tropika*, 21(3), 192–201. <https://doi.org/10.7226/jtfm.21.3.192>
- Henchion, M., Hayes, M., Mullen, A., Fenelon, M., & Tiwari, B. (2017). Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium. *Foods*, 6(7), 53. <https://doi.org/10.3390/foods6070053>
- Joshi, T., Mandal, S. K., Asati, V., Deepa, P. R., & Sharma, P. K. (2024). Arid/semi-arid flora as a treasure trove of bioactives and bioenergy: the case for underutilized desert legumes towards environmental sustainability. *Environmental Science and Pollution Research*, 31(27), 39025–39036. <https://doi.org/10.1007/s11356-023-29274-2>
- Joshi, T., Sehgal, H., Mandal, S. K., Joshi, M., Deepa, P. R., & Sharma, P. K. (2023). Nutraceutical and flavor profiles in underutilized desert legumes of India: gene editing strategies towards sustainable food development. *Journal of Plant Biochemistry and Biotechnology*, 32(4), 743–750. <https://doi.org/10.1007/s13562-023-00836-2>
- Kankara, S. S., Ibrahim, M. H., Mustafa, M., & Go, R. (2015). Ethnobotanical survey of medicinal plants used for traditional maternal healthcare in Katsina state, Nigeria. *South African Journal of Botany*, 97, 165–175. <https://doi.org/10.1016/j.sajb.2015.01.007>
- Kankara, S. S., Nuhu, A. I., Haruna, M. R., Bindawa, K. A., Abubakar, I. B., & Bello, A. (2022). Indigenous traditional knowledge of medicinal plants used for the management of HIV / AIDS opportunistic infections in Katsina State, Nigeria. *Ethnobotany Research and Applications*, 23. <https://doi.org/10.32859/era.23.35.1-17>
- Kankara, S. S., Samira, I., Abdullahi, K. B., Darma, A. M., Ibrahim, H. Z., & Muhsina, U. (2024). Setting conservation priorities for mimosoides of medicinal importance in the northern part of Katsina State, Nigeria. *Ife Journal of Science*, 26(2), 495–510. <https://doi.org/10.4314/ijfs.v26i2.20>
- Kankara, S. S., Tukur, K., Bello, A., Lawal, U., & Bindawa, K. A. (2020). Medicinal Plants used for Complementary and Alternative Cancer Therapy in Katsina State, Northwestern Nigeria: doi. [org/10.26538/tjnpr/v4i9.21](https://doi.org/10.26538/tjnpr/v4i9.21). *Tropical Journal of Natural Product Research (TJNPR)*, 4(9), 621–629. <https://doi.org/10.26538/tjnpr/v4i9.21>
- Lawal, I. O., Rafiu, B. O., Ale, J. E., Majebi, O. E., & Aremu, A. O. (2022). Ethnobotanical Survey of Local Flora Used for Medicinal Purposes among Indigenous People in Five Areas in Lagos State, Nigeria. *Plants*, 11(5), 633. <https://doi.org/10.3390/plants11050633>
- Leonti, M. (2022). The relevance of quantitative ethnobotanical indices for ethnopharmacology and ethnobotany. *Journal of Ethnopharmacology*, 288, 115008.
- Mechaala, S., Bouatrous, Y., & Adouane, S. (2022). Traditional knowledge and diversity of wild medicinal plants in El Kantara's area (Algerian Sahara gate): An ethnobotany survey. *Acta Ecologica Sinica*, 42(1), 33–45. <https://doi.org/10.1016/j.chnaes.2021.01.007>
- Mothupi, F. M., & Shackleton, C. M. (2025). Traditional knowledge and consumption of wild edible plants in rural households, Limpopo Province, South Africa. *Journal of Ethnobiology and Ethnomedicine*, 21(1), 23. <https://doi.org/10.1186/s13002-025-00773-5>.
- Ngamsou Abdel, K., Mala, W. A., Chimi, P. M., Funwi, F. P., Engoulou, C., Messi Effa, J. A., Kouoguem Kamdem, M. E., Nzoeyuem Djonko, F., Landry Fokoua, U., Brice Adounga, S., & Marguerite Mbolo, M. (2024). Ethnobotanical study and vulnerability of medicinal plants used against the symptoms of COVID-19 in the Lomié subdivision, East Region of Cameroon. *Heliyon*, 10(7), e28247. <https://doi.org/10.1016/j.heliyon.2024.e28247>
- Obakiro, S. B., Kiyimba, K., Lukwago, T. W., Lulenzi, J., Owor, R. O., Andima, M., Hokello, J. F., Kawuma, C., Nantale, G., Kibuule, D., Anywar, G., Waako, P., & Gavamukulya, Y. (2023). Ethnobotanical study of plants used in the management of diabetes mellitus in Eastern Uganda. *Phytomedicine Plus*, 3(4), 100486. <https://doi.org/10.1016/j.phyplu.2023.100486>

- Owor, R. O., Kawuma, C., Nantale, G., Kiyimba, K., Obakiro, S. B., Ouma, S., Lulenzi, J., Gavamukulya, Y., Chebijira, M., Lukwago, T. W., Egor, M., Musagala, P., Andima, M., Kibuule, D., Waako, P., & Hokello, J. (2024). Ethnobotanical survey and phytochemistry of medicinal plants used in the management of HIV/AIDS in Eastern Uganda. *Heliyon*, 10(11), e31908. <https://doi.org/10.1016/j.heliyon.2024.e31908>
- Pacifici, M., Foden, W. B., Visconti, P., Watson, J. E. M., Butchart, S. H. M., Kovacs, K. M., Scheffers, B. R., Hole, D. G., Martin, T. G., Akçakaya, H. R., Corlett, R. T., Huntley, B., Bickford, D., Carr, J. A., Hoffmann, A. A., Midgley, G. F., Pearce-Kelly, P., Pearson, R. G., Williams, S. E., ... Rondinini, C. (2015). Assessing species vulnerability to climate change. In *Nature Climate Change* (Vol. 5, Issue 3, pp. 215–225). Nature Publishing Group. <https://doi.org/10.1038/nclimate2448>
- Poudyal, B. H., Khatri, D. B., Paudel, D., Marquardt, K., & Khatri, S. (2023). Examining forest transition and collective action in Nepal's community forestry. *Land Use Policy*, 134, 106872. <https://doi.org/10.1016/j.landusepol.2023.106872>
- Prakash, S., & Verma, A. K. (2022). Anthropogenic Activities and Biodiversity Threats. *International Journal of Biological Innovations*, 04(01), 94–103. <https://doi.org/10.46505/ijbi.2022.4110>
- Putra, R., Waterman, J. M., Mathesius, U., Wojtalewicz, D., Powell, J. R., Hartley, S. E., & Johnson, S. N. (2022). Benefits of silicon-enhanced root nodulation in a model legume are contingent upon rhizobial efficacy. *Plant and Soil*, 477(1–2), 201–217. <https://doi.org/10.1007/s11104-022-05358-9>
- Ralte, L., Sailo, H., & Singh, Y. T. (2024). Ethnobotanical study of medicinal plants used by the indigenous community of the western region of Mizoram, India. *Journal of Ethnobiology and Ethnomedicine*, 20(1), 2. <https://doi.org/10.1186/s13002-023-00642-z>
- Rao, P. V. S., & Chellaiah Periyasamy. (2020). Biodiversity, Conservation and Medicinal Uses of Seaweeds: The Glimpses. In *Medicinal Plants: Biodiversity, Sustainable Utilization and Conservation* (pp. 21–32). Springer Singapore. https://doi.org/10.1007/978-981-15-1636-8_2
- Reyes-Garcia, V., Huanca, S., Vadez, V., Leonard, W., & Wilkie Reyes-Garcia, D. (2006). *Cultural~ Practical~ and Economic Value of Wild Plants: A quantitative Study in the Bolivian Amazon 1*.
- Saulawa, B. G., Athlopheng, J., Darkoh, M. B. K., & Mosethi, B. (2018). Impact of desertification on livelihoods in Katsina State, Nigeria. *Journal of Agriculture and Life Sciences Vol*, 5(1). <https://doi.org/10.30845/jals.v5n1a5>
- Satheesh Naik, S. J., Bohra, A., Basavaraja, T., Mishra, R. K., Padmaja, G., & Poornima, K. N. (2020). *Diversity of Phytophthora Stem Blight of Pigeonpea and Its Sustainable Management* (pp. 121–130). https://doi.org/10.1007/978-3-030-35947-8_7
- Shah, A., Rahim, S., Nosheen, S., & Shahzad, G. (2023). Medicinal plants used against anxiety and hypertension by the indigenous people of Sargodha division and allied areas, Pakistan. *Ethnobotany Research and Applications*, 25, 1-15.
- Tamene, S., Negash, M., Makonda, F. B., Chiwona-Karlton, L., & Kibret, K. S. (2023). Ethnobotanical study on medicinal plant knowledge among three ethnic groups in peri-urban areas of south-central Ethiopia. *Journal of Ethnobiology and Ethnomedicine*, 19(1), 55. <https://doi.org/10.1186/s13002-023-00629-w>
- Yahara, T., Javadi, F., Onoda, Y., Paganucci De Queiroz, L., Faith, D. P., Prado, D. E., Victor23, J. E., & Nkonki23, T. (2013). *Global legume diversity assessment: Concepts, key indicators, and strategies*. <https://doi.org/10.12705/622.12>
- Yahaya, O. Y. (2021). Assessment of Farm Households' Vulnerability to Desertification in Rural Dry Lands of Katsina State, Nigeria. *Tanzania Journal of Science*, 47(3), 1007–1019. <https://doi.org/10.4314/tjs.v47i3.12>
- Yaradua, S. S., & El-Ghani, M. A. (2015). (2015). Ethnobotanical Survey of Edible Plants Sold in Katsina Metropolis Markets. *International Journal of Science and Research (IJSR)*, 4(12), 884–889. <https://doi.org/10.21275/v4i12.SUB15244>
- Yirgu, A., Mohammed, K., & Geldenhuys, C. J. (2019). Useful medicinal tree species of Ethiopia: Comprehensive review. *South African Journal of Botany*, 122, 291–300. <https://doi.org/10.1016/j.sajb.2019.03.026>

ENHANCED PROPERTIES AND DURABILITY OF RATTAN USING JERNANG, TEAK LEAF EXTRACT, AND RATTAN VINEGAR

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ENHANCED PROPERTIES AND DURABILITY OF RATTAN USING JERNANG, TEAK LEAF EXTRACT, AND RATTAN VINEGAR. Rattan is a non-timber forest product with high export potential and economic value. The use of natural dyes from processing waste and plant materials provides an environmentally friendly alternative for rattan coloring while increasing product value. This study aimed to evaluate rattan processing waste and teak leaves as sources of natural dyes to improve rattan quality and durability. Dyes were extracted using maceration and ultrasound-assisted extraction with water as the solvent and evaluated based on yield and color stability. The selected dye was applied through vacuum impregnation at 50 cmHg for 30 min, followed by pressure impregnation at 7 kgf/cm² for 2 h, using citric acid as a mordant. Treated rattan was evaluated for color change, physical and mechanical properties, and functional groups using Fourier transform infrared spectroscopy (FTIR). The best treatment was coated with rattan vinegar at 25% and 50% (w/v) and tested against dry-wood termites and powder-post beetles. Ultrasound-assisted extraction produced higher yields of 10.64% from rattan processing waste and 15.90% from teak leaves, with greater color stability against ultraviolet exposure and oxidizing agents than maceration. Vacuum-pressure impregnation produced noticeable color changes and generally improved physical and mechanical properties with increasing dye concentration. ED-U-30 showed a 33.85% decrease in ΔE after leaching. ED-U-30 combined with 50% rattan vinegar resulted in the lowest weight losses from dry-wood termites (1.76%) and powder-post beetles (1.25%). The combined application of natural dyes and rattan vinegar improved rattan quality and durability.

Keywords: durability, impregnation, maceration, natural dyes, rattan vinegar, ultrasound-assisted extraction.

PENINGKATAN SIFAT DAN KEAWETAN ROTAN MENGGUNAKAN JERNANG, EKSTRAK DAUN JATI, DAN ASAP CAIR ROTAN. Rotan sebagai hasil hutan bukan kayu yang memiliki potensi ekspor dan nilai ekonomi tinggi. Penggunaan pewarna alami dari limbah pengolahan dan bahan nabati dapat menjadi alternatif pewarnaan yang lebih ramah lingkungan serta meningkatkan nilai produk rotan. Penelitian ini bertujuan mengevaluasi potensi limbah pengolahan jernang dan daun jati sebagai sumber pewarna alami untuk meningkatkan kualitas dan keawetan rotan. Ekstraksi pewarna dilakukan menggunakan metode maserasi dan ultrasound-assisted extraction (UAE) dengan air sebagai pelarut. Ekstrak dievaluasi berdasarkan rendemen dan stabilitas warna. Pewarna terbaik diaplikasikan pada rotan melalui impregnasi vakum pada 50 cmHg selama 30 menit yang dilanjutkan dengan tekanan 7 kgf/cm² selama 2 jam menggunakan asam sitrat sebagai mordant. Rotan hasil impregnasi diuji perubahan warna, sifat fisik dan mekanis, serta gugus fungsi menggunakan Fourier transform infrared spectroscopy (FTIR). Perlakuan terbaik kemudian dilapisi asap cair rotan pada konsentrasi 25% dan 50% (b/v), diuji terhadap rayap kayu kering dan kumbang bubuk kayu. Hasil menunjukkan UAE menghasilkan rendemen lebih tinggi, yaitu 10,64% dari limbah pengolahan jernang dan 15,90% dari daun jati, serta menghasilkan warna yang lebih stabil terhadap ultraviolet dan oksidator dibandingkan maserasi. Impregnasi vakum-tekan menghasilkan perubahan warna yang nyata serta secara umum memperbaiki sifat fisik dan mekanis rotan seiring peningkatan konsentrasi pewarna. Perlakuan ED-U-30 menunjukkan penurunan ΔE sebesar 33,85% setelah pelindian. Kombinasi ED-U-30 dengan asap cair rotan 50% menghasilkan kehilangan bobot terendah, yaitu 1,76% akibat serangan rayap kayu kering serta 1,25% akibat kumbang bubuk kayu. Penggunaan pewarna alami bersama asap cair rotan berpotensi meningkatkan kualitas, nilai, sekaligus keawetan rotan.

Kata kunci: Idasap cair, impregnasi, keawetan, maserasi, pewarna alami, ultrasonikasi.

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I. INTRODUCTION

Rattan is a valuable non-timber forest product with significant potential as a raw material for furniture and handicrafts. The largest producer in the world in terms of rattan production is Indonesia, which contributes about 85% of the world's total production, or 690,000 tons per year (Kemenperin, 2024). Indonesia is home to about 350 rattan species. In relation to the 13 reported rattan genera in the world, there are 10 types that are indigenous to Indonesia, thus making the country among the world's centers of rattan diversity (Jasni et al., 2012). Among these types, mandola rattan (*Calamus oxleyanus*), naturally found in the tropical forests of Sumatra and Kalimantan, is known for its excellent structural qualities. It is noted for its larger diameter, relatively short internode length, smooth texture, and creamy to light brown color (Karipalai et al., 2019). As such, the mandola rattan is a high-grade material that can be effectively used as structures in the manufacture of furniture especially chair, table, and sofa frames (Putri et al., 2016). Despite its usefulness, rattan is viewed as having a dull color (Rowell, 2005) and poor durability (Satiti et al., 2017).

According to Chowdhary (2024), rattan furniture design should also align with color and aesthetics to meet customers' needs. Apart from increasing visual appeal of the product, the coloration is an important stage of the finishing since it adds great market value to the rattan items. Synthetic dyes are primarily used in rattan furniture finishing because they offer bright, durable colors, easy application, and affordable prices (Paryanto et al., 2012). The use of spray finishing and dyeing with synthetic dyes helped Hartanto and Rudyanto (2017) to obtain a wide range of colors. However, there are serious concerns associated with the use of synthetic dyes since they often contain carcinogenic and allergenic substances (Komarawidjaja, 2016). While they were regulated in some industries, they are still widely used in rattan finishing since there is no better alternative yet. Therefore,

researchers have focused on plant-based natural dyes as an environmentally friendly replacement of synthetic dyes.

Natural dyes are mainly derived from roots, bark, leaves, flowers, and plant shells (Yuniati et al., 2024). A promising natural dye source for rattan is jernang, a deep-red resin (dragon blood resin) coating the fruit of rattan species in the genus *Daemonorops*. Jernang has long been used as a natural coloring agent and an active ingredient in medicinal and cosmetic products (Mahlinda et al., 2020; Sari et al., 2022). However, its processing waste (JPW) remains severely underutilized, as it is currently used primarily as fertilizer (Waluyo, 2008). The red color of JPW indicates a high residual content of active resin pigments. Extraction of JPW by decoction using water at a temperature of 96–98 °C still produces jernang in the form of a red extract, with a yield of approximately 5.15% (Emha, 2020). This yield value is considerably lower than that of jernang extract obtained through the traditional processing of *Daemonorops acehensis* Rustiarni fruit by the Acehese community, which reaches 12.15% (Waluyo, 2013). Redness of jernang is due to the presence of flavonoids, especially nondracorhodin and nondracorubin (Asra et al., 2021). Likewise, teak leaves, considered agricultural waste, have shown potential as sources of natural dye. According to Charoensit et al. (2021), teak leaf extract is composed of anthraquinones, which have different color characteristics such as tectoleafquinone (red), anthracteone (orange) (Lacret et al., 2011), and tectoquinone (yellow) (Bhuyan et al., 2005). It can be seen from the studies that jernang and teak leaves are among the best candidates for natural dye, which can help in decreasing the dependence on rattan.

The pigmented compounds must be extracted from the plant source in order to be able to serve as natural dyes. Some of the methods used for extracting the pigment compounds from the teak leaves and jernang include decoction and boiling (Emha, 2020; Wiyono and Kartikawati, 2017). The process

involves subjecting the materials to heat at a temperature of 96-98 °C, in order to accelerate the dissolution of the water-soluble compounds. While traditional methods of extracting compounds from teak leaves and jernang have proven to be effective in many instances, exposure to extremely high temperatures leads to thermal degradation of compounds such as anthocyanins and flavonoids. Besides, traditional techniques require long extraction periods and a considerable amount of solvents. In addition, traditional extraction methods pose the risk of thermal degradation of thermolabile compounds (Azizi et al., 2023). To avoid heat-induced degradation, maceration can be used at room temperature, although it requires long extraction periods, filtration, and evaporation. Maceration is easy, inexpensive, and appropriate for thermolabile compounds because it does not use any heat (Ghozali et al., 2023). As an alternative, ultrasound-assisted extraction (UAE) provides an efficient, eco-friendly method in which the use of ultrasonic waves generates. The yield pattern derived using UAE has been observed to be similar to the results reported by Sukandar et al. (2022). Nonetheless, there have been no studies about the integration of processes of natural-dye extraction, rattan dyeing, and preservation after that, despite individual study conducted on these areas. Such aspects have been individually studied in several recent international researches. The research performed by Vespignani et al. (2023) was related to wood dyeing using environmentally friendly technology. In contrast, Lee et al. (2022) focused on using pyroligneous acid for wood preservation through vacuum-pressure impregnation. However, no research has examined the use of these three technologies together.

Natural dyes have the potential to improve the appearance of rattan, but the problem here is the inability of natural dyes to hold their colors since the colors are easily lost (Vespignani et al., 2023). In order to solve this problem, it is necessary to use a mordant such as citric acid, which will react with -OH groups in the cellulose to form covalent

bonds, hence increasing the bonding ability of the substrate and dye (Bogoriani, 2011). The use of the citric acid mixture was found to be more effective in maintaining its color for ten washing cycles in the color fastness test as explained by Dafiq et al. (2025). This issue can be addressed with faster methods such as vacuum impregnation (Augustina et al. 2024), which significantly reduces dyeing time and improves effectiveness. According to the research carried out by Nguyen et al. (2018), the vacuum-pressure method proved to have an impressive impact on dyeing, penetration, and color changes, especially for the samples dyed at 1000 kPa with pressure time of 120 minutes. Besides color fastness, rattan is very vulnerable to biodeterioration from fungi and drywood beetles. The novelty of this study is the integration of three sequential treatment stages in a single rattan system: (1) UAE extraction of natural dyes from jernang processing waste and teak leaves, (2) combination of natural dyes with citric-acid-assisted vacuum-pressure impregnation of rattan for coloration, and (3) rattan-vinegar post-preservation for protection against drywood termites and powderpost beetles. Therefore, a preservation treatment is essential to enhance durability (Hamdi, 2012). One promising approach is applying rattan vinegar as a coating material, as it contains phenolic compounds and tar that are toxic to insects (Hossain et al. 2013), thereby offering potential to improve rattan resistance to biodeteriorating agents. The low concentration of liquid smoke used may cause low preservative retention in wood; therefore, Fakkar et al. (2023) determined that the minimum percentage of liquid smoke should be around 25%. Therefore, this study aimed to compare maceration and UAE to identify an efficient and stable natural-dye extraction method, characterize rattan after vacuum-pressure dye impregnation, and evaluate changes in color, physical and mechanical properties, and functional groups. The study also assessed the effects of rattan-vinegar post-treatment on the resistance of the optimally dyed rattan to drywood termites and powderpost beetles.

II. MATERIAL AND METHOD

A. Materials

The research was conducted from February 2024 to March 2025. Extraction and durability testing of rattan were conducted at the Non-Timber Forest Products Laboratory and the Termite Laboratory, Department of Forest Products, Faculty of Forestry and Environment, IPB University. Other experiments were performed at the Integrated Laboratory of Bioproducts (ILaB), Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN), Cibinong, Bogor. Mandola rattan (*Calamus oxleyanus*) sourced from Cirebon, Indonesia, with a length of 5 cm, and oven-dried at 103 ± 2 °C for 24 h before use. Teak leaves (young leaves) were sourced from the National Research and Innovation Agency (BRIN), Cibinong, Bogor, Indonesia, and the jernang processing waste (JPW) was sourced from Aceh, Indonesia. All chemicals used in this study were commercially available. Citric acid was obtained from a Merck distributor, and distilled water was obtained from a commercial supplier. Rattan vinegar was obtained from the Integrated Forest Products Laboratory, Bogor, Indonesia.

B. Methods

1. Raw Material Preparation

The jernang processing waste (JPW) was ground into powder with a 40-60 mesh particle size. Teak leaves (D) were cut into small pieces. The moisture content of the powder was determined by weighing approximately 2 g (initial weight), drying it in an oven at 103 ± 2 °C for 24 h until a constant oven-dry weight was reached, and repeating the process three times (triplicate analysis, $n=3$).

2. Natural Dye Extraction, Extract Color Stability, and Rattan Color Evaluation

Extraction was done using maceration and ultrasound-assisted extraction (UAE) with water as the solvent. Maceration was performed at room temperature for 24 h, while UAE

was conducted at 40 Hz for 30 min. For each extraction, 300 g of sample (JPW powder or teak leaves with known moisture content of 19.64% and 8.64%) was mixed with 1500 mL of water, and the process was repeated three times. The filtrate was then evaporated at 40–60 °C using a rotary evaporator. Two milliliters of filtrate were utilized to calculate the concentration of the extract through the drying process in 103 ± 2 °C, while the rest of the solution was dried in 40–60 °C and acted as a source of the natural dye material. Extraction yield was calculated using the calculation of Kusuma & Aprileili (2022). This yielded four different extracts, as outlined in Table 1 below.

Table 1. Sample code and description of the extract

Codes	Descriptions
EJ-M	Jernang waste with the maceration method
EJ-U	Jernang waste with the UAE method
ED-M	Teak leaves with the maceration method
ED-U	Teak leaves with the UAE method

The color stability of the extracts was analyzed in triplicate ($n=3$) by UV-Visible Spectrophotometer using the method of Kurniati et al. (2012), in a wavelength range of 200-600 nm. The extract solutions were made by dissolving 30 g of extract in 150 mL of distilled water. Color stability was analyzed according to the absorbance variation caused by certain conditions such as sunlight exposure, pH level, and oxidizing agents. In the sunlight condition, 10 mL of extract solution was put in a test tube and exposed to direct sunlight for 3 hours; absorbance was taken every hour. In the pH condition, the extract solutions were varied by adding buffer to get pH 2, 3, 5, and 8, then the absorbance of each solution was taken. In oxidizing agent condition, 10 mL of solution was added to 1 mL of 30% H₂O₂. The absorbance was recorded at 0 h, 3 h, 4

h, and 5 h of oxidant exposure. Based on the extraction yield and color stability analysis, the most appropriate extract from each source was selected.

3. Rattan Impregnation

The natural dyes were prepared from the EJ and ED extracts based on extraction yield and color stability. The concentrations of dyes were determined by conducting some initial experiments prior to the actual experiment. Concentrations below 15% (w/v) produced insufficient color intensity on the rattan surface, whereas concentrations above 30% (w/v) produced saturation without meaningful improvements in color depth or stability. The final design therefore used two factors: extract type (jernang processing-waste extract and teak leaf extract) and extract concentration (15% and 30% w/v), with 5% citric acid (w/v) added as a mordant (Table 2). Rattan samples, 5 cm long with an average diameter of 2 cm, were dried at 103 ± 2 °C until a constant oven-dry weight (W1) was reached. The samples were immersed in the natural-dye impregnation solution and placed in an impregnation chamber under vacuum (50 cmHg for 30 min), followed by pressure (7 kgf/cm² for 2 h). After impregnation, the samples were dried again at 103 ± 2 °C until a constant oven-dry weight (W2) was achieved. The impregnation process was conducted at room temperature (approximately 25–27 °C).

Rattan Color Measurement and Leaching Test

Rattan color was measured using a color reader (Konica Minolta CR-10+) before and after the leaching test to evaluate color stability. The leaching test was performed by immersing

the samples in hot water and heating them in a water bath at 40 °C for 3 h. After treatment, the samples were drained and dried at room temperature. Color change was evaluated by comparing the samples' L*, a*, and b* values before and after soaking, following the method of Muflihati et al. (2014).

4. Physical and Mechanical Properties of Rattan

The samples were evaluated for physical and mechanical properties, including moisture content, density, natural-dye uptake as weight percent gain (WPG), bulking coefficient (BC), and liquid uptake (LU), and hardness, following Augustina et al. (2024). A total of 10 rattan samples were used for each treatment.

5. FTIR Testing

The functional groups of rattan were analyzed using Fourier Transform Infrared Spectroscopy (FTIR) to identify potential chemical changes after treatment. The spectra were recorded in the mid-infrared region from 4000 to 400 cm⁻¹, averaging 32 scans at a resolution of 4 cm⁻¹ to ensure a reliable signal-to-noise ratio (Solihat et al., 2022).

6. Durability Testing of Rattan

To determine the optimal natural dye formulation for subsequent durability testing, a multi-criteria decision scoring matrix was established based on physical and mechanical performance metrics. Six target parameters were evaluated: moisture content, density, weight percent gain (WPG), bulking coefficient (BC), liquid uptake (LU), and hardness. Based on the characterization results of rattan impregnated with the best formula using the scoring method—showing superior physical and mechanical properties—the samples

Table 2. Sample code and description of rattan impregnation

Codes	Descriptions
K	Rattan untreated/no coloration
EJ-U-15	Coloration of rattan with 15% concentration of jernang waste extract
EJ-U-30	Coloration of rattan with 30% concentration of jernang waste extract
ED-U-15	Coloration of rattan with 15% concentration of teak leaves extract
ED-U-30	Coloration of rattan with 30% concentration of teak leaves extract

were subsequently subjected to preservation treatment using rattan-vinegar (RV) solutions at concentrations of 25% and 50% (w/v). Durability testing against drywood termites was conducted over 12 weeks following SNI 7207-2014, with a slight modification in which the termites were placed not on the longest surface of the rattan but instead on one of its ends (BSN 2014), while resistance to powderpost beetles was evaluated over three months, referring to the method of Febrianto et al. (2014). The same six criteria and 1–3 scoring scale were applied consistently to all formulations as a study-specific comparative decision matrix; no independent external validation of the scoring matrix was performed. Both drywood-termite and powderpost-beetle durability assessments were performed under controlled laboratory conditions. For durability testing, K denotes untreated rattan; ED-U-30 and EJ-U-30 denote rattan colored with 30% teak-leaf and jernang-waste extracts obtained by UAE, respectively. RV denotes rattan vinegar, and RV25 and RV50 indicate post-treatment with 25% and 50% (w/v) rattan-vinegar solutions. Thus, ED-U-30+RV25, EJ-U-30+RV25, ED-U-30+RV50, and EJ-U-30+RV50 denote the corresponding combined coloration and rattan-vinegar treatment.

C. Analysis

The extract yield and color characteristics were statistically analyzed using a two-factor completely randomized design (CRD)

(Rahmawati and Erina, 2020), with raw material type (jernang/J and teak leaves/D) and extraction method (maceration and UAE) as factors. Extract color stability was analyzed using a three-factor CRD for each stability test, with raw material type (jernang processing waste and teak leaves), extraction method (maceration and UAE), and test level/exposure period as factors. The third factor comprised four levels for each test: pH 2, 3, 5, and 8; UV exposure at 0, 1, 2, and 3 h; and oxidant exposure at 0, 3, 4, and 5 h. The characteristics of rattan impregnated with natural dyes—including color, physical, and mechanical properties—were analyzed using a one-factor CRD, with natural dye formulation as the factor. Statistical significance was evaluated at $p < 0.05$. Before the analysis of variance (ANOVA), the assumptions of normality and homogeneity of variance were tested. Where significant main or interaction effects were detected ($p < 0.05$), Duncan's Multiple Range Test (DMRT) was conducted for post-hoc pairwise comparisons. The optimal dyeing formulation for rattan was determined using a scoring method based on moisture content, density, and natural dye uptake (WPG, BC, and LU). A score of 1 indicated poor performance, 2 indicated good performance, and 3 indicated very good performance. The best formula was determined from the total points. Data on rattan durability against termites and powder-

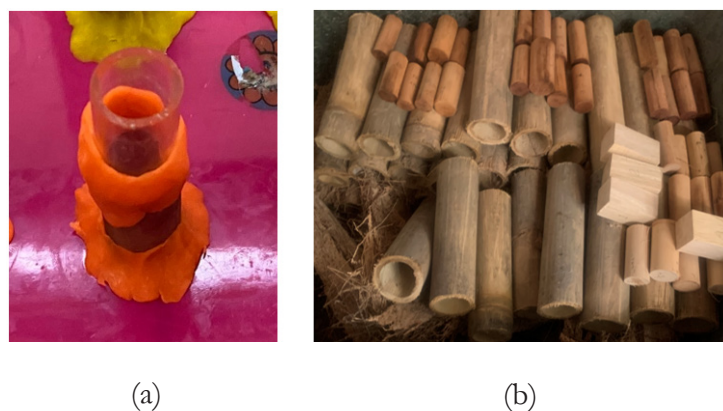


Figure 1. Durability-test setup: (a) funnel placement on one end of the rattan specimen for drywood-termite testing; (b) rattan samples placed in bamboo culms infested with powderpost beetles for powderpost-beetle testing

post beetles were statistically analyzed using a one-factor Completely Randomized Design (CRD), with treatment formulation as the factor and seven levels: K, ED-U-30, EJ-U-30, ED-U-30+RV25, EJ-U-30+RV25, ED-U-30+RV50, and EJ-U-30+RV50. All statistical analyses were conducted using RStudio (Lusiana & Mahmudi 2021), while FTIR results were analyzed descriptively. Raw-material moisture content, extraction yield, extract color stability, and extract color characterization were determined in triplicate ($n = 3$), whereas physical, mechanical, and impregnation-property measurements used 10 rattan specimens per treatment. Before ANOVA and DMRT, normality and homogeneity of variance were tested, and the data met these assumptions.

III. RESULT AND DISCUSSION

A. Appearance, Yield, and Color Stability of Natural Dye Extracts

The plant source and extraction method significantly influenced the appearance, yield, and color stability of the natural dye extracts. Sambodo et al. (2022) reported a notably high extract yield of 33.09% (w/w) from teak leaves (*Tectona grandis*), attributed to the thin leaf structure and the efficient dissolution of bioactive compounds via 70% ethanol maceration. In contrast, Sari and Handika (2020) observed that dragon's blood resin extracted from *Daemonorops draco* had a comparatively low maximum yield of 20.02% in 100% ethanol extraction because of its more compact resin structure and less porous tissues. In addition to this, results by Sulaiman et al. (2020) also demonstrate that small-sized jernang fruits and the use of more powerful solvents (ethanol-chloroform) increase extract yield.

Interaction between raw materials and extraction methods towards the yield of the extract was highly significant ($p < 0.05$). Duncan's test showed that there was a highly significant difference between the four extracts derived from the different raw materials with

different extraction methods. The maximum extract yield was recorded by ED-U, followed by ED-M, EJ-U, and EJ-M (Table 3). The results show that UAE is a more efficient extraction technique than maceration for both raw materials. Familasari et al. (2023) also noted the same trend in their study. This is due to the cavitation energy of UAE, which creates micro-solvent bubbles that break down the cell walls (Budiastra et al., 2020). The ultrasonic waves lead to the generation of bubbles followed by implosive collapse in the liquid solvent, resulting in the creation of microjets and high-pressure shearing force. The force helps in breaking the rigid lignocellulosic cell walls of teak leaves and jernang waste, enabling solvent penetration and rapid mass transfer of intracellular polyphenols without the need for a long-time heating process. As a result, heat-labile chromophores like flavonoids and anthocyanins are successfully extracted without any damage due to heat, maintaining their chemical stability and resistance against UV and photochemical oxidation. This explanation aligns well with the results of Tiwari (2015) and Linares and Rojas (2022), who found that cavitation helps prevent oxidation of thermolabile pigments during green extraction. This explanation supports the recently published international UAE studies which reported that acoustic cavitation enhances solvent penetration and effective diffusivity, facilitates mass transfer of pigments, and may help in avoiding prolonged thermal exposure (Linares and Rojas, 2022; Thakur et al., 2022). The EJ-M yield obtained in this study (Table 3) was higher than that reported by Emha (2020) using the decoction method (5.15%). The lower yield from decoction is likely due to the high temperatures (96–98 °C) used, which can damage or volatilize thermolabile compounds (Anwar et al., 2025), thereby reducing extract yield (Asendy et al., 2018). Nonetheless, the yields in this study were still lower than that of rattan fruit extract obtained by traditional extraction methods (12.15%) (Waluyo, 2013). The ED-U yield achieved here using UAE with water as the solvent was 15.90%, lower than

the 19.69% reported by Budiman et al. (2020) using the same raw material and method but with ethanol as the solvent. This difference highlights the strong influence of solvent type on extraction yield (Satriawan and Wijaya, 2023).

The interaction between the raw material and the extraction method influenced the L^* , a^* , and b^* values ($p < 0.05$). Based on Duncan's Multiple Range Test, there were no significant differences in L^* , a^* , and b^* values between jernang extracts obtained via maceration (EJ-M) and those obtained via UAE (EJ-U); however, both differed significantly from teak leaf

extracts obtained via either maceration (ED-M) or UAE (ED-U) (Table 4). The L^* values of EJ ranged from 17.31 to 18.88, indicating low lightness, whereas ED showed higher L^* values of 34.42 to 36.89. All a^* values were positive, confirming a red component in both extracts; the red component was greater for ED (35.93 to 39.05) than for EJ (17.21 to 17.27). Positive b^* values indicated a yellow component, which was also greater for ED (38.09 to 38.26) than for EJ (17.11 to 17.92). Higher positive L^* values indicate greater lightness (Muflihahati et al., 2014). Because Table 4 reports the absolute CIELAB coordinates of independent extract samples

Table 3. Yield of natural dye extracts

Extraction Methods	Raw Materials	
	Jernang extract yield (%)	Teak leaf extract yield (%)
Maceration	8.81 ± 0.25^a	12.04 ± 0.51^b
UAE	10.64 ± 0.67^{ab}	15.90 ± 0.17^c

Notes: Values are reported as mean $\pm$ SD. Different lowercase superscript letters indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

Table 4. CIELAB color characteristics of natural dye extracts

Color characterization of Extracts	Jernang Extract		Teak leaves Extract	
	Maceration	UAE	Maceration	UAE
Name of Color	<i>Maroon</i>	<i>Maroon</i>	<i>Dark Red</i>	<i>Fire Brick</i>
L^*	17.31 ± 0.89^a	18.88 ± 0.73^a	34.42 ± 0.59^b	36.89 ± 0.56^b
a^*	17.27 ± 2.79^a	17.21 ± 1.81^a	39.05 ± 0.39^b	35.93 ± 1.53^b
b^*	17.11 ± 0.27^a	17.92 ± 0.40^a	38.09 ± 0.15^b	38.26 ± 1.25^b

Notes: Values are reported as mean $\pm$ SD. Different lowercase superscript letters within the same row indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

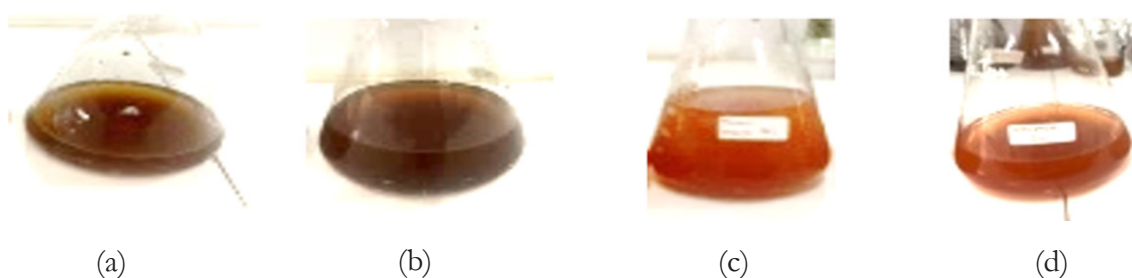


Figure 2. Appearance of natural dye extracts: (a) macerated jernang processing-waste extract; (b) UAE jernang processing-waste extract; (c) macerated teak leaf extract; (d) UAE teak leaf extract.

without a predefined reference color, ΔE was not calculated for this extract-comparison table. Overall color change (ΔE) was calculated for the rattan before and after leaching and is reported in Table 6. The similar CIELAB profiles obtained by maceration and UAE indicate that the mild UAE conditions did not cause a major shift in extract color (Figure 2).

B. Color Stability

Color stability and intensity are important factors that determine a product's attractiveness and quality, as they not only enhance visual appeal but also increase consumer acceptance and market competitiveness. In natural-based materials such as rattan and wood products, inconsistent coloration may reduce perceived quality, whereas durable and vibrant hues indicate better performance and durability of the dyeing treatment (Loppies et al., 2020). The analysis of variance showed that neither the interaction between extract type and pH value nor the effect of each factor significantly influenced the absorbance (Figure 3). The extracts contained flavonoid and anthocyanin compounds, which are more stable under acidic conditions (Simanjuntak et al., 2014).

Observations of color stability in jernang waste extract and teak leaf extract revealed that ultraviolet exposure caused pigment degradation in the maceration method, as indicated by decreasing absorbance, fading color, and clearer appearance with more prolonged exposure. The three-factor ANOVA showed a significant interaction among raw material type, extraction method, and exposure period under UV exposure ($p < 0.05$). DMRT was therefore applied to the 16 raw-material $\times$ extraction-method $\times$ exposure-period combinations. The macerated extracts showed time-dependent changes in absorbance, with ED-M showing the clearest decline; in contrast, EJ-U and ED-U retained the same DMRT group (d) across all exposure times, indicating no significant change within the UAE extracts during the 3-h UV test (Figure 4). Rundubelo et al. (2019) also reported that protracted ultraviolet exposure increases pigment degradation, decreases absorbance, and causes color fading due to the decomposition of anthocyanin compounds.

Degradation by oxidizing agents (Figure 5) further showed that H_2O_2 accelerated pigment photodegradation, as its reactive groups broke down pigment molecules, leading to

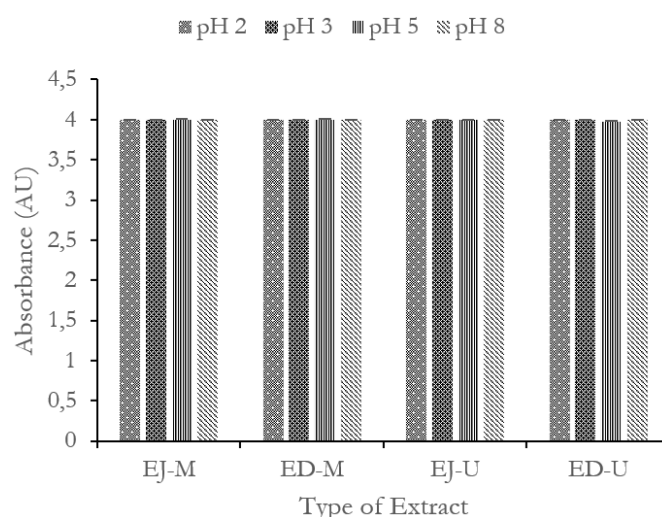


Figure 3. Effect of pH on the color stability of the natural dye extracts base on absorbance. EJ-M = jernang extract obtained by maceration; ED-M = teak leaf extract obtained by maceration; EJ-U = jernang extract obtained by UAE; ED-U = teak leaf extract obtained by UAE.

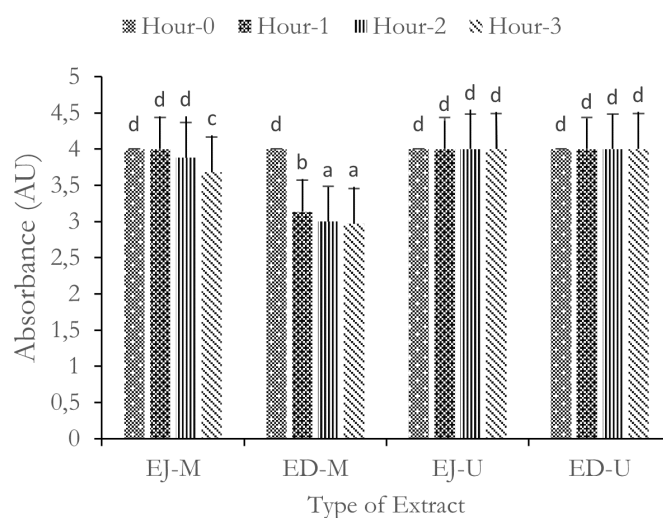


Figure 4. Effect of ultraviolet exposure on the color stability of the natural dye extracts base on absorbance. EJ-M = jernang extract obtained by maceration; ED-M = teak leaf extract obtained by maceration; EJ-U = jernang extract obtained by UAE; ED-U = teak leaf extract obtained by UAE. Different letters above the bars indicate significant differences according to Duncan's multiple range test at the 5% significance level.

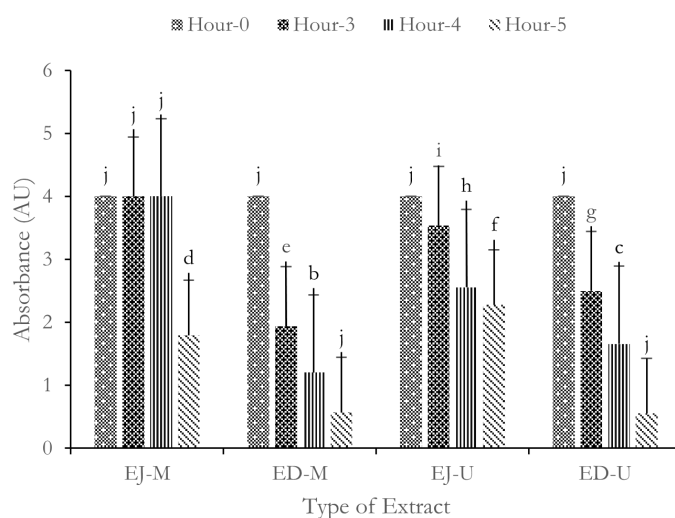


Figure 5. Effect of oxidant exposure on the color stability of the natural dye extracts base on absorbance. EJ-M = jernang extract obtained by maceration; ED-M = teak leaf extract obtained by maceration; EJ-U = jernang extract obtained by UAE; ED-U = teak leaf extract obtained by UAE. Different letters above the bars indicate significant differences according to Duncan's multiple range test at the 5% significance level.

discoloration or fading (Rosamah et al., 2013). The three-factor ANOVA likewise showed a significant interaction among raw material type, extraction method, and exposure period under oxidant exposure ($p < 0.05$). DMRT across the 16 raw-material $\times$ extraction-method $\times$ exposure-period combinations

showed significant time-dependent changes in absorbance, as indicated by changes in statistical groupings across exposure times (Figure 5). Based on yield and color stability, the UAE method was identified as the most effective extraction technique for producing EJ and ED for natural dye formulation. According

to Linares and Rojas (2022), in anthocyanin extraction, the UAE method showed superior features, including more efficient solvent use (acidified water and ethanol), pH stability, and optimal solvent viscosity to preserve pigment mass

C. Physical and Mechanical Properties of Dyed Rattan

The physical and mechanical properties of impregnated rattan, including moisture content, density, natural dye absorption (WPG, LU, BC), and hardness, are summarized in Table 5. Analysis of variance (ANOVA) showed that the impregnation treatment did not significantly affect the moisture content (MC) of the rattan ($p > 0.05$). The moisture content of rattan ranges from 9.77% to 12.52%, which is within the acceptable limit for rattan ($\leq 14\%$) as specified by SNI 7208 (2017). The results also indicated that the density of impregnated rattan increased compared to the control and rose with higher extract concentrations (Table 5).

Analysis of variance (ANOVA) showed that the impregnation treatment had no significant effect ($p > 0.05$) on the density of the rattan, resulting in no requirement for further Duncan's multiple range post-hoc testing (Table 5). Nevertheless, a numerical increase in bulk density (from 0.49 g/cm³ in the control to 0.75–0.86 g/cm³ in impregnated samples). A density value above 0.25 g/cm³ indicates that rattan is suitable for industrial applications

(Yang et al., 2020; Hadi et al., 2013).

Analysis of variance (ANOVA) test showed that the impregnation process had a significant effect on the WPG, LU, and BC of rattan ($p < 0.05$). Duncan's Multiple Range Test (DMRT) analysis (Table 5) showed that the WPG of ED-U-15% ($51.10 \pm 2.91\%$) was significantly smaller compared to EJ-U-15% ($67.25 \pm 6.14\%$) and EJ-U-30% ($78.53 \pm 11.50\%$), whereas ED-U-30% had the highest WPG value ($97.15 \pm 19.61\%$) and differed significantly from other treatments. The LU of ED-U-15% ($72.07 \pm 13.06\%$) was significantly smaller compared to EJ-U-15% ($89.63 \pm 12.50\%$), EJ-U-30% ($93.67 \pm 8.13\%$) and ED-U-30% ($97.93 \pm 16.94\%$). There was no significant difference between EJ-U-15%, EJ-U-30%, and ED-U-30% LU values. Also, the BC of ED-U-15% ($5.26 \pm 1.56\%$) was significantly smaller compared to EJ-U-30% ($10.04 \pm 2.68\%$) and ED-U-30% ($10.75 \pm 7.10\%$). No significant difference was observed between EJ-U-30% and ED-U-30%. However, there was no significant difference between EJ-U-15% ($6.68 \pm 2.39\%$) BC and former. Increase in WPG values was accompanied by increase in LU and BC, especially in 30% extract concentration. Higher values of WPG, LU and BC show the fact that more amount of the impregnating solution had been absorbed into the structure of the rattan (Prihatini et al., 2023). High value of WPG found in ED-U-30% suggests that more quantity of the extract along with the

Table 5. Physical and mechanical properties of dyed rattan.

Treatments	Moisture Content (%)	Density (g/cm ³)	WPG (%)	LU (%)	BC (%)	Hardness (kgf/mm ²)
K	11.20 ± 0.40	0.49 ± 0.08	-	-	-	2.03 ± 0.40^b
EJ-U-15%	9.77 ± 4.41	0.75 ± 0.10	67.25 ± 6.14^b	89.63 ± 12.5^b	6.68 ± 2.39^{ab}	2.97 ± 0.78^{ab}
EJ-U-30%	12.25 ± 3.80	0.86 ± 0.11	78.53 ± 11.5^b	93.67 ± 8.13^b	10.04 ± 2.68^b	4.12 ± 0.34^a
ED-U-15%	9.90 ± 4.56	0.76 ± 0.18	51.10 ± 2.91^a	72.07 ± 13.06^a	5.26 ± 1.56^a	3.25 ± 1.33^{ab}
ED-U-30%	12.52 ± 4.82	0.81 ± 0.12	97.15 ± 19.61^c	97.93 ± 16.94^b	10.75 ± 7.10^b	3.81 ± 0.24^a

Notes: Values are reported as mean $\pm$ SD. Different lowercase superscript letters within the same column indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

material formed due to reaction with citric acid has been deposited into the rattan matrix. At an applied pressure of 7 kgf/cm², the aqueous dye-mordant solution penetrated the porous vascular matrix and the lumen space. After the drying process in the oven, the deposited extract and the cross-linked citric acid have remained inside the lumen space and microfibrillar spaces.

The ANOVA results showed that impregnation significantly affects rattan hardness ($p < 0.05$). From the analysis using DMRT (Table 5), the high degree of hardness noted at high levels of the extract could be attributed to deposition of more extracts and mordant related materials. Impregnation allows penetration of the dye-mordant aqueous solution through the cell structure. In the course of drying the material in the oven, the deposits could stay in the cell walls and lumen, resulting in mass deposition. Such a process would be consistent with the WPG and BC increase and possibly increase the rattan resistance to localized deformation during indentation. This phenomenon was also observed in modified wood, where vacuum pressure impregnation facilitates modifier absorption

and deposition into both cell lumens and cell wall sections, thereby increasing mechanical resistance (Augustina et al., 2023; Augustina et al., 2024; Wahyuningtyas & Dirna, 2025). Such results could also be consistent with the extractive deposition and crosslinking effects resulting in cell wall densification and hardness improvement (Malik & Ozarska, 2019).

D. Color Change and Leaching of Dyed Rattan

Using EJ and ED extracted by UAE, the dyeing process changed untreated rattan from pale taupe to dark gold, saddle, coconut, and russet, depending on treatment. After the hot-water fastness test, the corresponding colors changed to camel, deer, light taupe, and taupe (Table 6). The Δa^* and Δb^* values differed significantly among treatments ($p < 0.05$), whereas the changes in lightness (ΔL^*) and overall color difference (ΔE) were not statistically significant. Before leaching, the overall color differences (ΔE) were 19.16 for EJ-U-15, 26.53 for EJ-U-30, 22.77 for ED-U-15, and 23.40 for ED-U-30. After leaching, ΔE decreased to 8.65, 12.96, 8.94,

Table 6.. Color change in dyed rattan before and after leaching.

Sample	Color	CIE Lab				Rattan
		ΔL	Δa	Δb	ΔE	
K	Pale taupe	—	—	—	—	
EJ-U-15	Dark gold	-13.54 ± 5.81	6.77 ± 1.82^b	11.26 ± 0.41^b	19.16 ± 4.51	
EJ-U-30	Saddle	-12.87 ± 5.47	13.93 ± 3.23^a	17.84 ± 1.05^a	26.53 ± 1.51	
ED-U-15	Coconut	-13.99 ± 10.27	13.14 ± 1.46^a	11.03 ± 4.54^b	22.77 ± 9.27	
ED-U-30	Russet	-15.74 ± 4.61	14.25 ± 3.01^a	6.23 ± 3.73^b	23.40 ± 1.34	
EJ-U-15 (Leaching)	Camel	-5.87 ± 4.71	3.48 ± 1.35^a	4.46 ± 1.97^{ab}	8.65 ± 3.91	
EJ-U-30 (Leaching)	Deer	-7.63 ± 6.67	7.83 ± 0.96^a	5.38 ± 1.83^a	12.96 ± 4.41	
ED-U-15 (Leaching)	Light taupe	-5.20 ± 4.58	5.89 ± 1.54^{ab}	2.44 ± 0.92^{ab}	8.94 ± 2.44	
ED-U-30 (Leaching)	Taupe	-13.07 ± 3.10	8.07 ± 1.56^a	1.16 ± 2.01^b	15.48 ± 3.50	

Notes: Values are reported as mean $\pm$ SD. Different lowercase superscript letters within the same column indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

and 15.48, respectively. ED-U-30 showed the smallest proportional decrease in ΔE (33.85%), indicating the greatest color retention among the tested formulations. Natural dyes such as flavonoids and anthocyanins can penetrate rattan pores and interact through hydrogen bonding between hydroxyl groups and dye functional groups (Vespignani et al., 2023). The color data, together with the FTIR results (Figure 6), support retention of the dye-rattan interaction after the hot-water leaching test.

From FTIR analysis (Figure 6), it was observed that there are changes in the absorption bands at various wavenumber values showing interaction between natural dyes and rattan material. For the FTIR spectrum of the control sample, some peaks were identified such as -OH group at 3333.96 cm^{-1} , which is involved in hydrogen bonding with dyes, an aromatic C=C stretch for lignin at 1593.61 cm^{-1} , alcohol and ether groups present in hemicellulose and cellulose at 1237.18 cm^{-1} and 1032.66 cm^{-1} , respectively; and a peak at 559.08 cm^{-1} in the fingerprint region of the spectrum. On coloring of the rattan by using a 15% concentration of teak leaf extract, changes have been observed in O-H and C=O absorption bands, such as the formation

of a hydrogen bond at 3330.36 cm^{-1} and an increased carbonyl absorption band at 1712.14 cm^{-1} . With increasing dye concentration up to 30%, more intense peaks of hydroxyl (3347.03 cm^{-1}) and carbonyl (1714.85 cm^{-1}) bands were observed. The similar pattern was identified for jernang extract with hydrogen bonds recorded at 3336.49 cm^{-1} (15%) and 3335.92 cm^{-1} (30%), as well as carbonyls at 1720.35 cm^{-1} and 1721.84 cm^{-1} . The use of citric acid as a mordant is confirmed by the presence of carbonyl peaks around 1710-1720 cm^{-1} in the samples processed with this acid. The increase in the intensity of C=O vibrations in this range is explained by esterification of carboxyl groups of citric acid with hydroxyl groups of the lignocellulosic material. As a result, citric acid can act as a polycarboxylic crosslinker and provide additional interactions between the lignocellulosic substrate and phenolic molecules of dyes. Indeed, recent research conducted on an international level and dealing with the problem of dyeing fabrics with natural dye describes citric acid as a crosslinking agent promoting esterification and contributing to improved retention and durability of natural dye (Darmawan et al., 2024; Dai et al., 2023).

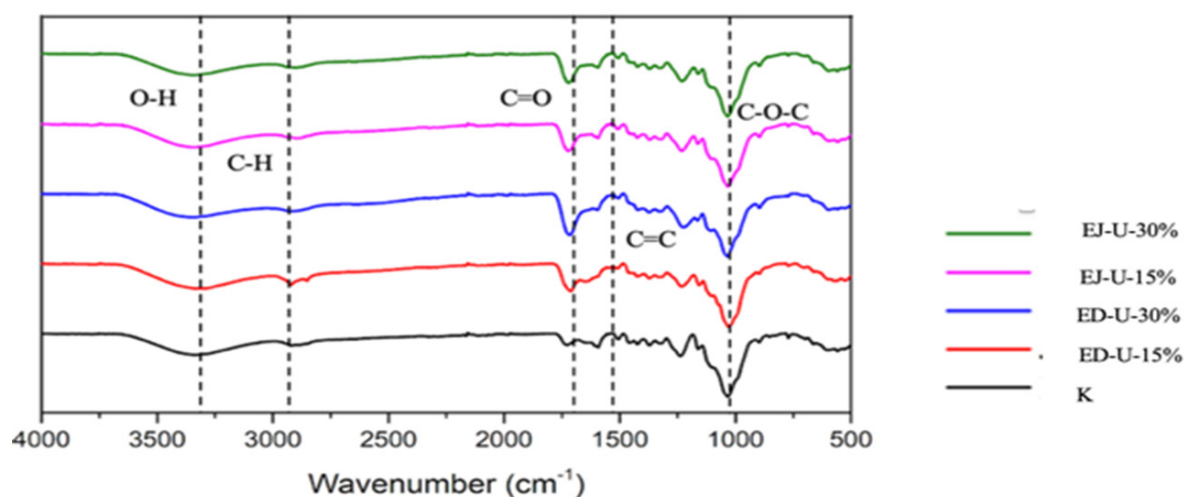


Figure 6. FTIR observation of rattan coloration using natural dyes in each treatment applied. Spectra are shown for untreated rattan (K) and rattan dyed with 15% and 30% jernang or teak leaf extracts.

E. Durability of Rattan Coloration and Rattan's Vinegar Coating

ANOVA using the one-factor CRD showed that treatment formulation significantly affected drywood-termite weight loss, drywood-termite mortality, and powderpost-beetle weight loss ($p < 0.05$). DMRT was then applied across the seven treatment formulations in Table 7. For drywood-termite weight loss, ED-U-30+RV50 had the lowest mean ($1.76 \pm 1.40\%$) and differed from the control, while several other treated formulations shared overlapping DMRT groups. For termite mortality, all RV-treated formulations were in the same statistical group (a), whereas the extract-only formulations were in group b and the control was in group c. For powderpost-beetle weight loss, RV-treated formulations had lower values than the control, and RV25 and RV50 formulations frequently shared overlapping statistical groups. Thus, the one-factor analysis compares the complete treatment formulations; rattan-vinegar concentration was not analyzed as an independent factor (Table 7). The relatively lower weight loss in the treated samples indicates that the natural dye extracts, as well as the vinegar, played a key role in making the

wood resistant to drywood termites. This is because the protective mechanism could have resulted from the deposition of extractives in the rattan, thereby making it less favorable to termites. The use of vinegar in the treatments may also have been important for this reason. However, the lack of a significant difference in some treatment combinations suggests that increasing the amount of vinegar did not necessarily increase the wood's resistance to termites. Similar results were obtained from powderpost beetle exposure, with all treated samples exhibiting less weight loss than the control sample. The lowest weight loss was recorded in ED-U-30+RV50 ($1.25 \pm 0.81\%$) and EJ-U-30+RV50 ($1.27 \pm 0.55\%$). All these treatments belonged to the same statistical group, indicating no significant difference in their protective effects against powderpost beetles. The fact that the weight loss in the treated rattan is much lower than in the control sample means that it exhibits better resistance to powderpost beetle infestation. The lower weight loss of treated rattan indicates greater resistance to drywood termite attack and greater preservative effectiveness (Sumariyanto et al., 2013).

Table 7. Durability of dyed rattan with rattan-vinegar coating against drywood termites and powderpost beetles.

Treatment Code	Drywood Termite Weight Loss (%)	Drywood Termite Mortality (%)	Powderpost Beetles Weight Loss (%)
K	6.82 ± 0.15^a	44 ± 3.46^c	6.93 ± 1.79^a
ED-U-30	3.35 ± 1.02^{bc}	54 ± 2.00^b	4.06 ± 1.54^b
EJ-U-30	3.94 ± 1.65^b	51.33 ± 2.30^b	3.50 ± 0.69^{bc}
ED-U-30+RV25	2.61 ± 0.82^{bc}	81.33 ± 1.15^a	1.49 ± 0.53^{cd}
EJ-U-30+RV25	2.93 ± 0.40^{bc}	81.33 ± 2.30^a	1.56 ± 1.13^{cd}
ED-U-30+RV50	1.76 ± 1.40^c	82.67 ± 4.16^a	1.25 ± 0.81^d
EJ-U-30+RV50	2.45 ± 0.52^{bc}	84.67 ± 3.05^a	1.27 ± 0.55^d

Notes: K = untreated rattan; RV = rattan vinegar; RV25 and RV50 denote 25% and 50% (w/v) rattan-vinegar post-treatments, respectively. Values are reported as mean $\pm$ SD. Different lowercase superscript letters within the same column indicate significant differences according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

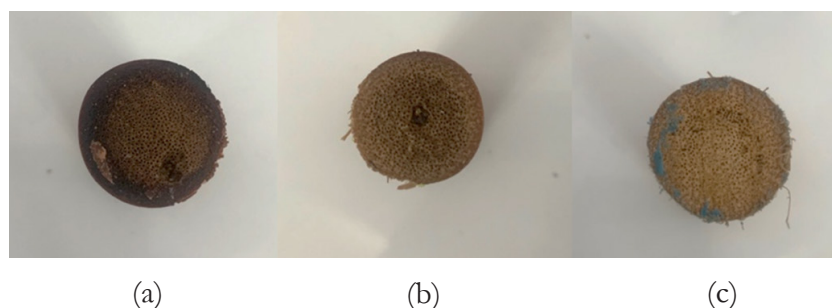


Figure 7. The effect of rattan's vinegar on drywood termites (a) control of rattan, (b) rattan with extract, (c) rattan with extract and rattan's vinegar.

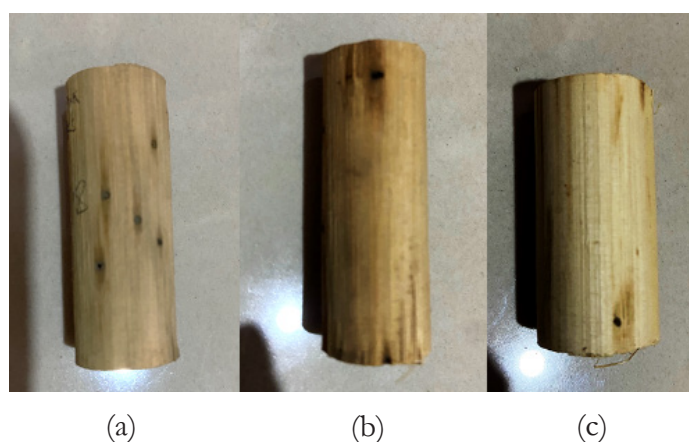


Figure 8. Effect of rattan vinegar on powderpost-beetle resistance: (a) untreated rattan; (b) rattan treated with natural dye extract; (c) rattan treated with natural dye extract and rattan vinegar.

Mortality increased in samples treated with the extract and in samples treated with the extract combined with rattan vinegar compared with the control. Mortality was higher in the combined treatments than in extract-only treatments. Analysis of variance (ANOVA) confirmed that treatment formulation significantly affected termite mortality ($p < 0.05$). Duncan's multiple range test showed that adding rattan vinegar significantly increased mortality, although the concentration level did not. Samples treated with rattan vinegar consistently showed higher termite mortality than those without. Such improved resistance against *Cryptotermes cynocephalus* (termite mortality rate $> 81\%$) and *Heterobostrychus* sp. (weight loss rate $< 1.6\%$) is supported by the biological activity

of pyroligneous acids, which consist mostly of organic acids and phenolic substances. It has been demonstrated that wood vinegar could increase the rate of termite mortality in a concentration-dependent manner (Oramahi et al., 2022) and could be a slow-acting toxic preservative after vacuum-pressure impregnation (Lee et al., 2022). At the physiological level, pyroligneous acid can decrease digestive and detoxifying enzyme activity and deplete energy reserves in stored-product insects, which may explain the observed reductions in feeding and survival (Homayoonzadeh et al., 2022). According to Iacomino et al. (2024), acetic acid and phenolic derivatives are key components of wood vinegar, and their biological activity depends significantly on concentration and application conditions.

Overall, this information corroborates the current effects of reduced weight loss and increased mortality of termites and suggests that the use of rattan vinegar can be efficient as a biopreservative provided its concentration is optimal. Thus, this study proves that extracts of jernang or teak leaves along with rattan vinegar can enhance the biological resistance of rattan to the insects studied

IV. CONCLUSION

The UAE method had higher efficiency compared to the maceration technique by improving the yield of teak leaf extracts from 12.04% to 15.90% and the yield of jernang processing-waste extracts from 8.81% to 10.64%. UAE extracts were more stable under UV and oxidizing conditions. pH had no significant effect on extract absorbance. Before the hot-water fastness test, ΔE values were 19.16 (EJ-U-15), 26.53 (EJ-U-30), 22.77 (ED-U-15), and 23.40 (ED-U-30); after leaching, they decreased to 8.65, 12.96, 8.94, and 15.48. ED-U-30 exhibited the lowest percentage decrease in ΔE (33.85%) and thus the best color retention after leaching. The dyeing process increased density, dye content, and hardness, while FTIR analysis confirmed interaction between the dye, citric acid mordant, and rattan components. Rattan vinegar treatment after dyeing enhanced the anti-termite activity towards drywood termites and powderpost beetles compared with untreated rattan.

The combination of these two processes could serve as an alternative, biological technique for rattan processing. Further research is needed to investigate long-term exposure to outdoor climate, extended UV radiation, biodeterioration resistance, and economic feasibility in industry conditions

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REFERENCES

- Anwar Y, Fikri MSA, Rahmadani NF, Ikramullah N, Permatasari N, Rahmah S, Istiqomah F, Regina, Surahman DD. (2025). Ekstraksi rimpang jahe: mengungkap khasiat dari metode dekok dan infusa. *JPKM*. 5(3):185-195. DOI/Link: <https://doi.org/10.36312/nuras.v5i3.504>
- Arif S, Irawan D, Jalnudin M. (2019). Analisis sifat mekanis perbandingan campuran komposit kayu jati dengan matrik epoxy untuk material kampas rem cakram. *J Tech*. 7(2):58-63. doi: 10.30869/jtech.v7i2.385. DOI/Link: <https://doi.org/10.30869/jtech.v7i2.385>
- Arman M, Bakri S, Majid RA. (2021). Pemanfaatan asap cair hasil pirolisis Batubara sebagai pestisida organik pada rayap (*Coptotermes curvignathus Holmgren*). *JTK USU*. 10(2):77-81. DOI/Link: <https://doi.org/10.32734/jtk.v10i2.5604>
- Asendy DA, Widarta IWR, Nocianitri KA. (2018). Pengaruh waktu maserasi terhadap aktivitas antioksidan ekstrak kulit buah jeruk lemon (*Citrus limon* Linn). *JITP*. 7(3):102-109. DOI/Link: <https://doi.org/10.24843/itepa.2018.v07.i03.p04>
- Asra R, Andryani D, Adriadi A, Fijridiyanto IA, Witono JR, Gailing O. (2021). Etnobotan rotan jernang (*Calamus spp.*) pada masyarakat sarolangun, jambi. *Buletin Kebun Raya*. 24(2):76-84. doi:10.14203/bkr.v24i2.724. DOI/Link: <https://doi.org/10.14203/bkr.v24i2.724>
- Augustina S, Marbun SD, Sudarmanto, Narto, Trisatya DR, Santoso EB, Pramadani D, Afni NN, Fariha TA, Tobing GWL, Syafi'i W, Cahyono TD, Novriyanti E, Bula M, Bahanawan A, Sejati PS, Kim NH, Dwianto W, Gérardin P. (2023). Dimensional stability and mechanical properties of citric acid impregnated samama wood (*Anthocephalus macrophyllus* (Roxb) Havil) at high curing temperatures. *Journal of the Korean Wood Science and Technology*. 51(6):431-446. DOI: <https://doi.org/10.5658/WOOD.2023.51.6.431>. Journal link: https://www.woodj.org/archive/view_article?pid=wood-51-6-431.

- Augustina S, Dwianto W, Wahyudi I, Darmawan W, Malik J, Maulana S, Gérardin P. (2024). Treatability and dimensional stability of three hardwood species using different types of water-soluble impregnating agent. *European Journal of Wood and Wood Products*. 82(5):1421-1433. DOI: <https://doi.org/10.1007/s00107-024-02096-w>. Journal link: <https://link.springer.com/article/10.1007/s00107-024-02096-w>.
- Azizi M, Yunus C, Irianto I, Qomaryah L, Ali G, Rohman N. (2023). Advancements and challenges in green extraction techniques for Indonesian natural products: a review. *S Afr J Chem Eng*. 46(4):88-98. doi: 10.1016/j.sajce.2023.08.002. DOI/Link: <https://doi.org/10.1016/j.sajce.2023.08.002>
- Baharuddin A, Aisyah, Saokani J, Risnah IA. (2015). Karaterisasi zat warna daun jati (*Tectona grandis*) fraksi methanol: n-heksana sebagai photosensitizer pada dye sensitized solar cell. *Chimica et Natra Acta*. 3(1):37-41. doi: 10.24198/cna.v3.n1.9174. DOI/Link: <https://doi.org/10.24198/cna.v3.n1.9174>
- Bhuyan, R., and Saikia, C. N. (2005). Isolation of colour components from native dye-bearing plants in northeastern India. *Bioresource Technology* 96: 363–372. DOI/Link: <https://doi.org/10.1016/j.biortech.2004.02.032>
- Bogoriani NW. (2011). Studi pemanfaatan zat warna alami dan asam sitrat sebagai mordan terhadap kayu jenis akasia dengan metode *stimulan mordanting*. *J Kimia*. 5(1):51-56. Link: <https://garuda.kemdiktisaintek.go.id/journal/view/931?issue=Vol.+5%2C+No.+1+Januari+2011>
- [BSN] Badan Standardisasi Nasional. (2014). SNI 7207:2014 Uji ketahanan kayu terhadap organisme perusak kayu. Jakarta: BSN. Link: <https://pesta.bsn.go.id/produk/detail/9766-sni72072014>
- Budiastra IW, Mardjan SS, Azis AA. (2020). Pengaruh amplitudo ultrasonik dan waktu ekstraksi terhadap rendemen dan mutu oleoresin pala. *JTEP*. 8(2):45-52. doi: 10.19028/jtep.08.2.45-52. DOI/Link: <https://doi.org/10.19028/jtep.08.2.45-52>
- Budiman A, Miranda ARV, Syarifah A. (2020). Formulasi dan uji stabilitas fisik krim ekstrak daun jati (*Tectona grandis* L.) sebagai pewarna rambut. *JFI*. 17(1):52-62. DOI/Link: <https://doi.org/10.31001/jfi.v17i1.758>
- Charoensit, P., Sawasdipol, F., Tibkawin, N., Suphrom, N., and Khorana, N. (2021). Development of natural pigments from *Tectona grandis* (teak) leaves: Agricultural waste material from teak plantations. *Sustainable Chemistry and Pharmacy* 19: 100365. <https://doi.org/10.1016/j.scp.2020.100365>
- Chowdhary, C. L. (2024). Marketing mix of the rattan business in Nepal. *Preprints* 1–10. DOI/Link: <https://doi.org/10.20944/preprints202406.0623.v1>
- Dai Y, Li H, Xu L, Zhang L, Cai X, Yan J. (2023). Cetylpyridinium chloride cationic finishing improves the dyeing and antibacterial properties of madder dyed cotton. *Coloration Technology*. 139(6):667-677. DOI: <https://doi.org/10.1111/cote.12677>. Journal link: <https://onlinelibrary.wiley.com/doi/10.1111/cote.12677>.
- Dafiq MAA, Hamid JQA, Fahriyah AR, Aulia LS, Kusumastuti Y, Arianto T, Adabiyah R. (2025). Penerapan teknik ecoprint dengan asam sitrat sebagai mordan untuk meningkatkan daya rekat warna pada kain dalam profuksi fashion berkelanjutan. *Jurnal Ilmu Pendidikan dan Sains*. 1(2):7-14. Doi: 10.71024/visionedusins.2025.v1i2.62 DOI/Link: <https://doi.org/10.71024/visionedusins.2025.v1i2.62>
- Darmawan A, Widowati, Riyadi A, Muhtar H, Kartono, Adhy S. (2024). Enhancing cotton fabric dyeing: optimizing mordanting with natural dyes and citric acid. *International Journal of Biological Macromolecules*. 276(Pt 2):134017. DOI:<https://doi.org/10.1016/j.ijbiomac.2024.134017>. Journal link: <https://www.sciencedirect.com/science/article/pii/S0141813024048220>.
- Emha ARR. (2020). Toksisitas ekstrak limbah pengolahan jernang [skripsi]. Bogor: Institut Pertanian Bogor. Link: https://repository.ipb.ac.id/handle/123456789/7469/browse?etal=-1&offset=9550&order=ASC&rpp=20&sort_by=1&type=title
- Fakkar G, Sumardi I, Suhaya Y. (2023). Efikasi asap cair dari limbah pengolahan industry gondorukem pada kayu karet terhadap rayap kayu kering (*Cryptotermes cynocephalus* L.). *JPHH*.41(1):1-10. Doi:10.55981/

- jphh.2023.675. DOI/Link: <https://doi.org/10.55981/jphh.2023.675>
- Familasari S, Sari RK, Syafii W, Carolina A, Cahyaningsih U, Sa'diah S. (2023). Ultrasound-assisted extraction of antimalarial compounds from the Bidara Laut (*Strychnos ligustrina*) heartwood. *Jurnal Sylva Lestari*. 11(3):360-369. DOI: <https://doi.org/10.23960/jsl.v11i3.682>. Journal link: <https://sylvalestari.fp.unila.ac.id/index.php/JHT/article/view/682>.
- Febrianto F, Gumilang A, Maulana S, Busyra I, Purwaningsih A. (2014). Keawetan alami lima jenis bambu terhadap serangan rayap dan bubuk kayu kering. *J Ilmu Teknol*. 12(2):146-156. Link: https://www.researchgate.net/publication/283730626_Natural_Durability_of_Five_Bamboo_Species_Against_Termites_and_Powder_Post_Beetle
- Ghozali MR, Aziz S, Gunarti NS, Fikayuniar L. 2023. *Metode Fitokimia untuk Farmasi*. Bantul:Jejak Pustaka. Link: <https://books.google.co.id/books?id=uLPoEAAAQBAJ>
- Hadi YS, Rahayu IS, dan Danu S. (2013). Physical and mechanical properties of methyl methacrylate impregnated jabon wood. *J Indian Acad. Wood Sci*. 10(2):77-80. DOI/Link: <https://doi.org/10.1007/s13196-013-0098-3>
- Hadikusumo SA. 2004. *Pengawetan Kayu*. Yogyakarta: Fakultas Kehutanan UGM. Link: <https://journal.ugm.ac.id/jikfkt/article/view/6137>
- Hamdi S. (2012). Pengawetan rotan kurang dikenal sebagai bahan baku mebel menggunakan rendaman dingin. *Jurnal Riset Industri Hasil Hutan*. 4(2):11-15. DOI/Link: <https://doi.org/10.24111/jrihh.v4i2.1203>
- Hartanto S, Rudyanto T. (2017). Penelitian se-cang sebagai pewarna alami rotan dan aplikasinya pada produk *home décor*. *Dimensi*. 14(1):15-30. Link: <https://download.garuda.kemdikbud.go.id/article.php?article=3041263&title=PENELITIAN+SE-CANG+SEBAGAI+PEWARNA+ALAMI+ROTAN+DAN+APLIKASINYA+PADA+PRODUK+HOME+DECOR&val=27611>
- Homayoonzadeh M, Talebi K, Torabi E, Allahyari H, Nozari J, Scully ED. (2022). Effects of pyroligneous acid on life history and physiology of two pyralid pests of stored products. *Journal of Stored Products Research*. 97:101971. DOI: <https://doi.org/10.1016/j.jspr.2022.101971>. Journal link: <https://www.sciencedirect.com/science/article/pii/S0022474X22000443>.
- Hossain MM, Scott IM, McGarvey BD, Conn K, Ferrante L, Berruti F, Briens C. (2013). Toxicity of lignin, cellulose, and hemicellulose pyrolyzed bio-oil combinations: Estimating pesticide resources. *J Anal Appl Pyrolysis*. 99:211–216. DOI/Link: <https://doi.org/10.1016/j.jaap.2012.07.008>
- Iacomino G, Idbella M, Staropoli A, Nanni B, Bertoli T, Vinale F, Bonanomi G. (2024). Exploring the potential of wood vinegar: chemical composition and biological effects on crops and pests. *Agronomy*. 14(1):114. DOI: <https://doi.org/10.3390/agronomy14010114>. Journal link: <https://www.mdpi.com/2073-4395/14/1/114>.
- Jasni, Damayanti R, Kalima T (2012). *Atlas Rotan Indonesia*. Bogor:Kementerian Kehutanan Badan Penelitian dan Pengembangan Kehutanan. Link: <https://id.scribd.com/document/327163956/Atlas-Rotan-JIId-1-Cetakan-Ke-21>
- Karipalai IRP, Hendrik AC, Ballo A. (2019). Jenis rotan dan pemanfaatannya oleh masyarakat di taman hutan raya Prof Ir. Herman Johannes, Kabupaten Kupang. *Jurnal Pendidikan dan Sains Biologi*. 2(3):115-122. Doi:10.33323/indigeneous.v2i3.74 DOI/Link: <https://doi.org/10.33323/indigeneous.v2i3.74>
- [Kemenperin] Kementerian Perindustrian. (2024). *Industri Rotan Butuh Revitalisasi*. Jakarta: Kemenperin. Link: <https://indonesia.go.id/kategori/editorial/8728/industri-rotan-butuh-revitalisasi?lang=1>
- Komarawidjaja, W. (2016). Sebaran Limbah Cair Industri Tekstil dan Dampaknya di Beberapa Desa Kecamatan Rancaekek Kabupaten Bandung. *Jurnal Teknologi Lingkungan*. 17(2):118–125. <https://doi.org/10.29122/jtl.v17i2.1045>
- Kurniati N, Prasetya AT, Winarni. (2012). Ekstraksi dan uji stabilitas zat warna

- brazilein dari kayumsecang (*Caesalpinia sappan* L.). *Indo J Chem Sci* 1(1):33-36. DOI/Link: <https://doi.org/10.15294/ijcs.v1i1.587>
- Kusuma AE dan Aprileili DA. (2022). Pengaruh jumlah pelarut terhadap rendemen ekstrak daun katuk (*Sauropus androgynus* L. Merr). *J Farm Sains Obat Tradis.* 1(2):125-135. DOI/Link: <https://doi.org/10.62018/sitawa.v1i2.22>
- Lacret R, Varela RM, Molinillo JMG, Nogueiras C, Macias FA. (2011). Anthractone and naphthotectone, two quinones from a bioactive Extract. Of *Tectona grandis*. *Journal of Chemical Ecology.* 37:1341-1348. DOI/Link: <https://doi.org/10.1007/s10886-011-0048-8>
- Lasang MB, Aisyah, Iswadi, Bakar NA. (2019). Pengaruh kandungan senyawa pada ekstrak daun jati (*Tectona grandis*) terhadap nilai efisiensi dye sensitized solar cell (DSSC). *J Teknosains.* 13(1):45-54. DOI/Link: <https://doi.org/10.24252/teknosains.v13i1.9615>
- Lee CL, Chin KL, Khoo PS, Hafizuddin MS, H'ng PS. (2022). Production and potential application of pyroligneous acids from rubberwood and oil palm trunk as wood preservatives through vacuum-pressure impregnation treatment. *Polymers.* 14(18):3863. DOI: <https://doi.org/10.3390/polym14183863>. Journal link: <https://www.mdpi.com/2073-4360/14/18/3863>.
- Linares G, Rojas ML. (2022). Ultrasound-assisted extraction of natural pigments from food processing by-products: a review. *Frontiers in Nutrition.* 9:891462. DOI: <https://doi.org/10.3389/fnut.2022.891462>. Journal link: <https://www.frontiersin.org/journals/nutrition/articles/10.3389/fnut.2022.891462/full>.
- Loppies JE, Khaerunnisa, Rejeki ES, Yumas M, Lullung A. (2020). Stabilitas zat warna antosianin biji kakao pada berbagai kondisi kopigmentasi. *JIHPP.* 15(2):94-104. DOI/Link: <https://doi.org/10.33104/jihp.v15i2.6611>
- Lusiana ED dan Mahmudi M. (2021). *Anova untuk Penelitian Eksperimen Teori dan Praktik* dengan R. Malang:UB Press Link: <https://books.google.co.id/books?hl=id&id=qtk7EAAAQBAJ>
- Mahlinda, Thaliba A, Maurina L, Kurniawana R, Supardan MD. (2020). Ekstraksi getah jernang (*Daemonorops draco*) sistem basah dengan dua tahapan proses: perbedaan rendemen dan mutu. *J Ris Ind Has Hutan.* 12(1):29. doi: 10.24111/jrihh.v12i1.5924. DOI/Link: <https://doi.org/10.24111/jrihh.v12i1.5924>
- Muflihati, Nawawi DS, Rahayu IS, Syaffi W. (2014). Perubahan warna kayu jabon terwarnai ekstrak kulit kayu samak (*Syzygium inophyllum*). *J Ilmu dan Teknologi Kayu Tropis.* 12(1):11-19. DOI/Link: <https://doi.org/10.51850/jitkt.v12i1>
- Malik J & Ozarska B. (2019). Mechanical characteristics of impregnated white jabon wood (*Anthocephalus cadamba*) using merbau extractives and selected polymerised merbau extractives. *Maderas Ciencia y Tecnologia.* 21(4):573-586. DOI/Link: <https://doi.org/10.4067/S0718-221X2019005000413>
- Nguyen N, Ozarska B, Fergusson M, Vinden P. (2018). Dyeing of *Eucalyptus globulus* veneers with reactive dye using sequential vacuum and varied pressures. *BioRes.* 13(4):8690-8708. Doi:10.15376/biores.13.4.8690-8708. DOI/Link: <https://doi.org/10.15376/biores.13.4.8690-8708>
- Nuraeni N, Yuvie AR, Pratama PRS, Herianti D, Kusumaningtyas VA, Jasmansyah. (2022). Antifungal and wound healing activities of chitosan nanoparticles from green mussel shell (*Perna viridis*) and jernang (*Daemonorops draco*) ethanol extract dressing patch. *He: JSAC.* 2(2):33-39. DOI/Link: <https://doi.org/10.33751/helium.v2i2.6343>
- Oramahi HA, Tindaon MJ, Nurhaida, Diba F, Yanti H. (2022). Termicidal activity and chemical components of wood vinegar from nipah fruit against *Coptotermes curvignathus*. *Journal of the Korean Wood Science and Technology.* 50(5):315-324. DOI: <https://doi.org/10.5658/WOOD.2022.50.5.315>. Journal link: https://www.woodj.org/archive/view_article?pid=wood-50-5-315.
- Paryanto, Purwanto A, Kwartiningsih E, dan Mastuti E. (2012). Pembuatan zat warna alami dalam bentuk serbuk untuk mendukung industri batik di Indonesia. *Jurnal Rekayasa Proses,* 6(1): 26-29. DOI/

- Link: <https://doi.org/10.22146/jrekpros.2454>
- Prihatini E, Darmawan W, Wahyudi I, Iswanto AH. (2023). Effect of vacuum impregnation treatment on weight percent gain and dimensional stability of modified wood. *Wood Research*. 68(4):623-636. <https://doi.org/10.37763/wr.1336-4561/68.4.623636>
- Purnomo W, Khasanah LU, Anandito RBK. (2014). Pengaruh ratio kombinasi maltodekstrin, karagenan, dan whey terhadap karakteristik mikroenkapsulan pewarna alami daun jati (*Tectona grandis* L.F). *J Apl Teknol Pangan*. 3(3):99-107. Link: <https://garuda.kemdiktisaintek.go.id/author/view/3801819?jid=11158&jname=Jurnal+Aplikasi+Teknologi+Pangan>
- Putra RP. (2024). Pemanfaatan ekstrak kulit buah kopi robusta dalam pengembangan produk minuman cendol instan fungsional dengan sifat antioksidan tinggi dan kafein rendah. *JPTP*. 10(1):141-154. Doi: 10.26858/jptp.v10i1.3082. DOI/Link: <https://doi.org/10.26858/jptp.v10i1.3082>
- Putri IT, Hasyim AI, Lestari SUDAH. (2016). Nilai tambah, bauran pemasaran (marketing mix) dan perilaku konsumen dalam pengambilan keputusan pembelian produk rotan (kursi teras tenggok dan kursi teras pengki) di Kota Bandar Lampung. *Jurnal Agribisnis*. 4(1):48-55. DOI/Link: <https://doi.org/10.23960/jia.v4i1.1214>
- Rahmawati AS dan Erina R. (2020). Rancangan acak lengkap (RAL) dengan uji anova dua jalur. *J Pendid Fis*. 4(1):54-62. DOI/Link: <https://doi.org/10.37478/optika.v4i1.333>
- Rosamah E, Ramadan R, Kusuma IW. (2013). Stabilitas warna biji tumbuhan annatto (*Bixa Orellana* L.) sebagai bagan pewarna alami. *Prosiding Seminar Nasional Masyarakat Peneliti Kayu*. Kalimantan Timur. Link: <https://repository.unmul.ac.id/bitstream/handle/123456789/6823/1.%20Stabilitas%20Warna%20Biji%20Tumbuhan%20Annatto%20%28Bixa%20orellana%20L.%29.pdf?isAllowed=y&sequence=1>
- Rowell RM. (2005). *Handbook of Wood Chemistry and Wood Composites*. Boca Raton: CRC Press. DOI/Link: <https://doi.org/10.1201/b12487>
- Rozan SA. (2019). Aktivitas Antioksidan ekstrak dan fitosom ekstrak resin jernang (*Daemonorops draco* (Willd) Blume) [skripsi]. Bogor: Institut Pertanian Bogor. Link: <https://repository.ipb.ac.id/handle/123456789/101275>
- Rundubelo BA, Ridhay A, Hardi J, Puspitasari DJ. (2019). Uji stabilitas pigmen ekstrak ubi banggai (*Dioscorea bulbifera* var celebia Burkill) pada berbagai variasi pH dan lama paparan sinar matahari. KOVALEN: *Jurnal Riset Kimia*. (5):9-16. DOI/Link: <https://doi.org/10.22487/kovalen.2019.v5.i1.14562>
- Sambodo PA, Hastuti ED, Santoso U. (2022). Ekstraksi dan karakterisasi pigmen antosianin daun jati (*Tectona grandis* L. f.) menggunakan metode maserasi. *Jurnal Ilmu Pertanian Indonesia*, 27(2), 123–132 Link: <https://journal.ipb.ac.id/index.php/JIPI>
- Sari DN, & Handika M. (2020). Pengaruh jenis pelarut terhadap rendemen dan kandungan fitokimia ekstrak jernang (*Daemonorops draco*). *Jurnal Riset Teknologi Industri*, 14(2), 45–52 Link: <https://garuda.kemdiktisaintek.go.id/journal/view/17479>
- Sari RK, Prayogo YH, Rozan SA, Rafi M, Wientarsih I. (2022). Antioxidant Activity, Sun Protection Activity, and Phytochemical Profile of Ethanolic Extracts of *Daemonorops acebensis* Resin and Its Phytosomes. *Scientia Pharmaceutica*. 90(1):10. DOI/Link: <https://doi.org/10.3390/scipharm90010010>
- Satiti ER, Saputra NA, Kalima T. (2017). Komposisi kimia dan ketahanan rotan asal Sulawesi Tenggara terhadap serangan rayap tanah. *J Ilmu Teknol Kayu Tropis*. 5(2):175-184. DOI/Link: <https://doi.org/10.51850/jitkt.v15i2.396>
- Satriawan B dan Wijaya A. (2023). Pengaruh perbedaan jenis pelarut terhadap nilai rendemen ekstrak daun pepaya (*Carica Papaya* L.). *J Pharm UMUS*. 5(1):10-17. DOI/Link: <https://doi.org/10.46772/jophus.v5i1.728>
- Simanjuntak L, Sinaga C, Fatimah. (2014). Ekstraksi pigmen antosianin dari kulit buah naga merah (*Hylocereus polyrhizus*). *Jurnal Teknik Kimia USU*. 3(2):25-29. DOI/Link: <https://doi.org/10.32734/jtk.v3i2.1502>

- Solihat NN, Santoso EB, Karimah A, Madyaratri EW, Sari FP, Falah F, Iswanto AH, Ismayati M, Lubis MAR, et al. (2022). Physical and Chemical Properties of *Acacia mangium* Lignin Isolated from Pulp Mill Byproduct for Potential Application in Wood Composites. *Polymers*. 14(3):491. DOI/Link: <https://doi.org/10.3390/polym14030491>
- Sukandar D, Sulaswatty A, Hamidi I. 2022. Profil senyawa kimia minyak atsiri sereh wangi (*Cymbopogon nardus* L.) hasil hidrodistilasi dengan optimasi perlakuan awal sonikasi. *Alchemy Jurnal Penelitian Kimia*. 18(2):221-233. DOI/Link: <https://doi.org/10.20961/alchemy.18.2.60007.221-233>
- Sulaiman O, Hashim R, Saharudin NS, & Ibrahim MNM. (2020). Effect of fruit size and solvent type on dragon's blood resin extraction. *IOP Conference Series: Earth and Environmental Science*, 425(1), 012037. <https://doi.org/10.1088/1755-1315/425/1/012037>
- Sumariyanto A. (2013). Pengawetan kayu gubal jati secara rendaman dingin dengan pengawet boron untuk mencegah serangan rayap kayu kering (*Cryptotermes cynocephalus*). *J Ilm Kehutanan*. 7(2):93-107. DOI/Link: <https://doi.org/10.22146/jik.7516>
- Teng TJ, Arip MN, Sudesh K, Nemoikina A, Jalaudin Z, NG EP, Lee HL. (2018). Conventional technology and nanoparticle technology in wood preservation: a review. *Bioresources*. 13(4):9220-9252. doi: 10.15376/biores.13.4. DOI/Link: <https://doi.org/10.15376/biores.13.4>.Teng
- Thakur R, Gupta V, Dhar P, Deka SC, Das AB. (2022). Ultrasound-assisted extraction of anthocyanin from black rice bran using natural deep eutectic solvents: optimization, diffusivity, and stability. *Journal of Food Processing and Preservation*. 46(3):e16309. DOI: <https://doi.org/10.1111/jfpp.16309>. Journal link: <https://onlinelibrary.wiley.com/doi/10.1111/jfpp.16309>.
- Tiwari BK. (2015). Ultrasound: a clean, green extraction technology. *Trends in Analytical Chemistry*. 71:100 -109. doi: 10.1016/j.trac.2015.04.013. DOI/Link: <https://doi.org/10.1016/j.trac.2015.04.013>
- Vespignani L, Bonanni M, Marradi M, Pizzo B, Bianchini R, Goli G. (2023). Naturalized dyes: a new opportunity for wood coloring. *Polymers*. 15(17):3632. DOI: <https://doi.org/10.3390/polym15173632>. Journal link: <https://www.mdpi.com/2073-4360/15/17/3632>.
- Wahyuningtyas I, Dirna FC. (2025). The improvement of jabon wood density through furfuryl alcohol and nano-SiO₂. *Perennial*. 21(1):24-29. DOI: <https://doi.org/10.24259/perennial.v21i1.43187>. Journal link: <https://journal.unhas.ac.id/index.php/perennial/article/view/43187>.
- Waluyo TK. (2008). Teknik ekstraksi tradisional dan analisis sifat-sifat jernang asal Jambi. *JPHH*. 26(1): 30–40. doi: 10.20886/jpph.2008.26.1.30-40. DOI/Link: <https://doi.org/10.20886/jpph.2008.26.1.30-40>
- Waluyo TK. (2013). Perbandingan sifat fisiko kimia 5 jenis jernang. *J Penel Has Hutan*. 31(2):141-150. DOI/Link: <https://doi.org/10.20886/jpph.2013.31.2.141-150>
- Wiyono TS, Kartikawati D. (2017). Pengaruh metode ekstraksi sari nanas secara langsung dan osmosis dengan variasi perebusan terhadap kualitas sirup nanas (*Ananas comosus* L.). *Serat Acitya*. 6(2):108-118. DOI/Link: <https://doi.org/10.56444/sa.v6i2.785>
- Yuniati Y, Handarini K, Rahmiati R. (2024). Studi Pustaka:ekstraksi pewarna alami dari tanaman Indonesia. *Bioscientist: Jurnal Ilmiah Biologi*. 12(1):1099-1111. DOI/Link: <https://doi.org/10.33394/bioscientist.v12i1.11339>.
- Yang S, Xiang E, Shang L, Liu X, Tian G, Ma J. (2020). Comparison of physical and mechanical properties of four rattan species grown in China. *Journal of Wood Science*. 66:3. DOI/Link: <https://doi.org/10.1186/s10086-020-1850-0>

GUIDELINE FOR AUTHORS

AIM AND SCOPE

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Reference List

- American Society for Testing and Materials (ASTM). (1997). *Standard test methods for rubber products—Chemical analysis*. (ASTM-D297-93) American Society for Testing of Materials, USA.
- Ayuk, E.T., Duguma, B., Franzel, S., Kengue, J., & Zenkeng, P. (1999). Uses, management and economic potential of *Irvingia gabonensis* in the humid lowlands of Cameroon. *Forest Ecology and Management*, 113, 1-19.
- Chen, H.Q., Wei, J.H., Yang, J.L., Ziang, Z., Yang, Y., Gao, J.-H., ... Gong, B. (2012). Review : Chemical constituents of agarwood originating from the endemic genus *Aquilaria* plants. *Chemistry and Biodiversity*, 9, 236–250.
- Kementerian Kehutanan. (2009). *Keputusan Menteri Kehutanan No.SK/328/Menbut-II/2009 tentang Penetapan DAS Prioritas dalam rangka RPJM tahun 2010-2014*. Sekretariat Jenderal, Jakarta.
- Kenney, G.M., Cook, A., & Pelletier, J. (2009). Prospects for reducing uninsured rates among children: How much can premium assistance programs help. Retrieved from Urban Institute website: <http://www.urban.org/url.cfm?ID=411823>, at 1 October 2009.

- Kurinobu, S. & Rimbawanto, A. (2002). Genetic improvement of plantation species in Indonesia. In A. Rimbawanto, & M. Susanto (Eds.), *Proceeding of International Conference on advances in genetic improvement of tropical tree species*, 1-3 October 2002 (pp.1-6). Yogyakarta: Centre for Forest Biotechnology and Tree Improvement.
- Lee, S.S. (2003). Pathology of tropical hardwood plantation in South-East Asia. *New Zealand Journal of Forestry Science*, 33(3), 321-335.
- Lim, S.C. (1998). Barringtonia J.R. Forster, & J.G. Forster. In M.S.M. Sosef, L.T. Hong, & S. Prawirohatmodjo (Eds.), *Plant Resources of South-East Asia 5(3): Timber trees: Lesser-known timbers*. (pp. 98-102). Leiden: Backhuys Publishers.

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Water is a necessary part of every reasons's diet and of all the nutrient a body needs to function, it requires more water each daya than any other nutrients a body needs to function, it requires more water each day than any other nutrient (Whitney & Rolfes, 2011)

Or

Whitney and Rolfes (2011) state the body requires many nutrients to function but highlight that water is of greater importance than any other nutrient.

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