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Effect of Soil Conservation on Soil Erosion and Plant Performance under Pine–Durian Agroforestry Systems in Perhutani Production Forest

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ABSTRACT

Logging activities in pine production forests create open land that increases surface runoff and soil erosion, highlighting the need for soil conservation during the early stages of agroforestry development. This study evaluated the effectiveness of mechanical and vegetative conservation practices, including biogeotextiles, in reducing runoff and erosion and improving plant growth and farm profitability in an early-stage pine–durian agroforestry system. A randomized factorial block design with two factors and a non-factorial control was applied. Mechanical conservation treatments included no terraces, ridge terraces, and bench terraces, while vegetative conservation treatments consisted of chili monoculture, peanut monoculture, chili–peanut intercropping, and intercropping combined with biogeotextiles. Results showed that mechanical conservation significantly reduced runoff and erosion, with bench terraces providing the greatest reductions (33–53% runoff; 48–75% erosion), followed by ridge terraces. Biogeotextiles further reduced erosion by up to 68%, although they increased implementation costs. Pine and durian growth were not significantly affected, whereas chili productivity increased under intercropping and terraced systems. Economically, bench terraces produced the highest profitability (R/C >6). Overall, integrating mechanical and vegetative conservation effectively improved hydro-logical function, crop productivity, and farm income in pine–durian agroforestry systems.

1. INTRODUCTION

Perum Perhutani, as a state-owned enterprise managing forests in Java and Madura, develops pine resin (*Pinus merkusii*) production as raw material for turpentine and gum arabic (Nugrahanto *et al*., 2022). Productivity is increased by adding more trees for tapping and improving tapping technology (Imanuddin *et al*., 2020). Resin production peaks at around 26 years of age (±1,152 kg·ha^{-1}·year^{-1}) and declines after 50 years of age (±710 kg·ha^{-1}·year^{-1}) (Samis *et al*., 2023). Declining production encourages the logging of old-growth stands for regeneration, but without proper post-harvest management, this can lead to land degradation, loss of topsoil, reduced soil productivity, and disruption of forest ecological functions (Gartzia-Bengoetxea *et al*., 2021). The hydrological impacts include an increase in runoff of up to ± 30% and erosion of up to ± 25% compared to dense forests (Dharmawan *et al*., 2023). In addition, pressure from communities that use forest areas for seasonal crops also accelerates degradation due to soil erosion (Rudiarto *et al*., 2019; Rosmaeni *et al*., 2022).

Perhutani implements a post-harvest agroforestry system through the Community-Based Forest Management (PHBM) scheme as a land rehabilitation effort, combining forestry crops with seasonal crops to restore vegetation cover and increase income (Mujaddid *et al*., 2024). However, in the early stages of agroforestry, tree canopies and root systems have not yet developed optimally, resulting in low surface runoff control and soil stabilization capacity. These conditions cause increased surface runoff velocity and sediment transport to remain dominant, meaning that early agroforestry without the support of soil conservation measures has not been able to effectively reduce surface runoff and soil erosion (Niu *et al*., 2024). Without the support of soil and water conservation (SWC) measures such as terracing, ground cover plants, or surface runoff control structures, agroforestry has not been able to optimally reduce degradation (Lopes *et al*., 2025). The combination of vegetative and mechanical SCW has been proven to be 40–60% more effective than single methods in controlling erosion and increasing infiltration (Kumar *et al*., 2025).

Controlling land degradation in the early stages of agroforestry requires the integration of soil and water conservation engineering that directly modifies surface flow paths and the erosive energy of rainfall. Mechanical soil conservation measures such as gully terraces and bench terraces function as surface flow control structures by shortening slope length, reducing effective slope, and increasing water residence time on the soil surface, thereby significantly reducing surface runoff and soil erosion (Rutebuka *et al*., 2021). Vegetative soil conservation through intercropping systems plays a role in increasing soil structure strength through root development and surface biomass addition (Yang *et al*., 2023). Natural fiber biogeotextiles have also been shown to reduce runoff by 30–40% and erosion by 40–70% on various slope conditions (Manivannan *et al*., 2018), while improving soil microclimate and increasing corn yields by up to 43% on dry land (Mustikaningrum *et al*., 2018). The integration of vegetative conservation, terrace engineering, and biogeotextiles is a key approach to maintaining hydrological functions, reducing erosion, and ensuring the sustainability of pine forest ecosystems (Gartzia-Bengoetxea *et al*., 2021; Ministry of Environment and Forestry, 2024). Quantitatively, the combination of biogeotextiles and vegetation has been reported to reduce surface runoff by 44–62% and reduce soil loss by up to 99% on steep slopes (Liu *et al*., 2023), while agroforestry systems with terraces can reduce soil loss from 16.67 Mg ha^{-1} $year^{-1}$ to 2.17 Mg ha^{-1} $year^{-1}$ (a reduction of up to 87%) in Mexico (Sánchez-Bernal *et al*., 2013). Other soil conservation studies also show that mechanical techniques such as terraces can reduce soil loss by 44–52% and runoff by 36–46%, while vegetative measures alone reduce soil loss by only 5–18% (Singh *et al*., 2025).

Although a number of studies have reported the effectiveness of conservation techniques separately, studies that simultaneously integrate mechanical conservation (terracing), vegetative conservation (cover crops/intercropping), and biogeotextiles in the early phase of post-harvest pine agroforestry are still very limited, especially those that evaluate their integrated impact on hydrological, agronomic, and economic aspects. Thus, there is a knowledge gap regarding how the combination of these three approaches works synergistically in controlling runoff and erosion, affecting plant growth and yield, and determining the feasibility of farming. Therefore, this study aims to evaluate the effectiveness of various combinations of mechanical and vegetative soil conservation, including biogeotextiles, in controlling surface runoff and soil erosion, as well as their implications for plant growth and the feasibility of cultivating seasonal crops in the early phase of a post-harvest pine agroforestry system. This study explicitly fills the gap by evaluating the effectiveness of integrating mechanical-vegetative-biogeotextile conservation on hydrological response, plant growth and productivity, and economic performance in the early phase of post-harvest pine agroforestry systems.

2. MATERIALS AND METHODS

This study was conducted from December 20, 2024 to March 10, 2025 in a production forest area managed by Perum Perhutani Kesatuan Pemangkuan Hutan (KPH) Malang, specifically in Banturejo Hamlet, Bayem Village, Kasembon Subdistrict, Malang Regency, East Java Province (Figure 1). The research location is at coordinates 7.81 LS and 112.33 BT, with an altitude of about 400 m above sea level (masl). The soil type at the research location is Mollisol (Putra *et al*., 2015).

2.2. Research Design

This study used a Factorial Randomized Block Design (FRBD) with two treatment factors, namely a pine-durian-based agroforestry system with various types of vegetative soil conservation measures and various types of mechanical soil conservation measures. The first factor, namely vegetative soil conservation (V), consisted of four treatments: V_1 (chili monoculture), V_2 (peanut monoculture), V_3 (intercropping of chili + peanuts), and V_4 (intercropping of chili + peanuts + biogeotextile). The second factor, mechanical soil conservation (M), consists of three treatments: M0 (without terrace), M1 (ridge terrace, Figure 2a), and M2 (bench terrace, Figure 2b).

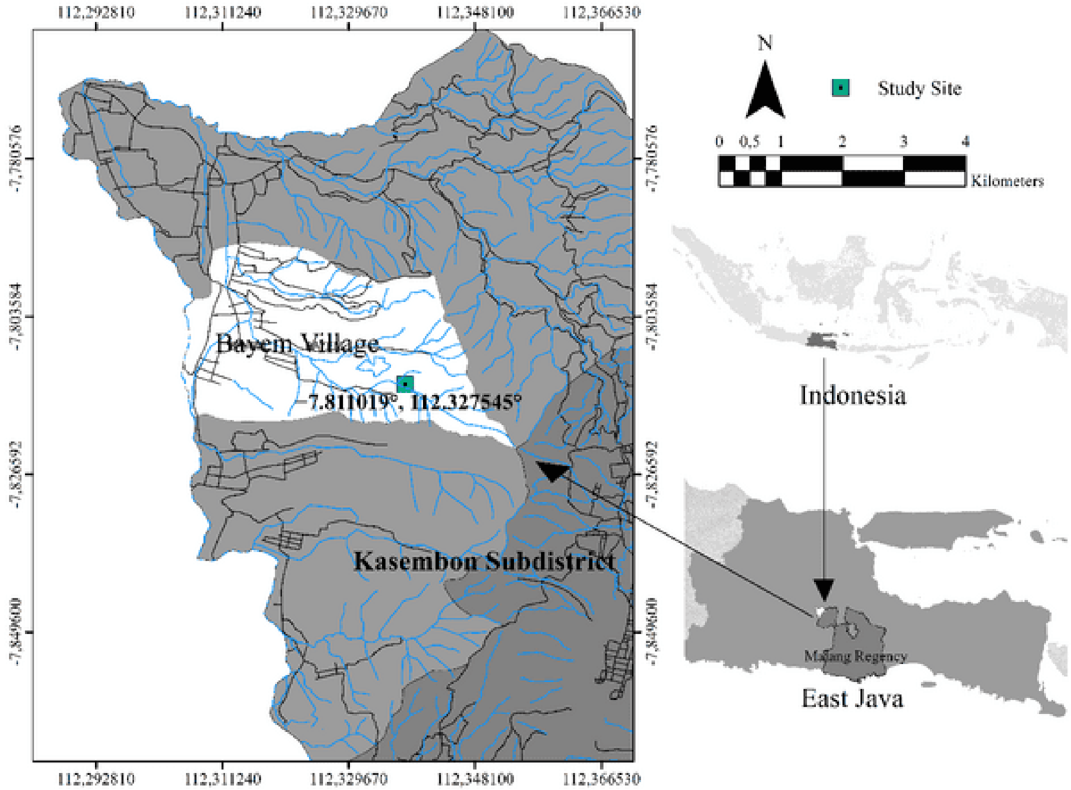

Figure 1. Research location in Bayem Village, Kasembon Subdistrict, Malang Regency, East Java Province.

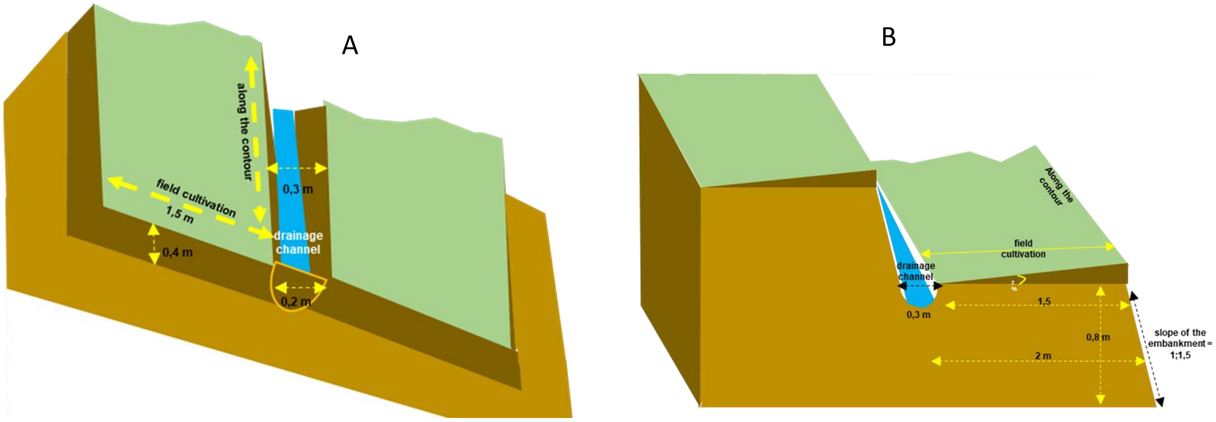

Figure 2. Design of ridge terrace (A) and bench terrace (B)

In addition to these two factors, one control treatment (K) was included, namely pine + durian planting without vegetative plants and without mechanical soil conservation measures, which was an additional non-factorial treatment. Thus, there were a total of 13 treatment combinations in this study (Table 1), and each treatment was repeated three times.

The biogeotextile used in this study employs a two-layer porous material technology consisting of woven polyethylene that functions as a mulch for soil erosion control, filled with 2 kg/m^2 or equivalent to 20 Mg/ha, to provide additional soil organic matter to improve fertility in drylands (Suprayogo *et al.*, 2022) (Figure 3).

Table 1. Treatments combinations of vegetative soil conservation and mechanical soil conservation in pine–durian agroforestry

Treatment code	Vegetative Soil Conservation	Mechanical Soil Conservation
K	Pine monoculture	-
V1M0	Pine + Chili	-
V2M0	Pine + Peanuts	-
V3M0	Pine + Chili + Peanuts	-
V4M0	Pine + Chili + Peanuts + Biogeotextile	-
V1M1	Pine + Chili	Ridge Terrace
V2M1	Pine + Peanuts	Ridge Terrace
V3M1	Pine + Chili + Peanuts	Ridge Terrace
V4M1	Pine + Chili + Peanuts + Biogeotextile	Ridge Terrace
V1M2	Pine + Chili	Bench Terrace
V2M2	Pine + Peanuts	Bench Terrace
V3M2	Pine + Chili + Peanuts	Bench Terrace
V4M2	Pine + Chili + Peanuts + Biogeotextile	Bench Terrace

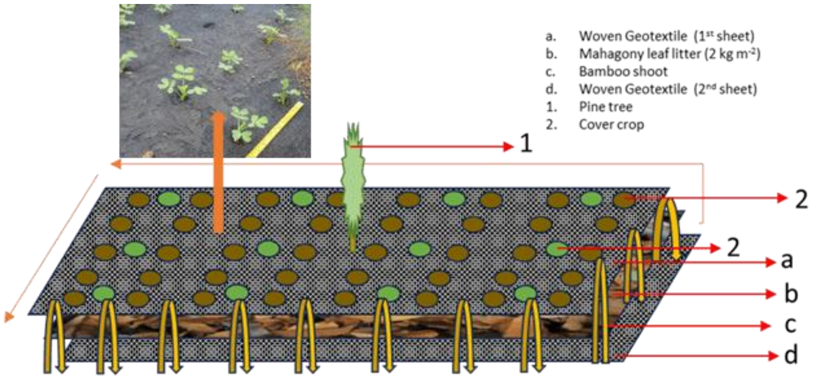

Figure 3. Design of biogeotextile application as an effort to implement soil conservation

The organic material used in this study was mahogany leaves, due to the abundant availability of mahogany leaf litter at the study site. Mahogany leaf litter (*Swietenia macrophylla* King) has a relatively fast decomposition rate, high N, P, and K content, and is capable of increasing organic carbon and soil fertility through the process of nutrient mineralization (Dinesha & Dey, 2024).

2.3. Rainfall Measurement

Rainfall measurements were taken to determine daily rainfall in order to understand surface runoff and soil erosion. Rainfall data was recorded using an Arduino ombrometer sensor (tipping bucket rain gauge – hall sensor) with a funnel cross-section measuring 5.5 cm × 3.5 cm and a tipping volume equivalent to 0.7 mm of rainfall. Recording is done automatically every minute, and the device is placed in the center of the study area to represent rainfall conditions across the entire soil erosion plot.

2.4. Measurement of Surface Runoff and Soil Erosion

The surface runoff and soil erosion measurement plot was constructed measuring 8 m × 9 m (Figure 4). In the plot with mechanical conservation treatment, five ridge terraces or benches measuring 8 m × 1.5 m were constructed. The plot boundaries were marked with 25 cm high plastic mulch to channel surface runoff into the surface runoff measuring device and prevent interplot flow.

Surface runoff and soil erosion measurements were carried out using a Chin-Ong meter (Widianto *et al*., 2004), which is a 3 mm thick iron plate measuring 50 cm × 25 cm × 15 cm, with a 5 cm diameter base hole connected to an iron pipe leading to a storage jerry can (Figure 4). Surface runoff water was channeled through a small pipe to a jerry can for volume measurement, while excess surface runoff was channeled to a drain. Surface runoff data was collected one day after each rainfall event, and surface runoff volume was calculated using equations (1)**.**

$$\text{Gutter Volume} = \text{L} \times \text{W} \times \text{H} \tag{1}$$

where *L* is gutter lenght (cm), *W* is gutter width (cm), *H* is gutter height (cm). If water is also stored in jerry cans, the volume is measured in milliliters and converted according to the equation (2)**.**

$$RO = \frac{V_a + \left(V_j \times \frac{100}{CF}\right)}{plot\ size} \tag{2}$$

where *RO* is surface runoff (mm), V_a *is* gutter volume (ml), V_j is jerry can volume (ml), *CF* is Correction factor, (0.70).

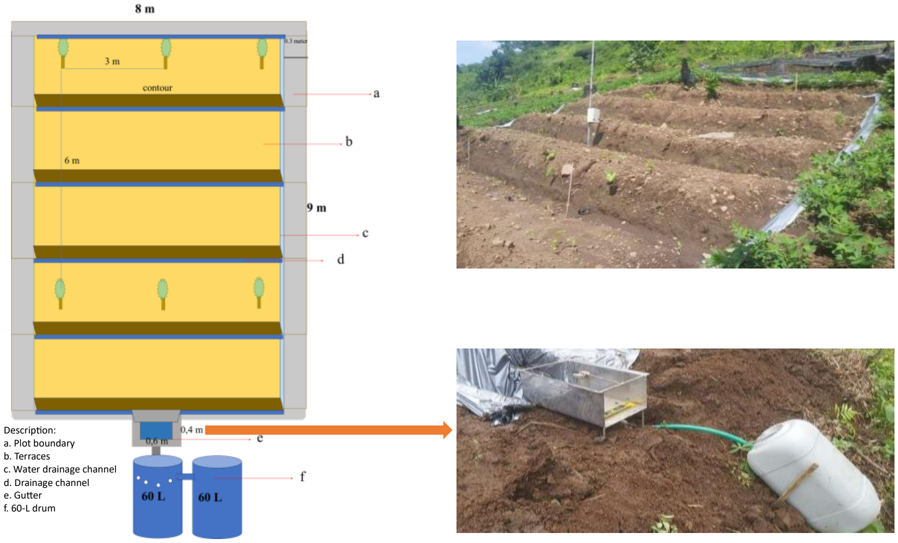

Figure 4. Plot of soil erosion and surface runoff measurements on experimental land

Soil erosion measurements were conducted by taking 500 ml subsamples of surface runoff water from jerry cans and gutters after stirring to homogenize the sediment concentration for sediment weight analysis. The samples were then filtered, dried in an oven to a constant weight, and the dry sediment mass was weighed. The total sediment weight was calculated using Equation (4)**,** while total soil erosion in Mg/ha was calculated based on Equation (5).

$$\text{Total mass of surface runoff} = [\frac{\text{vol A}}{\text{vol SA}} \times \text{SMJ}] + [\frac{100}{\text{FK}} \times \frac{\text{vol J}}{\text{vol SJ}} \times \text{GSM}] \tag{4}$$

$$\text{Total soil erosion (Mg/ha)} = \left(\frac{total\ runoff\ mass\ (g)}{treatment\ plot\ area\ (m^2)}\right) / 100 \tag{5}$$

where vol A is volume gutter (ml), vol SA is volume sampel gutter (ml), vol J is volume jerrycan (ml), SMJ is sample mass jerrycan (gram), GSM is gutter sample mass (gram), and CM is correction factor (0.70).

2.5. Measurement of Growth and Yield of Annual Crops

The growth rate and diameter of pine trees and seasonal plants were measured to determine growth dynamics during the observation period. Initial measurements were taken on the first day (T_0) and repeated periodically every n days for 80 days. After the final measurement on the nth day (T_1), the growth rate of pine trees, durian trees, chili plants, and peanut plants was calculated using equation (6),

$$\text{HGR} = \frac{\text{H}_1\text{-H}_0}{\text{D}} \tag{6}$$

where HGR is high plant growth rate (cm/day), H_0 is plant height on the first day of measurement, H_1 is plant height on the last day of measurement, and Dn is day-*n*. The increase in pine diameter was calculated using the equation (7).

$$\mathrm{IPD} = \frac{D_1 - D_0}{Dn} \tag{7}$$

where IPD is increase in plant diameter, D_0 is plant diameter on the first day of measurement, D_1 is plant diameter on the last day of measurement, Dn is day-*n*. The biomass rate of pine trees and durian trees was calculated using the following equation (8) by Chave (2004):

$$B = 0.0509 \times \rho \times D_1^2 \times T_1 \tag{8}$$

where B is tree biomass, ρ is density of wood (pine = 0.45 and durian = 0.57), D_1 is diameter of plants on the last day of measurement, and T_1 is plant height on the last day of measurement.

The yield of peanuts and chili peppers was observed in each treatment plot. Chili peppers were harvested in stages by picking ripe red fruits. The entire harvest from each plot was collected, weighed, and recorded in terms of the number and weight of fresh fruits. Peanut harvesting was carried out at physiological maturity by pulling out the entire plant, separating the pods from the vegetative parts, and weighing the total fresh pod yield. The harvest data was then expressed in weight per plot area and converted to hectares (Mg/ha).

2.6. Analysis of Farm Income

Farm income analysis was conducted to assess the economic feasibility of seasonal crops (chili and peanuts) in a post-harvest pine agroforestry system. Income was calculated based on the difference between total revenue (TR) and total costs (TC) during one planting season, referring to Soekartawi (2006), with the following general Equation (9):

$$\pi = \mathrm{TR} - \mathrm{TC} \tag{9}$$

$$TR = \text{crop yield (kg/ha)} \times \text{selling price (IDR/kg)} \tag{10}$$

where π is net farm income (IDR/ha), TR is total revenue, TC (total cost) is total production costs, consisting of: fixed costs, including land rent, equipment depreciation, and taxes, as well as variable costs, including seeds, fertilizers, pesticides, labor, and irrigation water. To assess economic efficiency, the revenue-to-cost ratio or R/C ratio is used, with the Equation (11). The farming activity is profitable if R/C > 1, break-even point if R/C = 1, and farming losses if R/C < 1.

$$\mathrm{R/C} = \frac{\mathrm{TR}}{\mathrm{TC}} \tag{11}$$

This analysis was conducted on each combination of vegetative and mechanical conservation treatments to determine the effect of conservation measures on the productivity and profitability of seasonal crops. Net income and R/C ratio values were analyzed descriptively and comparatively and tabulated in term of income per hectare tables.

2.7. Data Analysis

The observation data included rainfall, surface runoff, soil erosion, growth, and crop yield, which were analyzed using Analysis of Variance (ANOVA) according to a Factorial Randomized Block Design (RAKF) with two treatment factors, namely mechanical soil conservation and vegetative soil conservation, as well as one treatment for which no data analysis was performed (non-factorial). If the ANOVA results showed significant differences at a 5% confidence level, Duncan's Multiple Range Test (DMRT) was performed to distinguish between treatment means.

3. RESULTS AND DISCUSSION

3.1. Rainfall

During the experimental period, there were 39 days of rainfall with a total rainfall of 692 mm (Figure 5). Of these events, 69% were light rain (<20 mm/day), 18% were moderate rain (21– 50 mm/day), and 13% were heavy rain (51–100 mm/day). There were no instances of very heavy rainfall (>100 mm/day). These rainfall characteristics indicate that most rainfall events were in the low to moderate intensity category, with relatively limited frequency of heavy rainfall. This pattern is important because it determines the amount of kinetic energy of rainfall and the potential for soil erosion during the observation period.

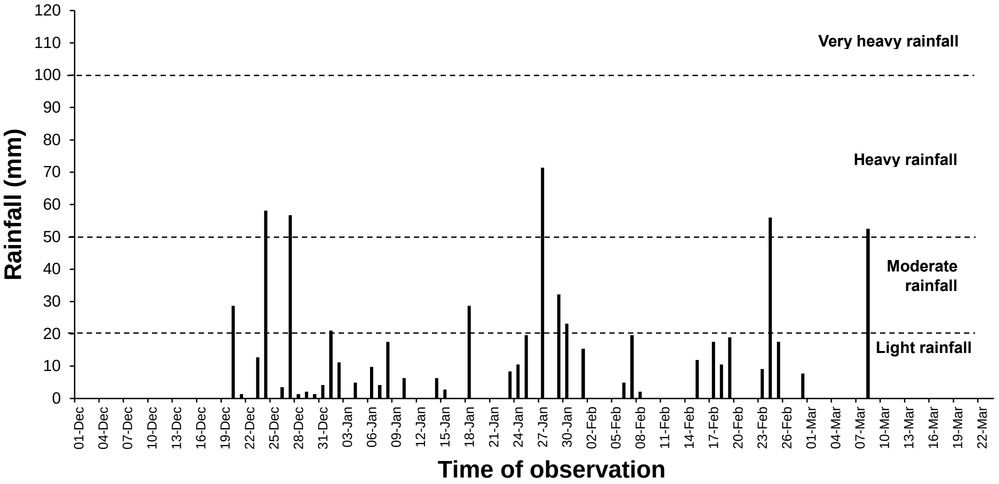

Figure 5. Rainfall distribution during the experiment in the area of Perhutani Production Forest, Kasembon, Malang

3.2. Surface Runoff and Soil Erosion

Mechanical conservation techniques had a very significant effect in reducing surface runoff in the early phase of pine–durian agroforestry (p<0.01), while vegetative conservation did not show a significant effect (p>0.05). Ridge terraces reduced runoff by 9–41%, while bench terraces were more effective with a reduction of 33–53% compared to the control, especially in the chilli–peanut intercropping system with biogeotextiles (Figure 6a). Regarding soil erosion, mechanical conservation (p<0.01) and vegetative conservation (p<0.001) each had a significant effect, but their interaction was not significant (p>0.05), indicating that both factors worked independently. Without terraces, annual crops did not differ significantly from the control. Conversely, the combination of intercropping + biogeotextile reduced erosion by 68%. Ridge terraces reduced erosion by 27–72%, while bench terraces were more effective with a reduction of 48–75%, especially in intercropping systems equipped with biogeotextile (Figure 6b).

Mechanical conservation techniques were the most decisive factor in reducing surface runoff and soil erosion in the early phase of pine–durian agroforestry. Ridge terraces and especially bench terraces proved to be more effective than early vegetative conservation, because physical modification of the slope directly shortened the slope length, reduced flow velocity, and reduced the erosive energy of water. In contrast, vegetative conservation has not yet shown a significant effect because seasonal plants are still in their early stages with limited canopies and root systems, so they are not yet able to control flow and retain soil particles effectively (Niu *et al*., 2025).

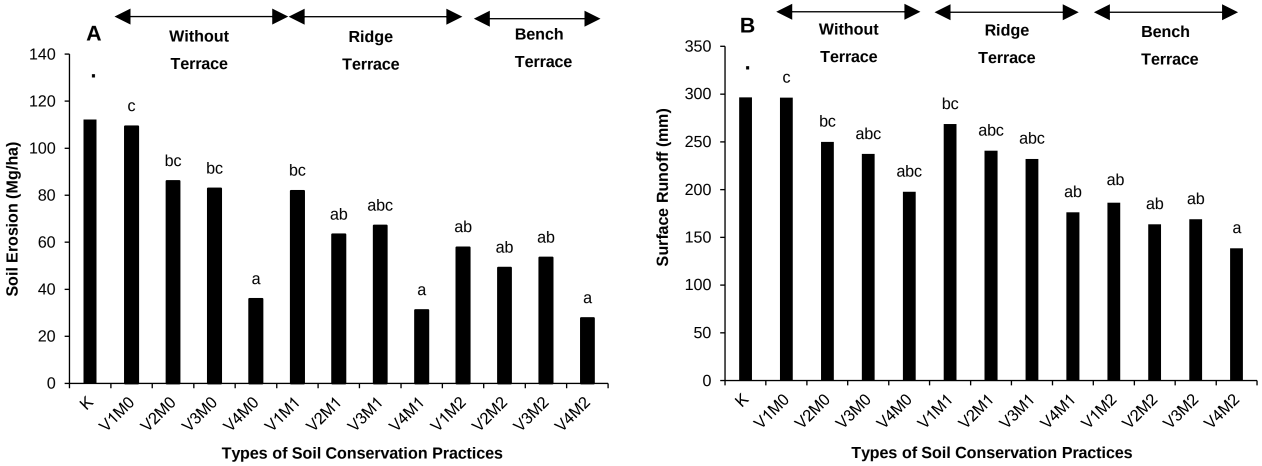

Figure 6. (a) Total surface runoff; (b) Total soil erosion

Mechanical conservation techniques were the most decisive factor in reducing surface runoff and soil erosion in the early phase of pine–durian agroforestry. Ridge terraces and especially bench terraces proved to be more effective than early vegetative conservation, because physical modification of the slope directly shortened the slope length, reduced flow velocity, and reduced the erosive energy of water. In contrast, vegetative conservation has not yet shown a significant effect because seasonal plants are still in their early stages with limited canopies and root systems, so they are not yet able to control flow and retain soil particles effectively (Niu *et al*., 2025).

The use of biogeotextiles has a more noticeable impact because they function as surface protectors that directly reduce rain energy, increase micro-surface roughness, and increase infiltration (Bhattacharyya *et al*., 2011), in line with various studies on the effectiveness of geotextiles and mulch in controlling erosion on sloping land (Tauro *et al*., 2018; Markiewicz *et al*., 2024; Sumiahadi *et al*., 2018). However, the higher effectiveness of bench terraces compared to ridge terraces shows that changes in slope geometry play a dominant role in erosion control, especially for moderate rainfall, while also increasing infiltration and reducing nutrient loss (Kumar *et al*., 2025). Therefore, terracing practices still need to be combined with soil cover to maintain conservation effectiveness throughout the year.

3.3. Growth of Pine and Durian Trees

The growth rates of diameter, height, and biomass of pine and durian showed relatively uniform patterns between treatments (Table 2). The variations that emerged were inconsistent and did not form a specific pattern. Statistically, the presence of annual plants (vegetative conservation) and the application of ridge terraces and bench terraces (mechanical conservation) did not significantly affect the initial growth of both tree species ($p>0.05$).

The growth rates of diameter, height, and biomass of pine and durian trees did not differ significantly between treatments, either due to the presence of annual crops or the application of conservation measures. This indicates that in the early stages, competition for resources (light, water, and nutrients) was still low because the canopy was not yet closed and the root system had not yet developed extensively, so the relationship between trees and annual crops tended to be complementary. This finding is in line with agroforestry studies which state that intercropping in the early years generally does not reduce tree growth, and may even be neutral or slightly positive due to soil cultivation and fertilisation (Imanuddin *et al*., 2020; Mappah *et al*., 2025). Theoretically, competition intensity increases with age and canopy closure (Gonçalves *et al*., 2021). Thus, the application of ridge terraces and bench terraces in this study played a greater role in modifying surface hydrological responses than in affecting resource availability for early tree growth.

Table 1. Growth of pine and durian trees

Treatment	**Growth Rate of Pine**			**Growth Rate of Durian**		
	Diameter (cm/day)	**Height (cm/day)**	**Biomass (Mg/day)**	**Diameter (cm/day)**	**Height (cm/day)**	**Biomass (Mg/day)**
K	0.0027	0.09	0.0030	0.0033	0.09	0.009
V1M0	0.0030	0.11	0.0030	0.0020	0.18	0.009
V2M0	0.0037	0.14	0.0033	0.0037	0.11	0.010
V3M0	0.0030	0.11	0.0033	0.0030	0.13	0.007
V4M0	0.0023	0.09	0.0027	0.0040	0.14	0.006
V1M1	0.0033	0.11	0.0033	0.0033	0.09	0.010
V2M1	0.0027	0.10	0.0030	0.0020	0.10	0.009
V3M1	0.0017	0.11	0.0030	0.0020	0.13	0.008
V4M1	0.0023	0.11	0.0030	0.0033	0.14	0.009
V1M2	0.0037	0.11	0.0030	0.0040	0.17	0.009
V2M2	0.0030	0.12	0.0027	0.0037	0.14	0.009
V3M2	0.0020	0.11	0.0033	0.0023	0.13	0.011
V4M2	0.0027	0.09	0.0037	0.0023	0.11	0.010

3.4. Growth and Yield of Annual Crops

Vegetative ($p<0.001$) and mechanical ($p<0.05$) conservation techniques significantly affected chilli growth, but only vegetative conservation had a significant effect on production yield ($p<0.05$). The intercropping system without terraces increased chilli yield by 2–2.5 times compared to monoculture without terraces. Ridge terraces increased yields by 2.9–3.3 times, while bench terraces were most effective with an increase of 2.5–4.75 times (Figures 7a–b). However, the application of biogeotextiles in intercropping tended to reduce yields, presumably due to the allelopathic effect of mahogany leaves as mulch.

In peanut cultivation, there was a significant interaction between vegetative and mechanical conservation on growth rate (p<0.05). Production was significantly influenced by vegetative (p<0.001) and mechanical (p<0.01) conservation, but without interaction between the two. Monoculture growth was relatively uniform (0.55–0.58 cm day^{-1}), except for intercropping with bench terraces, which decreased to 0.32 cm day^{-1} (Figure 7c). Peanut yields in intercropping without terraces decreased by 22–37%. Ridge terraces and bench terraces only increased monoculture yields by 1.1–1.2 times, while in intercropping they actually decreased by 8–20%, especially in combination with biogeotextiles, which again indicated the effect of allelopathy (Figure 7d).

The relatively uniform growth between treatments indicates that competition between annual crops and main trees is still weak in the early stages, so that resources are not yet a limiting factor. The decline in growth in the non-terrace system is more related to water limitations due to surface runoff than to biological competition, emphasising the importance of hydrological management on sloping land (Pedroza-Sandoval *et al*., 2024).

Chilli yields responded strongly to cropping patterns and mechanical conservation. Intercropping without terraces can increase yields through efficient use of light, water, and nutrients due to differences in canopy and root architecture (Wang *et al*., 2024), while ridge terraces and especially bench terraces further enhance production through increased infiltration, water retention, and nutrient distribution (Wang *et al*., 2023). Conversely, biogeotextiles did not increase chilli yields and in some combinations even reduced them, presumably due to the allelopathic effects of mahogany leaves (Mukaromah *et al*., 2016), which still requires further chemical verification.

Peanut production showed a different response; the decrease in yield in intercropping indicated higher sensitivity to light competition. Although terraces improved water and nutrient conditions, these improvements were not entirely

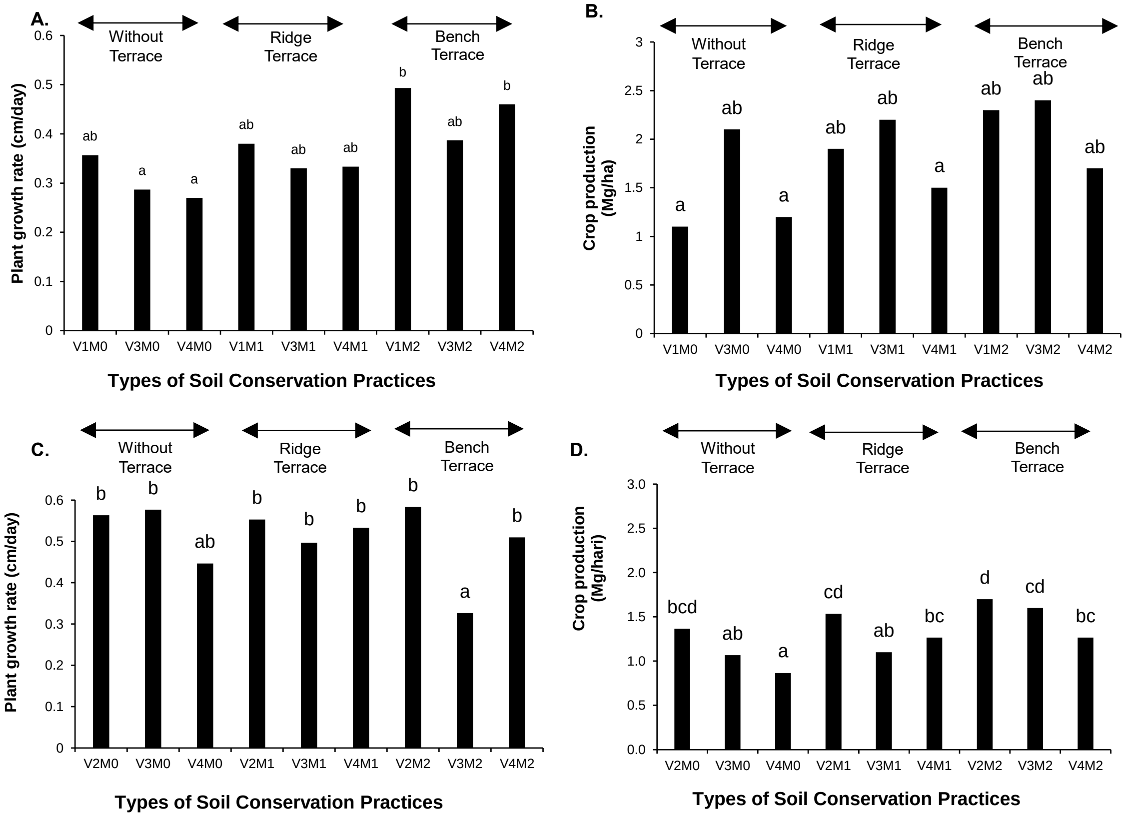

Figure 7. (A) Growth of cayenne pepper plants; (B) yield of cayenne pepper; (C) growth of peanut plants; and (D) yield of peanuts.

converted into yield when spatial design and canopy compatibility were unbalanced, making plant architecture management key to the success of legume intercropping (Hussainy *et al*., 2020).

3.5. Farming Results

Cost details show that differences between treatments mainly stem from variable costs (seeds, pesticides, labour, and conservation) (Table 3). The biogeotextile-based treatment (V4) had the highest total cost (19.7–22.7 million IDR/ha) due to high material and installation costs, followed by bench terraces (M2), while no terraces (M0) and ridge terraces (M1) had lower costs. The more intensive the conservation measures, the greater the initial costs required, indicating a trade-off between conservation and economics, although this investment has the potential to increase agronomic benefits and productivity (Hussain *et al*., 2021). Net income shows that mechanical conservation, especially bench terraces, provides the most significant profit increase in the early phase of pine agroforestry (Figure 8a). The system without terraces generated the lowest income due to high runoff and erosion, ridge terraces increased income through improved water retention and soil stability, while bench terraces were able to increase income more than fourfold, particularly in monoculture chilli and chilli– peanut intercropping.

Statistical analysis shows that vegetative conservation has a very significant effect on net income and R/C value (p<0.001). The chilli planting pattern provides the highest income, while the use of biogeotextiles reduce income due to the potential allelopathy of mahogany leaves. This trend is consistent with the R/C value: system with no terraces has low efficiency (1.5–3.5), increases in ridge terraces (3–5), and highest in bench terraces (5–7) (Figure 8b).

Monoculture chilli on terraces (V1M1 and V1M2) also showed strong economic performance with net income of 55–68 million IDR/ha and R/C 5.20–5.67, confirming that high-value horticultural commodities are highly responsive

Table 2. Farm business analysis in several experimental plots at a 1-hectare scale

Code	Fixed Costs (IDR/ha)	Variable Costs (IDR/ha)					Total Costs (IDR/ha)	Total Revenue (IDR/ha)
		Seed	Fertiliser	Pesticide	Labour	Conservation		
V1M0	738,000	1,350,000	750,000	2,071,000	5,300,000	1,400,000	11,609,000	39,600,000
V2M0	738,000	860,000	750,000	1,143,667	4,500,000	1,400,000	9,391,666	68,400,000
V3M0	738,000	2,210,000	1,350,000	2,601,000	6,300,000	1,400,000	14,599,000	82,800,000
V4M0	738,000	2,210,000	1,350,000	2,601,000	7,800,000	3,844,444	19,700,851	16,400,000
V1M1	738,000	1,350,000	750,000	2,071,000	5,550,000	2,700,000	13,159,000	18,400,000
V2M1	738,000	860,000	750,000	1,251,000	4,750,000	2,700,000	11,049,000	20,400,000
V3M1	738,000	2,210,000	1,350,000	2,493,667	6,550,000	2,700,000	16,041,666	88,400,000
V4M1	738,000	2,210,000	1,350,000	2,601,000	8,050,000	5,144,444	21,250,851	92,400,000
V1M2	738,000	1,350,000	750,000	2,071,000	6,200,000	3,500,000	14,609,000	105,600,000
V2M2	738,000	860,000	750,000	1,143,667	5,400,000	3,500,000	12,391,666	53,600,000
V3M2	738,000	2,210,000	1,350,000	2,601,000	7,200,000	3,500,000	17,599,000	69,200,000
V4M2	738,000	2,210,000	1,350,000	2,601,000	8,700,000	5,944,444	22,700,851	76,400,000

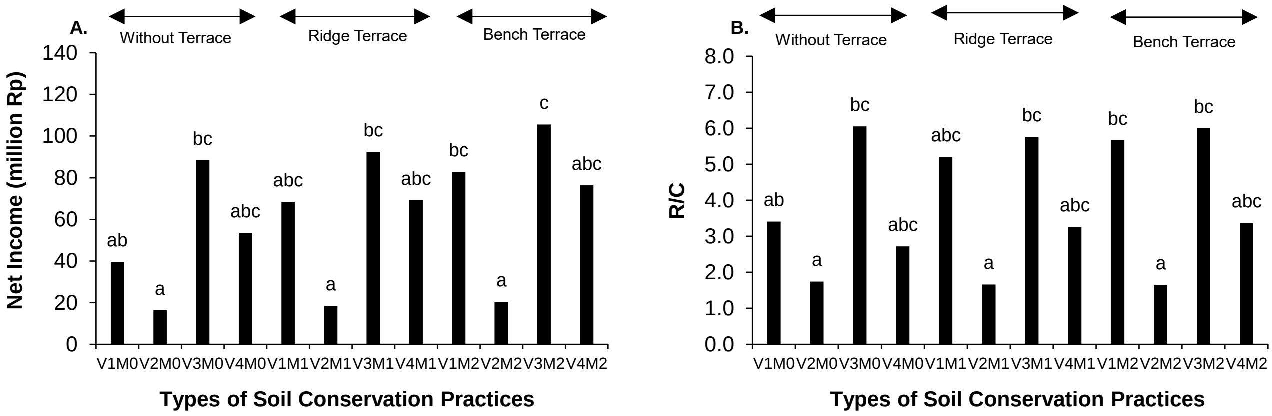

Figure 7. (A) Net farm income and (B) Ratio between Revenue and Cost

to improvements in hydrological conditions and soil fertility. Mechanical conservation (ridge terraces and bench terraces) and intercropping patterns significantly increased farm income, especially in the V3M2 treatment, which achieved the highest net income and an R/C value of more than 6. These findings are in line with Muliastuty *et al*. (2016), which showed that intercropping patterns and soil conservation techniques such as cross-slope ridges (K3 and K4) significantly increased farmers' income by reducing soil erosion to below the tolerance threshold and increasing crop yields. Agricultural income on sloping land decreases due to soil erosion, nutrient loss, and low crop productivity. Monoculture cropping patterns on sloping land also show a smaller contribution to income than intercropping. According to Li *et al*. (2025), initial investment in soil conservation on sloping land provides long-term economic benefits because the increase in crop yield is much greater than the additional cost of conservation. A similar pattern was observed in this study, where treatment M2 had higher conservation costs but still generated the highest net income and R/C value.

3.6. Synthesis of Soil Conservation Effectiveness in the Early Phase of Pine and Durian Agroforestry

The results of this study indicate the existence of an integrated soil conservation mechanism that links hydrology, crop productivity, and economic performance in the pine– durian agroforestry system. The application of mechanical conservation (ridge terraces and especially bench terraces) significantly reduced surface runoff and soil erosion. Reduced runoff increases water retention and infiltration, while reduced erosion preserves the topsoil, organic matter content, and nutrient availability. Combination with vegetative conservation, particularly intercropping, and biogeotextile support further strengthens soil stability, although allelopathic effects need to be considered in some commodities. These improvements in hydrological conditions and soil quality do not directly increase the initial growth of pine and durian trees, which tend to be stable between treatments. However, the benefits of conservation are very evident in annual crops, especially chillies, which show significant increases in growth and yield in systems with terraces, especially bench terraces. In contrast, peanuts are more sensitive to treatment combinations, including potential competition and allelopathic effects.

The mechanism of soil conservation effectiveness boils down to increased income and farming efficiency. Systems without terraces experience high runoff and erosion, which suppress productivity and profits. Ridge terraces moderately improve these conditions, while bench terraces result in more than a fourfold increase in income, with the highest R/C value. Thus, integrated soil conservation works through a chain of mechanisms: (1) runoff control → (2) reduced erosion → (3) improved soil health and water availability → (4) increased seasonal crop productivity → (5) increased farmer income, while forest tree growth remains stable as a long-term investment. This framework confirms that soil and water conservation is not only an ecological strategy, but also an agronomic and economic intervention that is integrated into a sustainable agroforestry system.

4. CONCLUSION AND RECOMMENDATIONS

This study concluded that integrated soil and water conservation—through a combination of mechanical conservation (ridge terraces and especially bench terraces) and vegetative conservation—effectively reduces surface runoff and soil erosion, improves water retention and maintains the quality of the topsoil, which ultimately increases the productivity of seasonal crops and farmers' incomes without disrupting the early growth of pine and durian trees. Bench terraces have been proven to provide the highest hydrological effectiveness and economic benefits, despite requiring higher initial costs. Therefore, it is recommended that post-harvest agroforestry management prioritize mechanical conservation on sloping land, combined with adaptive cropping patterns and the selection of mulch materials that do not cause allelopathy, in order to achieve a balance between ecological sustainability, soil health and the economic viability of farming.

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AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
AF	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	
KSW	✓	✓			✓					✓		✓		✓
CP	✓	✓			✓					✓		✓		✓
DS	✓	✓	✓		✓	✓			✓	✓	✓	✓		✓

C: Conceptualization
M: Methodology
So: Software
Va: Validation
Fo: Formal Analysis
I: Investigation
D: Data Curation
R: Resources
O: Writing - Original Draft
E: Writing - Review & Editing
Vi: Visualization
Su: Supervision
Fu: Funding Acquisition
P: Project Administration

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