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Economic Efficiency Assessment of Acacia mangium Plantations Managed for Small-Diameter Timber and the Potential Development of Large-Diameter Timber Production Scenarios in Bac Ninh Province, Vietnam

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Abstract

This study evaluates the economic efficiency of Acacia mangium plantation models managed for small-diameter timber under a 6-year rotation, while also estimating the potential revenue from a large-diameter timber production scenario based on a 15-year rotation in Bac Ninh Province, Vietnam. The study draws on data from 20 sample plots and interviews with 50 forest-growing households. The methods employed include forest growing stock estimation and financial analysis using Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR).

The results indicate that, at 6 years of age, standing timber volume ranges from 168.13 m³/ha to 260.36 m³/ha, with the highest volume recorded at a planting density of 3,330 trees/ha. Revenue from small-diameter timber harvesting ranges from 130.133 to 185.245 million VND/ha. The highest revenue is achieved at a planting density of 3,333 trees/ha (185.245 million VND/ha), followed by densities of 2,500 trees/ha (172.852 million VND/ha) and 2,000 trees/ha (169.060 million VND/ha), while the lowest revenue is recorded at a density of 1,333 trees/ha (130.133 million VND/ha). All four models demonstrate economic viability, with NPV values greater than zero. Among them, the model with a planting density of 2,000 trees/ha delivers the highest investment efficiency, with an NPV of 60.94 million VND/ha, a BCR of 2.77, and an IRR of 39.69%.

Under the large-diameter timber production scenario, the estimated revenue from the main harvest at age 15 ranges from 830.84 to 969.32 million VND/ha. This is approximately 2.24–2.62 times higher than the revenue generated by small-diameter timber model M1 and 2.46–2.87 times higher than that of model M3. Compared with small-diameter timber production over the same 15-year period, the large-diameter timber scenario offers the potential to increase revenue from the main harvest while reducing the frequency of reforestation investments. These findings provide a scientific reference for determining appropriate planting densities and guiding the transition of Acacia mangium plantation management toward greater economic value and sustainable forest management.

Keywords: *Acacia mangium; economic efficiency; planting density; small-diameter timber production; large-diameter timber production; Bac Ninh Province.*

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INTRODUCTION

Acacia plantations play an important role in the development of Vietnam's forestry sector, particularly in supplying raw materials for the wood-processing industry and generating employment and income for local communities. According to statistics presented at the "Vietnam Plant Varieties" conference in April 2019, Acacia plantations account for approximately 39% of the country's total plantation forest area. *Acacia mangium* is widely planted because of its relatively rapid growth, adaptability to a range of site conditions, and established market demand. However, most Acacia plantations in Vietnam are currently managed under short rotation periods of 5–7 years, primarily to supply raw materials for wood chip and paper production. Although this management approach provides relatively rapid financial returns, harvesting trees at such an early age limits their potential for diameter growth and the production of higher-value timber. Furthermore, frequent clear-cutting, particularly when accompanied by inadequate site preparation, can increase the risks of soil erosion, nutrient leaching, and overall soil degradation.

In response to the need to enhance the economic value of forest production and promote sustainable forest management, the cultivation of Acacia for large-diameter timber under longer rotation periods is emerging as a promising development strategy. Extending the rotation period allows trees to achieve greater diameter growth, thereby increasing the proportion of large-diameter timber and providing raw materials for higher-value-added wood-processing industries. In addition, maintaining forest stands over longer periods contributes to greater biomass accumulation and carbon sequestration, enhances soil protection, and helps mitigate the environmental impacts associated with frequent harvesting. Nevertheless, the transition from small-diameter to large-diameter timber production involves specific requirements in terms of initial capital investment, investment recovery periods, silvicultural techniques, and market demand. Therefore, a comprehensive assessment of the economic efficiency of existing production practices and the potential for value enhancement through extended rotation periods is essential.

Bac Ninh Province has favorable conditions for forestry development. By 2025, the total area of forest and forestry land is projected to reach 167,657.25 hectares, including 92,594.01 hectares of planted forests, with a forest coverage rate of 31.16%. Pure Acacia plantations cover 55,011.77 hectares, accounting for approximately 59.41% of the province's total planted forest area. These figures highlight the important role of Acacia plantations in local forestry production. Therefore, selecting appropriate rotation periods and forest management practices is essential not only for improving the investment returns of forest growers but also for supporting the province's broader strategy to enhance the economic value and sustainability of its forestry sector.

In recent years, several studies have examined the economic efficiency of Acacia plantations and the feasibility of developing large-diameter timber production models. For example, Ngo Van Ngoc et al. (2022) evaluated the economic efficiency of hybrid Acacia plantations in Kien Giang Province; T.T. Nguyen et al. (2014) analyzed the financial performance of long-rotation forestry models using indicators such as Net Present Value (NPV) and Internal Rate of Return (IRR); and Phung Thi Thanh Hai et al. (2020) investigated differences in soil nutrient accumulation between hybrid Acacia plantation models managed for small-diameter and large-diameter timber in Thanh Hoa Province. These studies provide a valuable foundation for understanding the production efficiency, financial performance, and ecological benefits of Acacia plantations. However, their findings are largely specific to particular species, geographical locations, and research objectives. The economic efficiency of *Acacia mangium* plantations managed for small-diameter timber under different planting densities remains insufficiently explored. Similarly, the potential revenue and broader economic, social, and environmental benefits associated with large-diameter timber production scenarios in Bac Ninh Province have not been adequately investigated.

To address these research gaps, this study evaluates the economic efficiency of *Acacia mangium* plantations managed for small-diameter timber, harvested at six years of age, by analyzing production costs, revenues, and financial indicators across different planting densities. Furthermore, it develops a large-diameter timber production scenario with a 15-year rotation to estimate potential revenue and assess the associated economic, social, and environmental benefits of extending the rotation period. The findings provide a scientific reference for selecting appropriate plantation management strategies, enhancing timber product value, and promoting sustainable forestry development in Bac Ninh Province.

LITERATURE REVIEW

Studies on Rotation Periods and Harvesting Ages of Plantation Forests

Determining the appropriate rotation period and optimal harvesting age is an important issue in forest economics, as harvesting time directly affects timber yield, product composition, and investment efficiency. From a theoretical perspective, the Faustmann forest rotation model (1849) provides the foundation for determining the optimal harvesting age by maximizing the present value of net revenues generated from successive forest rotations on the same area of forest land.

For Acacia plantations, short rotations are generally aimed at producing raw materials for the wood chip and paper industries, whereas longer rotations seek to increase stem diameter, the proportion of sawlog timber, and commercial value. In a study of hybrid Acacia plantations at Luong Son Forestry Company, Do Anh Tuan (2013) demonstrated that harvesting age affects stand volume, product composition, and financial performance. Nguyen Quang Ha and Duong Thi Thanh Tam (2016) emphasized that the determination of rotation periods should take into account the economic benefits of forest owners over the entire period of land allocation, rather than evaluating each rotation independently.

A study published in *Forest Policy and Economics* (2017) on the financial performance of Acacia plantations at Ben Hai Forestry Company found that the 10-year rotation option achieved higher NPV and IRR values than the 5-year and 6-year rotation options. Arvola et al. (2020) also suggested that the economic performance of Acacia plantations varies according to harvesting age and silvicultural practices, with thinning playing an important role in promoting diameter growth and generating additional intermediate timber products. For *Acacia mangium*, Le Duc Thang et al. (2023) found that stand diameter, height, and growing stock tended to increase with stand age. However, the most economically efficient harvesting option may vary depending on the evaluation criteria applied.

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Overall, there is no universally optimal harvesting age applicable to all production conditions. Instead, it depends on tree species, site conditions, planting density, silvicultural practices, timber prices, and investment costs. These considerations provide a basis for evaluating the economic efficiency of *Acacia mangium* plantation models under different planting densities and specific harvesting rotations.

Research Methods and the Basis for Assessing the Economic Efficiency of Plantation Forests

Assessing the economic efficiency of plantation forests involves examining the relationship between the benefits generated and the costs of resources invested over a production cycle. Given the long production period characteristic of forestry, costs are generally incurred during planting, tending, and protection stages, whereas revenues are concentrated primarily at the time of harvesting. Therefore, economic evaluation should account for the time value of capital through discounted cash flow analysis.

From a theoretical perspective, the Faustmann rotation model (1849) provides an important foundation for forest economic analysis by considering the present value of net revenues generated from successive rotations on the same area of land. On this basis, forest economic studies commonly employ cost-benefit analysis and financial indicators to evaluate and compare investment alternatives. Three widely used indicators are Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR). NPV reflects the present value of the difference between benefits and costs; BCR indicates the ratio of the present value of benefits to the present value of costs; and IRR represents the discount rate at which NPV equals zero. The combined application of these indicators enables an assessment of the economic value generated, the capacity to recover investment costs, and the profitability of different production alternatives.

In practice, studies assessing the economic efficiency of plantation forests commonly combine field surveys, timber yield statistics, classification of timber by commercial specifications, market price surveys, and cost estimation for each stage of production. Do Anh Tuan (2013) combined yield surveys, timber product classification, and financial analysis to identify an appropriate harvesting age. Recent studies on *Acacia mangium* have also demonstrated that using growth data and yield projections as the basis for calculating financial indicators can improve the reliability of economic assessments.

Thus, assessing the economic efficiency of plantation forests requires the integration of silvicultural data with financial and market information. Timber yield should be determined separately for each commercial product category; revenue should be calculated based on the corresponding yield and selling price; and costs should be aggregated according to the investment activities undertaken throughout the rotation period. This provides the methodological foundation for applying NPV, BCR, and IRR to evaluate the economic efficiency of *Acacia mangium* plantation models managed for small-diameter timber and harvested at six years of age under different planting densities in Bac Ninh Province.

Studies on the Development of Large-Diameter Timber Production and Its Economic, Social, and Environmental Benefits

The transition from small-diameter to large-diameter timber production is a strategic approach aimed at increasing the value of forestry products and meeting the demand for raw materials in the wood-processing industry. This approach requires an extended growing period combined with silvicultural practices such as thinning and density adjustment to promote diameter growth, improve timber quality, and increase the proportion of commercial timber. In Vietnam, TCVN 11567-1:2016, which provides technical guidelines for converting small-diameter hybrid Acacia plantations into large-diameter timber plantations, addresses relevant silvicultural requirements. Although this standard specifically applies to hybrid Acacia, certain silvicultural principles concerning density adjustment and the tending of selected crop trees may also serve as useful references for research on other Acacia species.

Regarding economic performance, Arvola et al. (2021) found that producing sawlogs from Acacia plantations in Central Vietnam has the potential to generate higher profits than producing wood chips. However, economic performance depends on harvesting age, forest management practices, and market accessibility. From an environmental perspective, Phung Thi Thanh Hai et al. (2020) reported that large-diameter hybrid Acacia plantation models in Thanh Hoa Province exhibited lower soil erosion rates and higher soil organic carbon levels than small-diameter timber models. However, differences in certain soil nutrient indicators were not consistent, suggesting that environmental impacts should be assessed separately across specific dimensions.

Overall, existing studies indicate that large-diameter timber production has the potential to increase product value, expand income-generating opportunities, and contribute to maintaining certain ecological functions of forests. Nevertheless, its actual performance depends on site conditions, planting material quality, planting density, thinning techniques, investment costs, and market fluctuations. Therefore, extending the rotation period does not necessarily guarantee higher economic efficiency under all production conditions.

The literature review indicates that although the economic efficiency, harvesting age, and development of large-diameter timber production in Acacia plantations have been examined in various localities, empirical evidence concerning *Acacia mangium* plantations in Bac Ninh Province remains limited. In particular, the financial performance of small-diameter timber production at six years of age under different planting densities, as well as revenue projections for a large-diameter timber production scenario with a 15-year rotation, requires further investigation based on local growth conditions, production costs, and timber prices. Accordingly, this study focuses on evaluating the economic efficiency of *Acacia mangium* plantation models managed for small-diameter timber using NPV, BCR, and IRR. It also estimates the potential revenue from a large-diameter timber production scenario at 15 years of age and discusses its potential economic, social, and environmental benefits.

METHODS AND MATERIALS

Research Subjects and Scope

Research subjects: Acacia mangium plantations managed for small-diameter timber production under a 6-year rotation in Bac Ninh Province.

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Research scope: The study was conducted in several areas of Bac Ninh Province where *Acacia mangium* plantations are established. Primary data were collected through interviews with 50 forest-growing households and measurements taken from 20 standard sample plots established in 6-year-old *Acacia mangium* stands. Data on plantation management practices, investment costs, and timber selling prices were collected in 2025.

Research Methodology

Data Collection Methods

Documentary review: Existing literature, specialized reports, previous research studies, legal documents, and technical guidelines related to the management, cultivation, and commercial production of *Acacia mangium* plantations were reviewed. These materials provided the basis for designing the survey questionnaires, selecting research indicators, and analyzing the study results.

Standard sample plot (SSP) method: Twenty standard sample plots (SSPs), each covering an area of 500 m², were established across sites with different site conditions, topography, and planting densities to represent the growth characteristics of 6-year-old *Acacia mangium* stands in the study area. The plots were located at the foot, middle slope, and crest of hills. Data collected from each plot included tree species, seedling origin, diameter at breast height ($D_{1.3}$), total tree height (Hvn), initial planting density, and the number of surviving trees at the time of the survey. These data were used to assess stand growth characteristics and estimate timber yield and product composition under different planting density scenarios.

Household interview survey: Interviews were conducted with 50 forest-growing households, supplemented by information obtained from timber traders and local forestry management officials. The survey focused on investment costs throughout the production cycle, including expenditures on seedlings, fertilizers, labor, machinery, and other related inputs. Information on timber yield, product specifications, and selling prices was also collected. Input costs and timber prices were based on actual local market rates in 2025 and were used to calculate production costs, revenue, and the economic efficiency of the selected production models.

Expert consultation: Opinions were obtained from managers, technical staff, and forestry experts regarding the cultivation, tending, and harvesting practices applied to *Acacia mangium* plantations, as well as factors affecting the profitability of small-diameter timber production and the feasibility of transitioning to large-diameter timber production. These insights were used to support the analysis and evaluation of the research findings and the development of the large-diameter timber production scenario.

Data Processing and Analysis Methods

Survey data were compiled, classified, and processed using descriptive statistical methods to analyze the growth characteristics, planting densities, timber yields, production costs, and revenues of *Acacia mangium* plantations.

Forest growing stock estimation: Calculations were performed using Microsoft Excel. The volume of standing trees was estimated using the following formula:

$$V = G \times H_{vn} \times f$$

Where: G is the cross-sectional area of the tree trunk at a height of 1.3 m; Hvn is the total tree height (to the tip); and f is the stem form factor (for planted forests, f is determined to be 0.473).

Methodology for calculating the economic efficiency of the model: The economic efficiency of small-timber business scenarios is evaluated using the following indicators: Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR). For the large-timber business scenario (with a 15-year rotation), the study forecasts the yield of commercial timber and estimates revenue based on timber recovery rates and local market prices.

* *Net Present Value (NPV):* This represents the difference between the present value of the cash inflow stream-calculated using a specific discount rate-and the present value of the investment costs.

The NPV indicator reflects the scale of profit per unit of area, either on an annual basis or over an entire production cycle; it is commonly used to assess the economic efficiency of a given model or cultivation practice. A higher NPV indicates greater investment efficiency. It is calculated using the following formula:

$$NPV = \sum_{t=1}^{n} \frac{(B_t - C_t)}{(1+r)^t}$$

* Internal Rate of Return (IRR): This metric represents the actual rate of return for a model; if capital is borrowed at an interest rate equal to this figure, the model reaches a break-even point. When the Net Present Value (NPV) is zero, the project generates a rate of return at least equal to the IRR.

$$IRR = r_1 + (r_2 - r_1) \times \frac{NPV_1}{NPV_1 + |NPV_2|}$$

IRR evaluation criteria: If IRR > r, the model is profitable; if IRR = r, the model breaks even; and if IRR < r, the model incurs a loss.

* Benefit-Cost Ratio (BCR): An indicator that reflects the efficiency of investment capital utilization, calculated using the following formula.

$$BCR = \frac{PV(DT)}{PV(CP)}$$

A cultivation model is only effective when the BCR (Benefit-Cost Ratio) is greater than 1. A higher BCR indicates greater efficiency.

Where: B_t is the revenue in year t; C_t is the cost in year t; r is the discount rate (assumed to be 10%); t is time (in years); n is the business cycle (the lifespan of the crop); PV(Revenue) is the present value of revenue; PV(Cost) is the present value of costs.

RESULTS

Current Status and Development Potential of *Acacia mangium* Plantations in the Study Area

To provide a general assessment of the development potential for *Acacia mangium* plantations, it is first necessary to examine the current status of forest area and composition within Bac Ninh Province. Specific data are presented in Table 1.

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Table 1: Current status and area of forests in Bac Ninh province in 2025

Land and Forest Types	Area (ha)	By Land-Use Purpose			Other Purposes
		Special-Use Forest	Protection Forest	Production Forest	
Total Forest Area and Area Planted with Forest Trees	**167.657,25**	**13.790,75**	**19.923,72**	**105.260,17**	**28.682,61**
1. Natural Forest	54.290,77	12.720,75	15.132,09	15144,84	11.293,09
2. Planted Forest	92.594,01	795,69	4.108,75	72.600,63	15.088,94
3. Area Planted with Forest Trees (Newly Planted Forests That Have Not Yet Met the Criteria for Forest Classification)	20.772,47	274,31	682,88	17.514,70	2.300,58

Data compiled from Decision No. 349/QĐ-UBND dated February 6, 2026, of the Chairman of the People's Committee of Bac Ninh province

As shown in Table 2, the survival rate ranges from 83.2% to 85.5%, with an upward trend from M1 to M4. The average diameter at breast height ($D_{1.3}$) increases from 12.8 cm in M1 to 16.1 cm in M4, while the total tree height (Hvn) varies between 14.4 and 14.6 m. In practice, plantations with higher planting densities tend to exhibit more vigorous height growth. The results indicate that differences between the models are more pronounced in terms of diameter growth than height growth. At higher densities, competition for space and nutrients among trees intensifies; consequently, trees that are less competitive may experience crown recession and stunted height growth. This leads to significant variation in height growth within high-density plantations a factor that warrants careful consideration when planning for large-diameter timber production, as the stem diameter is directly linked to timber specifications and end-use potential.

To better visualize the differences in diameter, height, and standing volume across plantations with varying planting densities, refer to Figure 1:

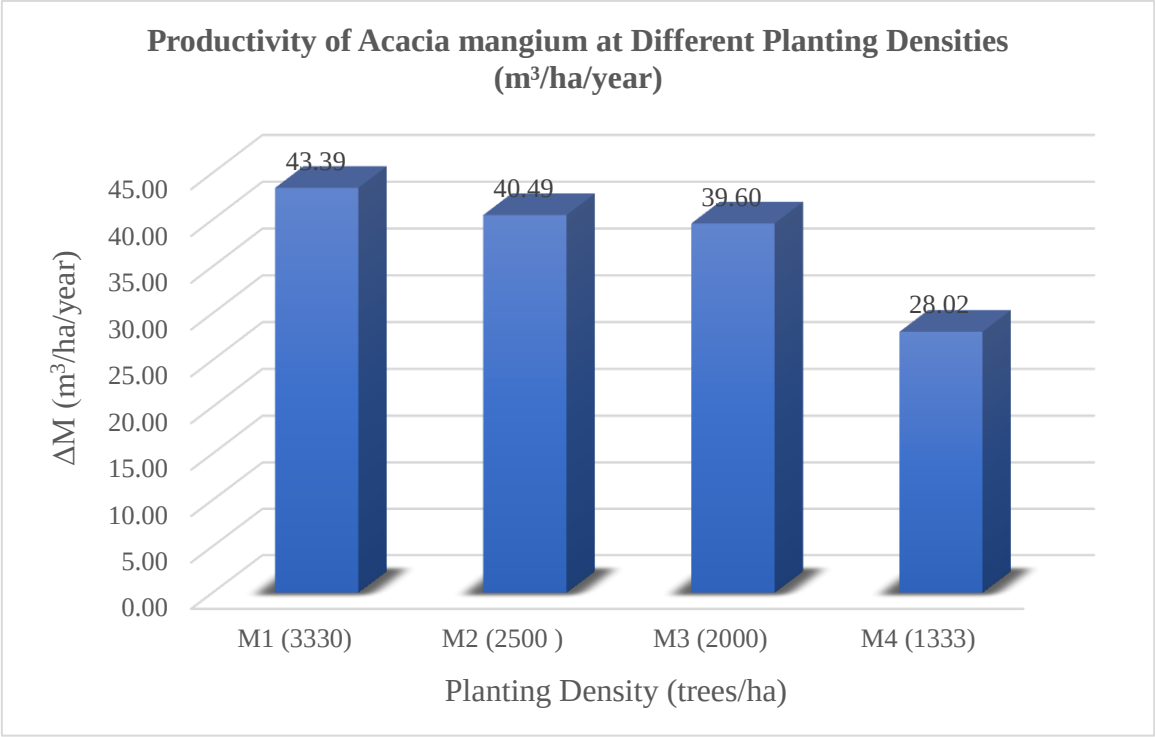

Figure 1. Productivity of Acacia mangium at Different Planting Densities at 6 Years of Age

As shown in Table 2 and Figure 1, clear differences in standing volume and mean annual increment (MAI, m³/ha/year) are observed among the different planting densities at 6 years of age. Standing volume decreases from 260.36 m³/ha at planting density M1 (3,330 trees/ha) to 242.94 m³/ha at M2 (2,500 trees/ha), 237.61 m³/ha at M3 (2,000 trees/ha), and 168.13 m³/ha at M4 (1,333 trees/ha). Similarly, MAI decreases from 43.39 m³/ha/year at M1 to 28.02 m³/ha/year at M4. Thus, M1 achieves the highest standing volume and MAI, whereas M4, despite having the largest mean diameter and the highest survival rate, records the lowest standing volume and productivity.

Overall, M1 (3,330 trees/ha) performs best in terms of standing volume per unit area, whereas M4 (1,333 trees/ha) produces trees with a larger mean diameter. However, these growth indicators alone are insufficient to determine which model delivers the highest economic efficiency. Such an assessment must also account for actual planting density, investment costs, timber prices by product specification, and total revenue. Therefore, selecting an appropriate management model requires an

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integrated analysis of growth performance, production costs, revenue, and profitability, which is presented in the following sections.

The survey results indicate that, in 6-year-old Acacia mangium stands, planting density is associated with differences in tree diameter and standing volume, whereas tree height and survival rates are relatively similar across the models. These indicators provide an important basis for evaluating the economic efficiency of current small-diameter timber production models and assessing the potential for transitioning to large-diameter timber production. Nevertheless, determining an appropriate planting density and rotation period requires a comprehensive assessment that considers investment costs, timber prices by product specification, and the accumulation of growing stock over the rotation period, rather than relying on any single growth indicator.

Economic Efficiency of the Small-Diameter Timber Production Model for Acacia mangium Plantations

Estimation of Investment Costs

Investment costs for plantation establishment are determined based on all direct input expenditures incurred from the first year through the end of the sixth year. The investment costs associated with establishing and tending 1 ha of Acacia mangium plantation up to 6 years of age are summarized in Table 3.

Table 3. Estimated Costs of Establishing and Tending 1 ha of Acacia mangium Plantation up to 6 Years of Age

Unit: Million VND

No.	Total Investment Costs	Production Costs Planting Density (trees/ha)			
		M1 (3330)	M2 (2500)	M3 (2000)	M4 (1333)
	Total Investment Costs	**58,540**	**48,175**	**41,300**	**33,564**
1	**Year 1**	**24,888**	**20,375**	**17,900**	**14,699**
	Site preparation (vegetation clearance, pit digging, basal fertilization, and pit filling)	6,000	5,400	5,200	4,800
	Seedlings	6,660	5,000	4,000	2,666
	Materials and fertilizers	5,495	4,125	3,300	2,199
	Planting labor	1,400	1,000	0,800	0,700
	Replacement seedlings	0,333	0,250	0,200	0,133
	Replanting labor	0,200	0,200	0,200	0,200
	Tending and fertilization in Year 1	4,800	4,400	4,200	4,000
2	**Year 2**	**15,326**	**12,700**	**10,800**	**8,833**
	Materials and fertilizers	7,326	5,500	4,400	2,933
	Tending and fertilization	8,000	7,200	6,400	5,900
3	**Năm thứ 3**	**16,326**	**13,500**	**11,400**	**9,233**
	Materials and fertilizers	7,326	5,500	4,400	2,933
	Tending and fertilization	8,000	7,200	6,400	5,900
	Pruning	1,000	0,800	0,600	0,400
4	**Years 4, 5, and 6**	**2,000**	**1,600**	**1,200**	**0,800**
	Forest protection and maintenance				
	Pruning	2,000	1,600	1,200	0,800

Source: Data source processed by the researcher (2025)

Investment costs include labor costs for vegetation clearance, pit digging, fertilizer application and pit filling, planting, replanting, forest tending, stand maintenance, and forest protection. Acacia mangium plantations are generally tended during the first three years, with two tending operations conducted each year. These operations mainly involve two activities: clearing vegetation, including shrubs, climbers, competing trees, and undesirable species, and applying fertilizers. From Years 4 to 6, the main silvicultural practices focus on forest protection and maintenance.

As shown in Table 3, the total investment costs for establishing and tending 1 ha of Acacia mangium plantation over a 6-year rotation vary considerably among planting densities. Specifically, the highest cost is recorded at a planting density of 3,330 trees/ha, reaching VND 58.540 million/ha, followed by densities of 2,500 trees/ha and 2,000 trees/ha, with costs of VND 48.175 million/ha and VND 41.130 million/ha, respectively. The lowest cost is recorded at a density of 1,333 trees/ha, amounting to VND 33.564 million/ha. These results indicate that higher planting densities lead

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to greater total investment costs per unit area, primarily due to increased requirements for seedlings, fertilizers, and labor.

In terms of the timing of investment expenditures, costs are concentrated mainly in the first three years, particularly in Year 1, when expenditures range from VND 14.699 million/ha to VND 24.888 million/ha, accounting for approximately 51.2–54.3% of the total costs over the entire rotation. From Year 4 to Year 6, annual investment costs decrease considerably, to only VND 0.8–2.0 million/ha. This is because the initial stage requires simultaneous implementation of activities such as vegetation clearance, pit digging, fertilizer application, planting, replanting, and initial tending. In Years 2 and 3, additional costs are incurred through periodic tending operations conducted twice a year, mainly involving the removal of shrubs, climbers, competing vegetation, and undesirable species, as well as fertilizer application. In addition, pruning costs are incurred in Year 3. This reflects a characteristic feature of forestry production, in which investment is concentrated in the initial establishment and tending stages, while maintenance costs in subsequent years are relatively low.

Revenue from the Acacia mangium Plantation Model for Small-Diameter Timber Production

Based on the survey results on timber yield and the composition of harvested timber products at 6 years of age, together with the timber utilization rate and actual local selling prices, this study estimates the expected revenue per hectare from Acacia mangium plantations managed for small-diameter timber production. The calculation results are presented in Table 4.

Table 4. Estimated Revenue per Hectare from 6-Year-Old Acacia mangium Plantations

No.	Product	Unit	Quantity	Unit Price (million VND/m³)	Total Amount (million VND)
M1 (3330 trees/ha)	Standing Volume	m^3/ha	260,4		
	Commercial Timber	m^3/ha	143,2	1,250	178,996
	Fuelwood	Ster	15,6	0,400	6,249
	Total				**185,245**
M2 (2500 trees/ha)	Standing Volume	m^3/ha	242,94		-
	Commercial Timber	m^3/ha	133,6	1,250	167,021
	Fuelwood	Ster	14,6	0,400	5,831
	Total				**172,852**
M3 (2000 trees/ha)	Standing Volume	m^3/ha	237,61		-
	Commercial Timber	m^3/ha	130,7	1,250	163,357
	Fuelwood	Ster	14,3	0,400	5,703
	Total				**169,060**
M4 (1333 trees/ha)	Standing Volume	m^3/ha	168,13		-
	Commercial Timber	m^3/ha	100,9	1,250	126,098
	Fuelwood	Ster	10,1	0,400	4,035
	Total				**130,133**

Source: Data source processed by the researcher (2025)

The results presented in Table 4 indicate considerable variation in total revenue per hectare from 6-year-old *Acacia mangium* plantations across different planting densities, ranging from 130.133 to 185.245 million VND/ha. Specifically, the planting density of 3,333 trees/ha generated the highest revenue (185.245 million VND/ha), followed by 2,500 trees/ha (172.852 million VND/ha) and 2,000 trees/ha (169.060 million VND/ha), while the lowest revenue was recorded at a density of 1,333 trees/ha (130.133 million VND/ha). Notably, revenue does not increase in direct proportion to planting density; rather, it depends on the growth capacity of the stand and its accumulation of commercial timber volume.

Nevertheless, determining an appropriate planting density requires an integrated assessment of both investment costs and economic efficiency indicators, such as NPV, IRR, and BCR, to identify an approach that ensures high productivity while maximizing the efficiency of capital and forest land utilization.

Economic Efficiency of the Acacia mangium Plantation Model for Small-Diameter Timber Production

The economic efficiency of the Acacia mangium plantation model for small-diameter timber production (6-year rotation) is evaluated using three indicators: Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit-Cost Ratio (BCR). NPV reflects the net income value of an investment project discounted to the present time; IRR indicates the profitability of the investment capital; and BCR reflects capital utilization efficiency through the relationship between the present value of revenue and costs. These indicators are calculated using a discount rate of 10% per year. The results are summarized in Table 5:

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Table 5. Economic Efficiency Indicators of the 6-Year-Old Acacia mangium Plantation Model

Planting Density	Economic Indicators		
	NPV (million VND/ha)	IRR (%)	BCR (Ratio)
M1 (3330 trees/ha)	55,76	31,79	2,14
M2 (2500 trees/ha)	57,41	35,72	2,43
M3 (2000 trees/ha)	60,92	39,69	2,77
M4 (1333 trees/ha)	45,36	37,80	2,62

Source: Data source processed by the researcher (2025)

The results presented in Table 5 show that all Acacia mangium plantation models at different planting densities have NPV values greater than 0, IRR values higher than the discount rate of 10%, and BCR values greater than 1. This demonstrates that all models are economically efficient and financially feasible over the 6-year rotation.

In terms of NPV, the planting density of 2,000 trees/ha (M3) achieves the highest value, with an NPV of VND 60.92 million/ha, followed by the density of 2,500 trees/ha (M2), with VND 57.41 million/ha. The lowest value is recorded for M4 (1,333 trees/ha), at VND 45.36 million/ha. This result indicates that M3 generates the highest net income per unit area.

Regarding IRR, all models have values higher than the discount rate of 10% per year. The model with a planting density of 2,000 trees/ha (M3) achieves the highest IRR, at 39.69%, followed by planting densities of 1,333 trees/ha (37.80%) and 2,500 trees/ha (35.72%), while the lowest IRR is recorded at a density of 3,330 trees/ha (31.79%). Similarly, the BCR is also highest for the model with a planting density of 2,000 trees/ha (2.77), followed by M4 (2.62), M2 (2.43), and M1 (2.14).

Thus, based on the NPV, IRR, and BCR indicators, a planting density of 2,000 trees/ha represents the most economically efficient plantation model under the conditions and within the scope of the study data. This may serve as a reference for selecting planting densities for Acacia mangium plantations to improve economic efficiency over a 6-year rotation.

Comparison of Small-Diameter and Large-Diameter Timber Production Models for Acacia mangium Plantations from a Sustainable Management Perspective

Forecast of Timber Yield and Revenue from the Large-Diameter Timber Production Model for Acacia mangium at 15 Years of Age

Unlike the short-rotation approach to small-diameter timber production in plantation forests, the large-diameter timber production model for Acacia mangium aims to extend the forest growth period, increase tree stem diameter and timber product quality, thereby enhancing commercial value per unit area. According to the technical guidelines issued together with Decision No. 2962/QĐ-BNN-TCLN dated July 30, 2019, by the Ministry of Agriculture and Rural Development, for Acacia mangium plantations established at an initial density of more than 1,200 to 1,600 trees/ha, the first thinning is carried out at 4–5 years of age, retaining 800–1,000 trees/ha; the second thinning is conducted at 8–9 years of age, retaining 550–600 trees/ha. This study selects a residual density of 600 trees/ha for calculating the large-diameter timber production scenario.

Based on the above technical guidelines and the results of field surveys in the study area, this study selects a large-diameter timber production scenario for Acacia mangium plantations with an initial planting density of 1,330 trees/ha. Thinning is carried out in two stages, with approximately 600 target trees/ha retained until the final harvesting age.

Based on the survey data on the growth rate of Acacia mangium trees in the study area, assuming no unusual weather conditions and that the current normal growth rate is maintained, 15-year-old Acacia mangium trees can achieve an average diameter at breast height of 35 cm and an average total height of 16 m. At a harvesting density of 600 trees/ha, the estimated standing volume reaches 461.58 m^3/ha. Assuming a commercial timber utilization rate of 60%, the harvestable commercial timber volume is estimated at 276.95 m^3/ha. According to the results of the local survey on large-diameter timber selling prices, prices range from VND 3.0–3.5 million/m^3. Accordingly, the estimated revenue from the final harvest at 15 years of age ranges from VND 830.84 to 969.32 million/ha. This is the forecast revenue from the final harvest and does not include revenue from thinning operations at 4–5 and 8–9 years of age.

However, the above forecast is based on a growth scenario using selected average parameters. It does not mean that all forest plots, under all site conditions, will achieve the same diameter, height, and standing volume indicators.

Comparison of Revenue between Small-Diameter and Large-Diameter Timber Production Models

The calculations presented in the previous section show that, over a 6-year rotation, model M1 (3,330 trees/ha) generates the highest revenue, reaching VND 185.245 million/ha, while model M3 (2,000 trees/ha) generates VND 169.060 million/ha but achieves the highest financial efficiency, as reflected by an NPV of VND 60.92 million/ha, a BCR of 2.77, and an IRR of approximately 39.69%. Therefore, it is necessary to distinguish between the revenue generated in a single rotation and capital utilization efficiency: M1 generates the highest revenue, whereas M3 demonstrates superior financial efficiency indicators.

To ensure consistency in the time period used for comparison, this study selects a 15-year period as the basis for analysis. With a 6-year rotation for small-diameter timber production, forest owners can complete two harvesting rotations within this period, corresponding to harvests in Year 6 and Year 12. On this basis, the revenues of the two models are consolidated and presented in Table 6.

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Table 6. Comparison of Revenue from Acacia mangium Plantation Models for Small-Diameter and Large-Diameter Timber Production over a 15-Year Period

Unit: Million VND

Indicator	Small-Diameter Timber Production, Density M1 (3,330 trees/ha)	Small-Diameter Timber Production, Density M3 (2,000 trees/ha)	Large-Diameter Timber Production, Initial Density 1,330 trees/ha
Rotation Period	6 year	6 year	15 year
Number of Harvests over 15 Years	2	2	1
Revenue per Rotation (million VND/ha)	185,245	169,095	–
Total Revenue (million VND/ha)	370,49	338,19	830,84–969,32

Source: Data source processed by the researcher (2025)

Note: Revenue from large-diameter timber refers to the primary harvest at 15 years of age and excludes income from thinning operations. Revenue from small-diameter timber represents the total nominal revenue over two rotations, assuming that both the timber price and yield remain constant in each rotation.

Table 5 shows that the cumulative revenue over two rotations from Acacia mangium plantations managed for small-diameter timber production reaches 370.49 million VND/ha for model M1 and 338.19 million VND/ha for model M3. For the large-diameter timber production model, revenue from the primary harvest at 15 years of age is estimated at 830.84–969.32 million VND/ha. These results indicate that, over the same 15-year period, revenue from the primary harvest under the large-diameter timber production model is approximately 2.24–2.62 times higher than the cumulative revenue from small-diameter timber production under model M1, and 2.46–2.87 times higher than that under model M3. Furthermore, while the small-diameter timber production model requires re-investment in plantation establishment twice, the large-diameter timber production model requires only one initial investment. This difference reflects the higher commercial value of large-diameter timber compared with timber intended for wood-chip production and highlights the potential to increase economic value by extending the rotation period and applying appropriate silvicultural practices.

Beyond the revenue generated from timber products, extending the rotation period of Acacia mangium plantations to 12–15 years creates opportunities to develop a multi-value forest management model that integrates large-diameter timber production with the provision of sustainable ecosystem services.

DISCUSSION

Economic Efficiency of Acacia mangium Plantations Managed for Small-Diameter Timber Production

The research results indicate that all four Acacia mangium plantation models managed for small-diameter timber production, with a 6-year rotation, are financially viable. The Net Present Value (NPV) of these models, which differ in planting density, ranges from 45.38 to 60.94 million VND/ha. This demonstrates that growing and harvesting Acacia mangium at 6 years of age can generate economic value while contributing to household incomes and the livelihoods of households engaged in forestry production.

The findings also show that model M1, with a planting density of 3,330 trees/ha, generates the highest revenue, at 185.245 million VND/ha per rotation, but is not the most financially efficient option. In contrast, model M3, with a planting density of 2,000 trees/ha, achieves an NPV of 60.94 million VND/ha, a Benefit-Cost Ratio (BCR) of 2.77, and an Internal Rate of Return (IRR) of 39.69%, the highest values among the four models. These results suggest that maximizing revenue does not necessarily mean maximizing investment efficiency; planting density significantly affects both plantation productivity and economic performance. This finding is consistent with existing research on Acacia plantations in Vietnam, which identifies initial planting density as a key factor influencing growth, yield, timber quality, and economic efficiency. It is also consistent with the study by Ngo Van Ngoc et al. (2022) on the productivity and economic efficiency of hybrid Acacia and hybrid Eucalyptus plantations in the Hon Dat area of Kien Giang Province. That study examines the effects of planting density on yield and economic efficiency, highlighting the importance of determining an appropriate density for the management of commercial forest plantations. However, because the research by Ngo Van Ngoc et al. focused on hybrid Acacia and hybrid Eucalyptus under specific site conditions, its findings serve only as a reference for understanding the relationship between planting density, yield, and economic efficiency. The specific values cannot be directly compared with those of the Acacia mangium plantation models in Bac Ninh. Similarly, research on Acacia plantation models in Yen Lap has also recognized the role of planting density in influencing plantation growth and yield.

At a broader level, a study by Maraseni et al. (2017) on the financial performance of Acacia plantation models in Vietnam demonstrates that different planting densities and rotation periods produce varying financial outcomes. Research conducted at Ben Hai Forestry Company indicates that rotation periods of 5, 6, and 10 years are all profitable, with the 10-year rotation generating higher Net Present Value (NPV) and Internal Rate of Return (IRR) values than the shorter rotations. These results suggest that the economic efficiency of forest plantations depends not only on initial planting density but also on harvesting age, product composition, and market demand for timber.

Furthermore, a study by Blackburn, Vu Dinh Huong, and Mendham (2020) on the economic efficiency of Acacia forest management strategies in Vietnam indicates that, among harvesting

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options ranging from 4 to 8 years, a 6-year rotation can achieve a high Internal Rate of Return (IRR). Therefore, growing Acacia mangium for small-diameter timber production under a 6-year rotation remains a financially viable option, particularly for forest growers who require a relatively early return on investment. Based on the study conducted in Bac Ninh, model M3 achieves the highest investment efficiency, although it does not generate the highest total revenue. These findings provide a basis for selecting appropriate planting densities and management strategies, while also highlighting the need for further research into extending the rotation period to enhance the value of timber products in the future.

Potential Economic, Social, and Environmental Benefits of Extending the Rotation Period of Acacia mangium Plantations

The research findings indicate that extending the rotation period of Acacia mangium plantations for large-diameter timber production, in addition to generating economic benefits from timber sales, with harvesting revenue ranging from VND 830.84 to 969.32 million/ha, approximately 2–3 times higher than the cumulative revenue from the 6-year small-diameter timber production model over the same 15-year period, also provides substantial environmental and social benefits, contributing to the sustainable management and use of forests and forest land.

From an environmental perspective: During the early stages of growth, Acacia mangium plantations have a limited capacity to provide ground cover. Trees are typically about 40–60 cm in height at one year of age; the forest canopy only begins to close by the third year. Due to their single-layer canopy structure, the capacity of these plantations to provide ground cover and protect the soil remains limited during the early years. In addition, tending and maintenance activities, such as vegetation clearance, weeding, and regular fertilizer application, often reduce the understory vegetation cover, leaving the soil surface exposed at certain times and vulnerable to the impacts of rainfall and surface runoff. At 4–6 years of age, canopy cover improves, thereby enhancing soil protection. However, this condition is maintained for a relatively short period because the plantations are usually harvested at six years of age.

Notably, the common management practice among local households is clear-cut harvesting, combined with slash burning to clear vegetation before replanting. Repeated clear-cutting and vegetation burning across successive rotations may result in the loss of vegetative cover, reduce the amount of organic matter added to the soil, and increase the risks of soil erosion, nutrient leaching, and soil degradation, particularly in areas with steep terrain and heavy rainfall. Therefore, extending the rotation period, combined with limiting large-scale clear-cutting and replacing slash burning with appropriate vegetation management practices, is important for maintaining vegetation cover, protecting soil structure and fertility, and improving the water retention and flow regulation functions of forest ecosystems.

A study by Bui Xuan Dung et al. (2023) in an upstream watershed in Hoa Binh Province found that, following clear-cut harvesting of Acacia plantations, soil porosity decreased by 8.35%, soil organic matter content declined by 20.91%, water infiltration rates decreased, and soil erosion increased. Similarly, a study by Kieu Thi Duong et al. (2024) in several upstream areas of Vietnam indicated that the water infiltration and water retention capacities of soils under Acacia plantations tended to decline over successive rotations. These findings demonstrate that maintaining vegetation cover and the litter layer, while minimizing the period during which soil remains exposed after harvesting, is essential for mitigating adverse impacts on soil and water resources. Accordingly, large-diameter timber production models with rotation periods of 10 years or more have the potential to improve soil protection functions and reduce surface runoff and erosion compared with short-rotation clear-cut harvesting practices. However, these benefits also depend on topography, soil conditions, rainfall, and specific management practices.

Another important benefit of the large-diameter timber production model is its potential to increase carbon accumulation and create opportunities for participation in forest carbon markets. A study by Levan et al. (2020) on Acacia mangium plantations in the Southeast region of Vietnam found that total ecosystem carbon stocks increased from 128.47 tonnes C/ha in 4-year-old plantations to 251.27 tonnes C/ha in 11-year-old plantations, with soil carbon and tree biomass accounting for the largest proportions. Notably, a study by Arvola et al. (2021) in Central Vietnam found that shifting from a 5-year rotation for timber production to large-diameter timber production with a longer rotation period could increase carbon stored in aboveground and belowground biomass by approximately 15–16%, while also improving the financial performance of timber production. A research report on the potential for enhancing carbon sequestration in Acacia plantations in Vietnam also estimated that converting from timber production to sawlog production and extending the rotation period from 5 to 11 years could increase additional carbon sequestration by approximately 4.2 tonnes of CO_2 equivalent/ha/year. This evidence indicates that extending the rotation period not only creates opportunities to enhance the value of timber products but may also increase climate benefits through carbon accumulation.

In addition to carbon services, the Forest Stewardship Council (FSC) certification for sustainable forest management is also an important instrument for improving market access and the commercial value of timber products. Applying FSC standards helps improve forest management practices and traceability, ensure environmental and social responsibility, and thereby enhance the ability to meet the requirements of export markets. According to the systematic review entitled Effectiveness and Economic Viability of Forest Certification (2022), among the cases reviewed, higher selling prices were reported for certified products. In some FSC-certified plantation models in Vietnam, primarily in Quang Tri Province, the price premium ranged from approximately 18–25%. A study by Hoang et al. on groups of households managing FSC-certified forests in Vietnam also reported a price premium of approximately 17–23% for certified timber compared with conventional timber during the survey years. Thus, FSC certification can provide advantages in terms of timber prices and market access, although the price premium is not fixed and depends on timber quality, market conditions, certification costs, and the capacity for coordination within the supply chain.

Therefore, the 12–15-year large-diameter timber production model has the potential to generate greater overall value through three main groups of benefits: (i) enhancing the value of timber products and harvesting revenue; (ii) strengthening soil protection, water regulation, and carbon accumulation functions; and (iii) expanding opportunities to access FSC sustainable forest management certification and forest carbon markets. Accordingly, the transition from small-diameter to large-diameter timber production is not

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simply a matter of extending the harvesting period; rather, it represents a transformation in forestry production practices, from extracting timber value in the short term to realizing the combined economic values and forest ecosystem services over the long term.

Challenges in Transitioning from Small-Diameter to Large-Diameter Acacia mangium Timber Production

Although large-diameter Acacia mangium timber production offers the potential to increase product value and enhance environmental benefits, local households in the study area predominantly opt for a short rotation period of approximately six years, aimed at producing small-diameter timber. Interviews with 50 forest-growing households in the study area reveal that 90–95% of respondents face difficulties and challenges when considering a transition from small-diameter to large-diameter timber production. This indicates that the barriers to such a transition do not arise from a single factor but are instead associated with the complex interplay of economic conditions, risk tolerance, technical capacity, market access, and policy frameworks.

First, constraints related to capital availability and livelihood pressures represent a significant obstacle for forest-growing households. Among the 50 surveyed households, 45–48 reported difficulties related to capital availability and the need for an early return on investment, equivalent to 90–96% of respondents. Although a six-year rotation for small-diameter timber production is not necessarily short for households whose income depends on forestry, it allows for faster capital recovery and opportunities for reinvestment. Conversely, extending the rotation period to 12–15 years means that capital remains tied up for a longer period, income is deferred, and pressure to meet household expenses increases. Consequently, in the absence of long-term credit and alternative livelihood opportunities, local households tend to favor small-diameter timber harvesting to reduce financial pressure.

Second, risk aversion is associated with the extended period required to maintain forest stands. Extending the rotation period increases the length of time that forest stands are exposed to risks such as wildfires, pests and diseases, and damage caused by storms or strong winds. The fact that 45–48 of the 50 surveyed households identified these risks highlights the widespread concern among forest growers. Damage occurring toward the end of the rotation period can significantly reduce the expected economic value, which is particularly critical given that forest owners have already committed their capital for many years. In the absence of adequate forest insurance or disaster recovery support mechanisms, harvesting at six years of age is viewed by many households as a strategy for limiting their exposure to these risks.

Third, limitations in knowledge and silvicultural techniques pose another challenge. Large-diameter timber production requires forest growers to have the capacity to select suitable planting stock, determine appropriate planting densities, carry out pruning and thinning, and manage selected crop trees. Some households are also concerned that trees retained for longer periods may develop internal decay, stem curvature, or pest and disease infestations, all of which can reduce timber quality at the time of harvest. If a large proportion of surveyed households lack adequate access to technical guidelines for large-diameter timber production, this indicates a need to strengthen forestry extension services and the transfer of technical knowledge. Establishing local demonstration plots would enable forest growers to observe firsthand tree growth patterns, stem quality, and the effectiveness of different forest-tending practices.

Fourth, uncertainty surrounding the market for large-diameter timber is another major obstacle that directly affects forest owners' decisions on whether to change their production practices. Currently, a well-established procurement network exists for small-diameter timber, making it easy to sell to traders or wood-chip processing facilities. In contrast, large-diameter timber is subject to stricter requirements regarding diameter, quality, and dimensions. It also requires an appropriate system for processing, transportation, and distribution. Local households are concerned that, after 12–15 years of investment, there may be no stable market for their timber or that the selling price may not adequately compensate for the extended investment period. Therefore, the development of areas dedicated to large-diameter timber production needs to be integrated with wood-processing enterprises, guaranteed timber off-take agreements, and clear benefit-sharing mechanisms.

Fifth, existing support policies and production linkages do not provide sufficient incentives. To transition to large-diameter timber production, households need support in terms of capital, technical expertise, sustainable forest management certification, and market access. If current policies fail to address the need for capital over such an extended production cycle and lack mechanisms to support the conversion of existing forest stands or share production risks, households are unlikely to proactively change their production practices. Consequently, it is essential to consider long-term credit policies, provide silvicultural technical support, develop forest insurance schemes, and strengthen partnerships between forest owners and wood-processing enterprises.

Overall, the interview findings indicate that the challenges associated with transitioning to large-diameter timber production are widely recognized among the surveyed households. This explains why, despite the potential of large-diameter timber production to increase product value and enhance environmental functions, local households continue to favor a shorter production cycle of approximately six years. Therefore, the transition to a new production model cannot rely solely on promoting the benefits of longer rotation periods; rather, it requires comprehensive solutions to alleviate capital constraints, manage risks, strengthen technical capacity, and ensure stable markets for the final products.

CONCLUSION AND RECOMMENDATIONS

Conclusion

The study indicates that all four production models for Acacia mangium plantations managed for small-diameter timber production under a 6-year rotation are economically viable. Among these, model M3, with a planting density of 2,000 trees/ha, achieves the highest investment efficiency, with an NPV of 60.94 million VND/ha, a BCR of 2.77, and an IRR of 39.69%. These findings confirm that planting density influences economic performance; however, a higher planting density does not necessarily guarantee optimal investment returns.

Under the large-diameter timber production scenario, with a 15-year rotation, revenue from the final harvest is estimated at 830.84–969.32 million VND/ha, demonstrating the potential to increase product value by extending the rotation period. In addition to the economic benefits, which are approximately 2–3 times higher than the cumulative revenue from small-diameter timber

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production models under 6-year rotations over the same 15-year period, growing Acacia mangium for large-diameter timber production also provides significant environmental and social benefits, contributing to the sustainable management and use of forests and forest land. Nevertheless, transitioning to this model presents numerous challenges, including capital and technical requirements, as well as production and market-related risks. A survey of 50 households reveals that 90–95% of respondents encounter difficulties and challenges when considering a transition to large-diameter timber production. Consequently, the development of large-diameter timber plantations should follow a structured roadmap tailored to the specific production conditions and investment capacity of forest owners.

Recommendations

Policies should be implemented to provide medium- and long-term credit support, high-quality planting materials, and technical guidance on plantation establishment, tending, thinning, and forest protection, thereby encouraging households to transition to large-diameter timber production. At the same time, it is essential to strengthen linkages between forest owners and timber-processing or trading enterprises through timber off-take agreements, which would help stabilize market outlets and mitigate market risks. For households that continue to focus on small-diameter timber production, planting densities should be selected based on site conditions and investment capacity. Under conditions similar to those examined in this study, model M3 may serve as a useful reference. Future research should conduct a comprehensive assessment of large-diameter timber production, encompassing thinning costs and revenues, final harvest revenue, and the time value of money over the entire rotation period, to provide a sound basis for comparing the economic efficiency of the two production models.

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