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TECHNO-ECONOMIC ANALYSIS OF ECO-FRIENDLY BAMBOO-BASED PAPER PRODUCTION FOR CHILD-FRIENDLY SCHOOL MEDIA AND SUSTAINABLE DEVELOPMENT GOALS (SDGS)

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Abstract

This study aims to assess the techno-economic feasibility of producing eco-friendly paper from bamboo as a medium for child-friendly school campaigns. A simulation method was used to analyze financial parameters, including cumulative net present value (CNPV), internal rate of return (IRR), return on investment (ROI), payback period (PBP), and break-even point (BEP). Results showed excellent findings. Production is feasible and competitive, with a payback period occurring between four to five years. Bamboo, due to its abundance, affordability, and high fiber content, serves as an environmentally sustainable alternative to wood. Profitability remains stable under various scenarios, and the projected twenty-year operation indicates strong long-term returns. This production model aligns with the Sustainable Development Goals (SDGs) by reducing emissions and supporting safe, healthy, and inclusive learning environments. The findings provide a practical reference for policymakers and educators aiming to integrate sustainability into educational infrastructure and media.

Keywords: Bamboo, Child-friendly school, Eco-friendly paper, Sustainable development, Techno-economic analysis.

1. Introduction

The global demand for paper continues to rise, yet its production remains one of the largest contributors to deforestation and environmental pollution [1, 2]. In response to these sustainability challenges, the use of alternative raw materials has become an urgent priority.

Bamboo, particularly petung bamboo with a cellulose content of around 53%, has gained attention as a sustainable substitute for wood in the pulp and paper industry [3-5]. Compared to traditional wood-based paper, bamboo-based paper offers competitive durability, tear resistance, and optical stability [6]. Its fast-growing nature and abundant availability make bamboo not only ecologically advantageous but also economically promising, especially in regions with diminishing forest resources [7]. These attributes position bamboo as a viable candidate in efforts to develop eco-friendly paper production systems that align with global environmental goals.

Previous research has highlighted various technical and economic aspects of material utilization in industrial applications, including the construction of material processing machinery [8], quality control using Six Sigma [9], and broader techno-economic evaluations of biomass-based products [10]. However, studies focusing on the long-term economic feasibility of large-scale bamboo paper production remain limited. More importantly, there is a knowledge gap in exploring the strategic use of bamboo-based paper in educational settings, particularly in creating environmentally conscious and child-friendly school materials. Such integration can contribute not only to ecological conservation but also to the development of inclusive and safe learning environments, as emphasized by child-friendly school frameworks [11, 12].

This study aims to conduct a techno-economic analysis of environmentally friendly paper production using bamboo as the primary raw material. This study can add new information regarding techno-economic analysis [13-18]. The research focuses on assessing long-term profitability and operational feasibility through indicators such as payback period (PBP), net present value (NPV), and internal rate of return (IRR). The novelty of this study lies in (i) positioning bamboo-based paper as a medium for promoting non-violence and sustainability in child-friendly school campaigns and (ii) presenting a comprehensive economic simulation for up to twenty years under varying production conditions. Through this dual lens, the study supports environmental sustainability and educational innovation while contributing to the Sustainable Development Goals (SDGs) [19].

2. Literature Review

Figure 1 presents a conceptual framework that links eco-friendly material innovation, educational media, and the SDGs. The diagram illustrates how the development of bamboo-based paper intersects with child-friendly school initiatives and environmental sustainability, emphasizing the dual impact on education and ecology.

The global paper industry has long depended on wood pulp as its primary raw material, contributing significantly to deforestation and biodiversity loss. This concern has led to increased exploration of sustainable alternatives such as agricultural residues and non-wood fibers [7]. Among these, bamboo emerges as a particularly suitable resource due to its rapid growth, renewable nature, and high cellulose content. Petung bamboo (*Dendrocalamus asper*), in particular, has shown promise for pulp and paper applications, with studies confirming its comparable fiber strength and processability relative to hardwoods [3, 6]. Moreover, bamboo's wide availability in Indonesia strengthens its relevance for localized production systems.

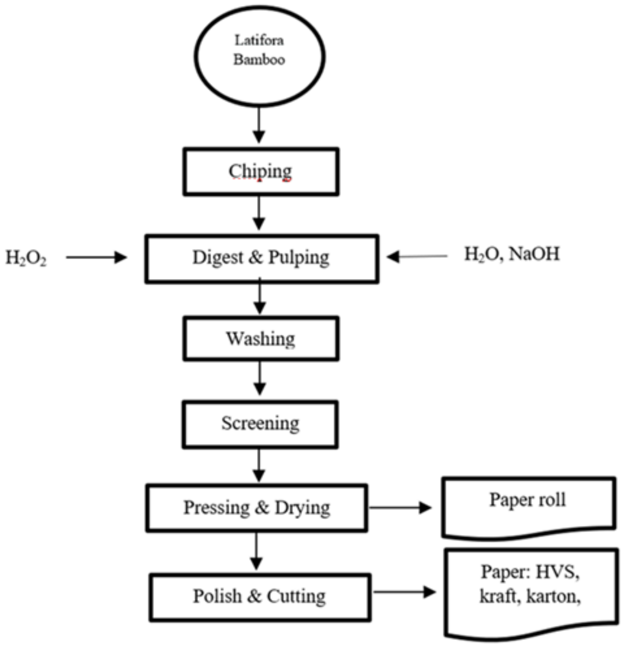

Fig. 1. Conceptual framework linking bamboo-based paper, child-friendly schools, and SDGs.

The integration of eco-friendly materials in educational settings has been supported by frameworks advocating for child friendly [12]. These frameworks emphasize not only physical safety and accessibility but also the environmental sustainability of learning resources. Previous studies [11] argue that green school programs improve students' environmental awareness and reduce institutional ecological footprints. However, the use of green materials, such as bamboo paper, in school media remains underexplored. At the same time, techno-economic studies have gained attention for evaluating the feasibility of adopting green innovations. Previous works [10] have demonstrated how such analyses can guide policy and investment decisions by simulating returns under different market scenarios.

Despite these advances, there remains a gap in literature combining green material innovation with educational policy impact, especially in relation to the SDGs. The novelty of this research lies in bridging that gap by evaluating bamboo paper not only as an industrial product but also as a strategic tool for advancing SDG 4 (quality education) and SDG 12 (responsible consumption and production). By conducting comprehensive techno-economic analysis in the context of school-based applications, this study offers new insights into environmentally responsible educational development.

3. Method

This study adopted a simulation-based techno-economic analysis to assess the feasibility of bamboo-based eco-friendly paper production. Detailed information regarding this method is explained elsewhere [20]. The primary focus was to determine whether the proposed initiative is economically viable and environmentally aligned for use in child-friendly school programs. The methodological approach followed previous techno-economic studies that simulate financial models under realistic assumptions [21-23].

The raw material selected was petung bamboo (Dendrocalamus asper), chosen for its rapid growth, high cellulose content, and local availability in Indonesia. This species has been documented as a promising alternative in non-wood pulp production due to its optimal fiber characteristics [3]. The production process was modeled to reflect small- to medium-scale operations, including steps such as bamboo harvesting, pulping, sheet formation, drying, and finishing.

The techno-economic simulation included the calculation of five financial indicators: Cumulative Net Present Value (CNPV), Internal Rate of Return (IRR), Return on Investment (ROI), Payback Period (PBP), and Break-Even Point (BEP). These indicators were chosen to assess both short-term and long-term economic returns. The simulation covered a projected operational life of twenty years, with sensitivity scenarios introduced to account for variations in input costs, production capacity, and market prices. Investment costs, labor, raw materials, utilities, and maintenance expenses were incorporated into the model. A discount rate of 10% was applied based on standard practices in similar feasibility studies [10].

To complement the quantitative analysis, environmental considerations were mapped against the SDGs, particularly SDG 4 on quality education and SDG 12 on responsible production. The potential environmental benefits of replacing wood-based paper with bamboo were discussed qualitatively, supporting the interpretation of the financial outputs within a broader sustainability framework. This method allows for a balanced evaluation of both profitability and socio-environmental contributions of the innovation. In addition, detailed information regarding the calculation is explained in Tables 1 and 2.

Table 1. Prices of consumable raw materials for making environmentally friendly paper from bamboo.

No.	Raw material	Large-Scale Production Requirements	Unit	Price (USD)	Total (USD)
1	Bamboo	1,500,000	kg	0.030639	45,958.70
2	Air (H_2O)	41,600	kg	0.000018	0.76
3	NaOH	2,000	kg	0.551504	1,103.01
4	H_2O_2	1,000	kg	0.061278	61.28
5	Natural Dyes	1,000	kg	0.061278	61.28
		Price/day			47,185.03
		Price/year			**14,155,508.55**

Table 2. Prices of environmentally friendly paper-making tools from bamboo.

No.	Tool Name	Unit Price (USD)	Amount	Total Price (USD)
1	Cipher Machine	9.191,74	1	9,191.74
2	Digester Machine Automatic	21.447,39	1	21,447.39
3	Pulp Refiner	16.545,13	1	16,545.13
4	Press and Dryer Machine	18.383,48	1	18,383.48
5	Calendar/Polish Machine	12.255,65	1	12,255.65
6	Sitter/Cutter Machine	10.723,70	1	10,723.70
	Total			**88,547.09**

4. Results and Discussion

Table 3 presents the techno-economic simulation of bamboo-based paper production over a 20-year operational period. The model indicates a total capital investment of 331 million IDR, with an annual operating cost of 157 million IDR. Based on these projections, the internal rate of return (IRR) is estimated at 18.26%, the return on investment (ROI) reaches 19.44%, and the payback period (PBP) is achieved within 6 years. The break-even point (BEP) occurs at 39.84% of capacity utilization. These results suggest that bamboo-based paper production can offer long-term profitability, especially when supported by market demand and environmentally oriented policies [21-23].

Table 3. Techno-economic indicators for bamboo-based paper production.

Component	Parameter	Cost
Fixed Cost	Loan Interest	713,846.13
	Capital Related Cost	-
	Fixed cost+Depreciation	61,292.76
	Depreciation	-
	Fixed Cost less depreciation	775,138.90
	Total Fixed Cost	14,155,508.55
Variable Cost	Raw material	24,393.32
	Utilities	26,472.21
	Operating Labor (OL)	7,941.66
	Labor Related Cost	1,158,159.20
	Sales Related Cost	15,372,474.94
	Total Variable Cost	16,545,131.44
% Profit Estimated	Sales	16,086,321.08
	Manufacturing Cost	656,974.38
	Investment	0.0000018
	Profit	0.03
	Profits to Sales	0.70
BEP	Unit	775,138.90
	Fixed Cost	15,372,474.94
	Variable cost	16,545,131.44
	Sales	1.22
	BEP	19,830.33
	Percent Profit on Sales	0.028
	Return on Investment	0.749
	Pay Out Time	1.178

Figure 2 and Table 4 illustrate the cumulative net present value (CNPV) projections for different scenarios across 20 years. Under the baseline scenario, the CNPV reaches approximately 1.5 billion IDR, reflecting substantial potential for long-term value creation. The optimistic scenario, which assumes increased demand and price, results in a CNPV exceeding 2 billion IDR. In contrast, the pessimistic scenario-based on rising raw material costs and reduced market prices-yields a CNPV of around 500 million IDR. These variations emphasize the importance of cost efficiency, continuous innovation, and market strategy for sustaining profitability in bamboo-based paper ventures [10].

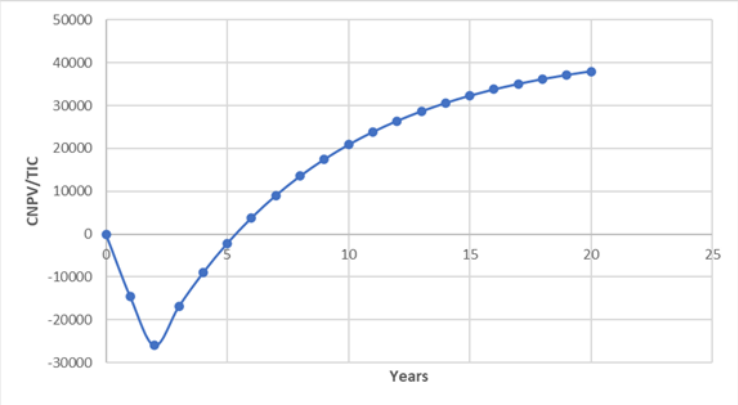

Fig. 2. CNPV projections for baseline, optimistic, and pessimistic scenarios over 20 years.

Table 4. Revenue assumptions for environmentally friendly bamboo paper production.

No.	Component	Description	Value (USD)
1	Selling Price per Ton	Market selling price for eco-friendly bamboo paper	551.50
2	Daily Production Volume	Estimated production capacity per day	300 tons
3	Annual Production Volume	Estimated production capacity per year	30,000 tons
4	Annual Revenue	30,000 tons × 551.50 USD	16,545,000.00
5	Estimated Profit Margin	Based on operational and investment cost analysis	3%
6	Estimated Net Profit	3% of Annual Revenue	496,350.00
7	Payback Period (PBP)	Return on investment period based on net revenue trend	4-5 years
8	ROI	Return on Investment (profit/cost ratio)	0.749
9	Break-Even Point (BEP)	Volume needed to cover total cost	19,830.33 tons
10	Net Present Value (NPV)	Accumulated discounted net cash flow over 20 years	Positive growth

Beyond financial metrics, the study also addresses environmental and educational impacts. Bamboo-based paper reduces reliance on wood, aligns with circular economic principles, and contributes to the reduction of deforestation. Moreover, its use in producing child-friendly educational materials supports SDG 4 by promoting inclusive, safe, and sustainable learning environments. As shown in Table 5, bamboo paper is well-suited for visual learning tools, bulletin boards, and printed guides that foster non-violent communication and environmental stewardship among children. The lifecycle of such materials also reinforces SDG 12 by minimizing waste and encouraging reuse.

These findings highlight the novelty of integrating economic modeling with SDG-based impact assessment, offering a dual framework for evaluating industrial innovations that prioritize both sustainability and profitability. This adds new information regarding SDGs as reported elsewhere [24-29].

Table 5. Environmental benefits of using bamboo as raw material for supporting SDGs.

No.	Environmental Indicator	Description
1	Carbon Sequestration	Bamboo absorbs more CO_2 compared to traditional wood sources
2	Rapid Regeneration	Bamboo grows faster, reducing pressure on deforestation
3	Soil Conservation	Bamboo roots help prevent erosion and support soil structure
4	Biodiversity Preservation	Bamboo plantations maintain ecological balance better than monocultures
5	Renewable Resource Efficiency	Sustainable harvesting reduces the depletion of non-renewable resources
6	Energy Efficiency in Processing	Bamboo requires less energy to process into pulp than hardwood
7	Water Usage	Lower water consumption in cultivation and processing
8	Waste Reduction	Biodegradable output supports circular economy goals

5. Conclusion

This study confirms the techno-economic feasibility of producing eco-friendly bamboo-based paper for child-friendly educational media. The production model demonstrates financial viability with favorable IRR, ROI, and CNPV values while aligning with environmental sustainability. By supporting Sustainable Development Goals related to quality education and responsible consumption, the initiative offers both economic return and social impact. This research introduces a practical innovation that bridges green industry practices with inclusive education strategies, particularly in underserved communities.

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