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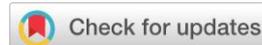
Utilization of Biomass in Sustainable Integrated Dairy and Coffee Farming: Case Study Boyolali, Central Java, Indonesia

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ABSTRACT

The agricultural sector plays a strategic role in improving economic sustainability and responding to environmental challenges. A sustainable agricultural approach based on the integration of coffee and dairy cattle is a potential solution to these challenges. This study aims to analyze financial feasibility by comparing two types of coffee and dairy cattle integration farming systems, namely type 1 (existing coffee-dairy cattle integration) and type 2 (improved integration). The difference between the two types lies in the connectivity of input and output use in the integration system. The method used is financial feasibility analysis with investment criteria indicators in the form of NPV, IRR, Net B/C, and payback period. The research was conducted in Boyolali Regency. The results of the financial feasibility analysis show that the improved coffee and dairy cow integration type (type 2) is financially superior to type 1, with an NPV of IDR 1,714,402,922.83 and an IRR of 22%, far exceeding type 1 (IRR of 16%), with a payback period of 6 years and 8 months. This financial benefit came from lower costs for feed, energy, and fertilizer, as well as big economic gains from diversifying products that came from making better use of waste. Using biodigester technology to turn biomass into energy is another way to cut down on greenhouse gas emissions from manure waste. These findings provide a strong basis for encouraging the implementation of improved coffee and dairy cow integration through a series of fiscal incentive policies and farmer assistance.

Introduction

The current trend in agricultural development focuses on sustainability by integrating agricultural systems where productivity can continue to increase without neglecting efforts to reduce environmental impact. The integrated dairy and coffee farming system is an effort to combine coffee production with dairy farming in a circular model that includes complete integration between crop production and livestock farming. Reducing dependence on external resources allows for greater environmental protection in the current coffee and dairy industries. Each system maximises resource support and has the potential further to improve economic aspects in a number of systems, thereby enhancing the environmental sustainability of these systems [1]. Resource and economic protection are key to high growth potential.

The potential of integrated coffee and dairy farming in several previous studies shows how this integrated system provides efficiency in resource use, as well as cost reductions and significant profits at the farm level [1]. One of the characteristics of this system is the nutrient recycling system, namely through the utilisation of dairy cow manure, which provides benefits for soil health and organic matter and meets fertiliser

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requirements for coffee cultivation [2]. The overall economic benefits of integrated farming systems have also increased, with agricultural biomass being used for bioenergy.

Beyond economic gains, environmental benefits are well documented. Integrated dairy-coffee farming has been associated with a 10% reduction in the carbon footprint of milk production, primarily due to more efficient nutrient cycling and decreased reliance on external feed and fertilizers [3]. Improved nutrient recycling enhances long-term soil fertility by boosting nitrogen, phosphorus, and potassium retention [4]. These outcomes align with the global goals of developing sustainable and low-emission agricultural systems.

However, despite its promising benefits, the economic feasibility of broader biomass utilization within integrated systems remains underexplored. Existing studies tend to emphasize technical and environmental outcomes, while long-term financial viability, particularly in developing countries where resource constraints may hinder adoption, is less frequently examined [5]. There is limited empirical research systematically evaluating the economic performance of biomass use, especially biogas, in integrated farming models.

Coffee and dairy cattle are leading commodities that have strategic economic value in Indonesia. The synergy between these commodities has promising potential for development under the principles of a bioindustrial agricultural system. One of the promising areas for the development of an integrated coffee and cattle farming system in Indonesia is Boyolali Regency, as this region has long implemented an integrated system, utilizing simple local resources such as cow manure as fertilizer to maintain the fertility of coffee plantations. More recently, innovations such as the utilization of biogas from dairy cow waste have been introduced as an effective mitigation strategy to reduce fossil fuel consumption in processing, while simultaneously supporting the transition towards renewable energy, offering environmental benefits, and fostering sustainable agricultural systems [6–8]. While the existing scientific literature has identified various benefits of integrated agricultural systems, it still demonstrates limitations in comprehensively assessing the full spectrum of biomass utilization and its associated economic implications within such systems.

Previous studies have not adequately considered the financial viability of integrated systems encompassing various types of product diversification, whether derived from primary product processing or biomass conversion. Many earlier studies have predominantly highlighted the economic benefits solely in terms of integrated and non-integrated systems [9,10]. Furthermore, the economic benefits of integrated agricultural systems have often been assessed exclusively based on the economic benefits of manure production [11]. While research exists on the financial viability of multi-product biomass systems utilizing microalgae for feed, biodiesel, and fertilizer [12], a comprehensive assessment within the specific context of an integrated coffee-dairy cow system remains limited. Thus, this study fundamentally differs from previous research by focusing on a comprehensive financial viability analysis of biomass utilization, including biogas, organic fertilizer, and feed, specifically within the context of an integrated coffee-dairy cow system.

This study fills methodological and empirical gaps by applying cost-benefit analysis (CBA). This approach allows us to systematically evaluate how resource efficiency and waste reduction strategies can be internalized into the economic decision-making framework at the farmer level. Therefore, the main objective of this study was to assess the financial viability and environmental implications of optimizing biomass utilization in integrated coffee-dairy farming systems using a robust CBA approach. A substantial contribution of this research is the provision of new empirical evidence that enriches the discourse on sustainable agriculture, particularly regarding the development of low-carbon and resource-efficient systems for small-scale farming.

Materials and Methods

Study Area

This study took place in Boyolali Regency, Central Java, from December 2023 to February 2024. The area is between 110° 22' and 110° 50' East Longitude and 7° 7' and 7° 36' South Latitude, and it is between 75 and 1,500 m above sea level (Figure 1). The study encompassed two sub-districts: Gladagsari (Type 1) and Ampel (Type 2). There are 22 sub-districts in Boyolali Regency, which cover an area of 1,096.61 km². A mixed-methods approach was utilised, integrating qualitative field observations with quantitative financial modelling through Cost-Benefit Analysis (CBA) to evaluate the financial viability and economic potential of biomass utilisation within an integrated coffee-dairy farming system.
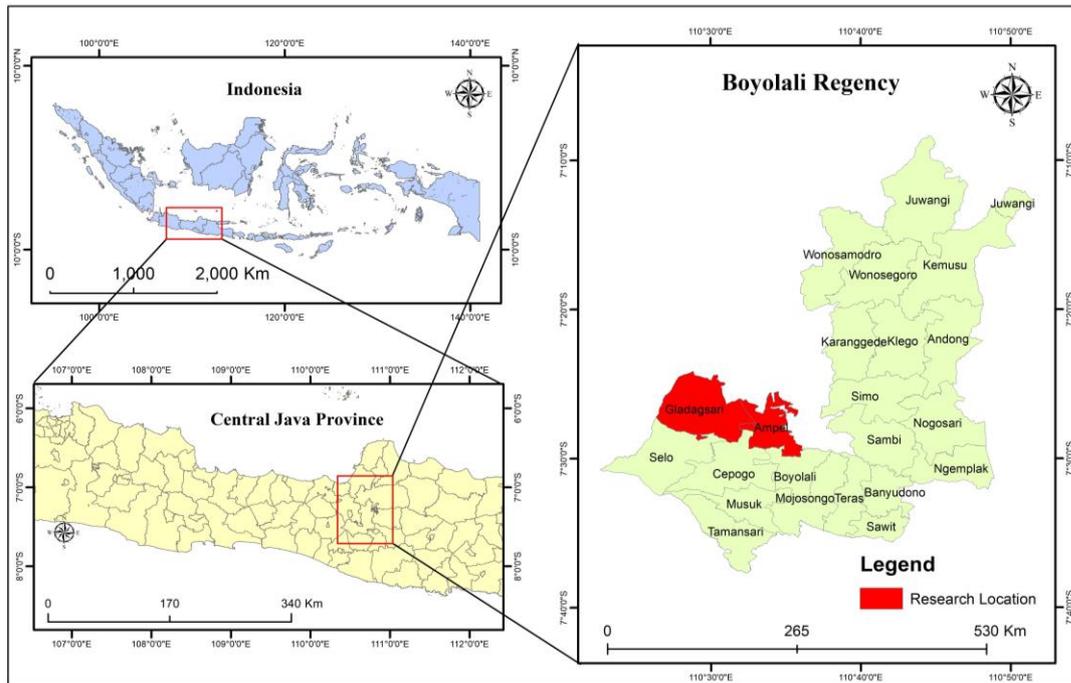
Figure 1. Map showing where the research on combining dairy and coffee cows took place in Boyolali Regency. From a geographical point of view, the map shows where the research is taking place. The study site is situated in Boyolali Regency, Central Java Province. In Boyolali Regency, the focus is on two subdistricts: Gladagsari Subdistrict, which shows the current coffee and dairy cow integration system (Type 1), and Ampel Subdistrict, which shows where the new coffee and dairy cow integration system will be put into action. Both areas are shown in red.

Research Design and Sampling

In Boyolali Regency, the integrated coffee-dairy farming system was analysed for various biomass products, related financial implications, and environmental impacts using a financial feasibility approach. Respondents were selected using purposive sampling, targeting coffee and dairy farmers/ranchers involved in bioindustry. A total of 30 respondents were evenly divided between the two integrated bioindustry systems, which were selected for comparative analysis based on their approach to managing agricultural biomass. The selected respondents met the criteria in accordance with the research objectives, whereby respondents were individuals who were directly involved in and implemented the coffee and dairy cow integration-based bioindustrial agricultural system, and who owned coffee cultivation and dairy cow breeding areas. For Type 1 farmers, who represent the existing system, we considered the practice of using processed coffee husks as animal feed and relying on unprocessed dry manure as fertiliser. On the other hand, the recommended Type 2 model involves the integration of biogas with coffee husk concentrate feed, utilising bioslurry from coffee cultivation as part of the system.

The use of a sample size of 15 respondents per type of integration (30 in total) was considered adequate for descriptive statistical analysis and exploratory comparison, in line with the literature stating that small sample sizes (8–20 respondents) are acceptable for limited populations or case studies, as referenced by Albert and Tullis [13]. Even though this sample size is limited, it is still representative of the local vernacular and enhances the comparative understanding of the two levels of integration. Although such insights may lack the capability of being extrapolated to a broader national context, the analytical finding are still rich and are findings of national relevance especailly of the underlying agroecological and socioeconomic conditions The chosen participants had to meet the following criteria: active involvement in the cultivation of Robusta coffee and dairy farming, regular trading of processed coffee and fresh milk to the agro-processing industry, and the practice of either integrated (Type 2) or simple (Type 1) biomass management.

Data Collection

Structured interviews were used to gather primary data on four topics: 1) farm characteristics (size of livestock, labor, and resources); 2) biomass management (composting, innovative feeding, and biogas use);

3) financials (input and output prices, costs, revenue, and investments); and 4) perceived benefits and constraints, as well as sustainability. Agricultural extension offices, BPS of Statistics reports, journals, and regulatory documents provide secondary data on market prices, input-output relationships, investment costs, and assumptions about the regulatory environment.

Cost-Benefit Analysis (CBA)

Financial feasibility analysis is a method in business analysis to identify and measure cash inflows and outflows. This analysis includes several components, such as investment cost calculations, tangible product cost assessments, operational cost expenditures, and income analysis from sales or other business revenues. The measurement indicators used in the analysis include Net Present Value (NPV), Net Benefit-Cost Ratio (Net B/C), Internal Rate of Return (IRR), and Payback Period. The results of the analysis are presented in a table, and a descriptive interpretation provides an overview of costs and revenues, as well as feasibility.

Net Present Value (NPV)

The Net Present Value (NPV) has been calculated to assess the profitability of biomass utilization over the specified duration. If NPV is greater than 0, it means that the project is financially possible. This can be written as (Equation 1):

$$NPV = \frac{\sum_{i=0}^{n}\frac{Bt-C}{(1+i)^t} - \sum_{i=0}^{n}\frac{Ct}{(1+i)^t}}{\sum_{i=0}^{n}\frac{B-C}{(1+i)^t}} \tag{1}$$

The variables used are defined as follows: Bt is the gross benefit received in year t, expressed in Indonesian Rupiah (IDR). Meanwhile, Ct is the gross cost incurred in year t, also expressed in IDR. where n indicates the economic life of the business being analyzed (in years), and t is the investment period, where t moves from year 1 to year n (t= 1,2,3…n). All cash flow calculations were discounted using an interest rate (i) expressed as a percentage (%).

Net Benefit-Cost Ratio (Net B/C)

The Net Benefit-Cost Ratio (Net B/C) is the ratio of the total positive net benefits to the total negative net benefits, both of which are discounted. This financial feasibility indicator shows the level of additional benefits obtained for each unit of additional cost incurred. In general, a project or investment is considered economically feasible (viable) if the resulting Net B/C value is greater than 1 (Net B/C > 1). This condition indicates that the total benefits received exceed the total costs incurred throughout the project's economic life. Mathematically, the Net B/C can be formulated as follows (Equation 2):

$$Net\ \frac{B}{C} = \frac{\sum_{i=0}^{n}\frac{Bt-Ct}{(1+i)^t}}{\sum_{i=0}^{n}\frac{Bt-Ct}{(1+i)^t}}\ \ Bt - Ct > 0 \tag{2}$$

Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) helps find the discount rate that makes the Net Present Value of a project equal to zero. The IRR represents the expected return rate over the investment's lifetime. The project is financially viable if the IRR is higher than the market interest rate or the cost of capital. The IRR is used to assess the return rate of a project against other possible investments. The IRR is calculated as follows (Equation 3):

$$IRR = i1 + \frac{NPV_1}{NPV_1 - NPV_2}\ (i_2 - i_1) \tag{3}$$

To find the Internal Rate of Return (IRR), it needs to interpolate between two Net Present Value (NPV) values that have opposite signs. In the formula, NPV_1 is a positive NPV value and NPV2 is a negative NPV value, both in Indonesian Rupiah (IDR). The discount rate that gives it a positive NPV_1 is i_1, and the discount rate that gives it a negative NPV_2 is i_2. Both are in per cent (%). You can use these variables to figure out i*, which is the project's Internal Rate of Return (IRR) in per cent (%).

Payback Period

Net cash flow is used to figure out the Payback Period (PP), which is a way to figure out how long it will take to get back all of the money that was invested. The shorter the Payback Period, the less risk there is for investors. So, shorter payback periods are good because they show that a project is financially stable and has cash on hand. For an investment to be possible, the calculated payback period must be shorter than the predetermined payback period.

Assumptions and Risk Analysis

This study applies several fundamental assumptions to enhance the validity and focus of the analysis. Business life is set at 10 years, aligning with the economic lifespan of dairy cows. All capital utilized is assumed to be self-financed (no interest in the loans). The interest rate is set at 6%, based on the Micro Credit Program capital interest rate, as determined by Regulation of the Minister for Economic Affairs Number 8 of 2019 concerning Guidelines for the Implementation of People's Business Credit. The prices of all inputs and outputs were derived from a field survey conducted in December 2023. Income tax calculations follow Government Regulation No. 46 of 2013, Article 4, which stipulates a final tax rate of 1% for businesses with gross circulation not exceeding IDR 4.8 billion. Additionally, it is assumed that cows are in lactation when they are purchased in the first year. The business base consists of 1 ha of coffee land and six cows each. In the process of processing coffee beans into ground coffee and fresh milk into yogurt, data allocation information is used, whereby 30% of the total production of coffee beans is allocated to making ground coffee. In comparison, 20% of the total production of fresh milk is allocated to yogurt production. The business base consists of 1 ha of coffee land and six cows each. In the process of processing coffee beans into ground coffee and fresh milk into yogurt, data allocation information is used, whereby 30% of the total production of coffee beans is allocated to making ground coffee. In comparison, 20% of the total production of fresh milk is allocated to yogurt production.

Data Processing and Validation Approach

Figure 2 illustrates the Research Process Flow. The data used in this study is primary data collected through structured interviews involving 30 respondents selected based on certain criteria. Secondary data was obtained from several sources, such as previous research journals, BPS data, and other research reports. Data validation was conducted to assess the quality of the data using a triangulation method. The balance analysis approach is used to perform the subsequent analysis, particularly to assess relevant key financial metrics, which include the NPV, Net B/C, IRR, and Payback period. This analysis was performed within two simplified scenarios: Type 1, current integration, and Type 2, enhanced integration. The conclusion of the comprehensive model was predicated on its alignment with global agri-food systems and its strategic importance in advancing four Sustainable Development Goals: SDG 2, SDG 7, SDG 12, and SDG 13.
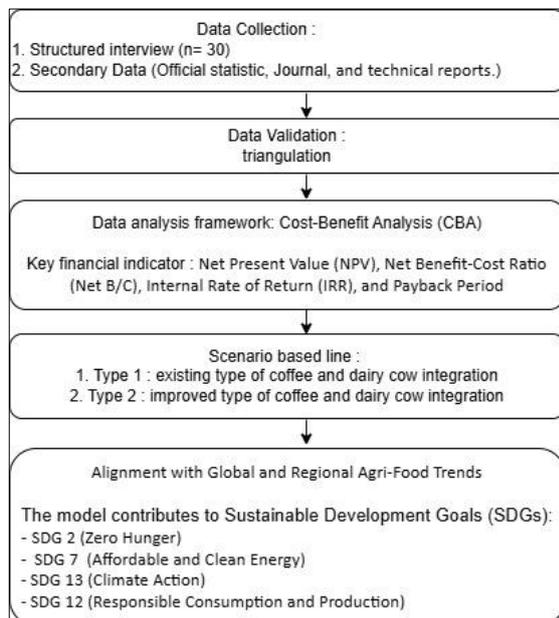

Figure 2. Research process flow and data validation. This flowchart contains the research process flow, which begins with data collection through interviews. The primary data consists of 30 respondents divided into two types: respondents from the integrated coffee and dairy farming system. Secondary data was obtained from journal literature, BPS statistical data, and several other sources. The validation process was carried out using the triangulation method. To answer the research objective regarding financial feasibility analysis, a comparison of financial feasibility between the two types, namely existing and improved integration, was conducted based on indicators such as NPV, IRR, Net B/C, and payback period. This model is highly relevant to the development of global food policy and the four indicators of the Sustainable Development Goals (SDGs).

Results

Overview of Dairy Cattle and Robusta Coffee Integration Farming

The integration of dairy cattle and robusta coffee farming represents a circular economy-based agricultural system that optimizes the mutual potential of plantation and livestock farming. This model integrates several components, including robusta coffee cultivation, ground coffee production, coffee pulp-based feed, dairy farming, anaerobic digestion, organic fertilizer production, and yogurt processing. By-products from each component are reused across the system to improve the overall efficiency and resource utilization. Table 1 outlines the core and derivative products of each integration type.

Table 1. Products and by-products in Type 1 and Type 2 Integrated Farming Systems. This table provides comparative information on the products generated from existing integration in type 1 and improved integration in type 2. The table shows that the by-products generated by type 2 are more diverse due to the optimal utilization of biomass with the help of biodigester technology.

No.	Product Category	Type 1	Type 2
1	Main Products	Milk, Yogurt, Ground Coffee, Coffee Beans	Milk, Yogurt, Ground Coffee, Coffee Beans
2	Derivative Products	Manure, Sun-dried Coffee Husk and Pulp Feed	Biogas, Bioslurry, Coffee Husk and Pulp Concentrate

Figure 3 illustrates the scheme of the coffee and dairy cattle integration process. In type 1, the fertilizer used for cultivation is produced from dried manure without anaerobic fermentation. In contrast, in type 2, coffee cultivation is carried out by applying fertilizer derived from nutrient-rich bioslurry produced through anaerobic digestion. This affects the nutrient content and overall efficiency of waste utilization. Coffee processing yields beans, as well as pulp and husk waste. Approximately 70% of the beans are sold to collectors, and 30% are processed into ground coffee. Coffee pulp, rich in carbohydrates, proteins, and minerals, is repurposed as dairy feed [14], reducing feed costs and strengthening plantation-livestock linkages.
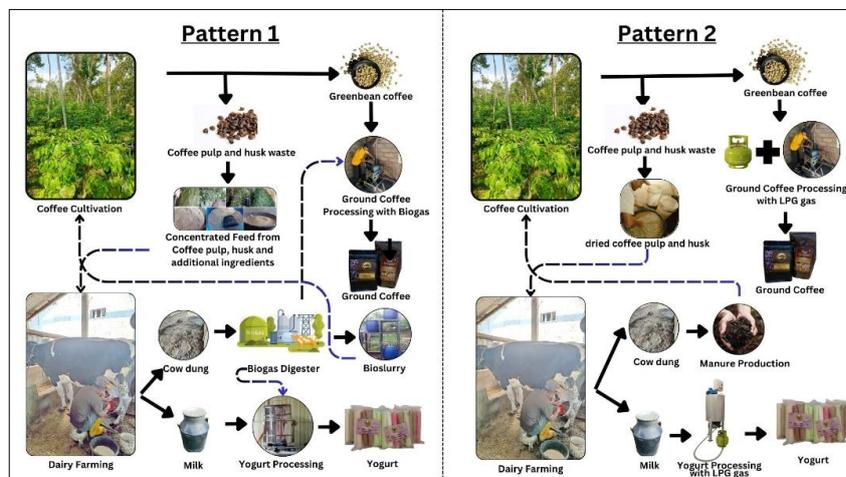

Figure 3. Schematic of coffee and dairy cattle integration farming process in each type. This diagram illustrates the input-output connectivity flow in the coffee and dairy cow integration process between the two types. The difference between the two types can be seen in the biomass processing of type 1 (existing integration type), which is carried out simply by drying and then used for cattle feed and coffee plant fertiliser. Meanwhile, type 2 optimises waste utilisation with the help of biogas digester technology to produce bioslurry and biogas, which will be used as fertiliser and energy sources for the coffee and yoghurt processing industries, while coffee husks will be processed with the addition of other ingredients to increase the nutritional value of cattle feed.

The feed methods differ: Type 1 uses sun-dried coffee pulp directly, whereas Type 2 enriches it with molasses, palm kernel meal, and soybean meal to enhance nutritional quality. This reduces the reliance on commercial feed and improves milk composition. Supplementing cattle rations with energy-rich ingredients increases milk fat and protein, providing benefits to tropical smallholders [15]. Dairy cattle provide milk and by-products, such as urine and dung. Some milk is processed into yogurt. Energy use differs between the

systems: Type 1 uses LPG, whereas Type 2 uses biogas from anaerobic digestion, reducing fossil fuel reliance and operating costs. The comprehensive financial implications of these system elements, including the optimization of biomass into value-added products, are detailed in Table 2.

Table 2. Contribution of System Elements to Financial Indicators. This table explains the financial impact that will be obtained if the biomass processing is optimised into value-added products on the financial feasibility of the business. The analysis results show that biomass processing in the form of cattle feed, bioslurry, and biogas significantly increases the NPV and IRR values and reduces operational costs, thereby driving profits in the integrated system business.

Element	Contribution	Financial Impact (% cost reduction or IRR/NPV change)
Coffee Pulp Feed	Reduces concentrate feed cost by 20–25%	+6.5% IRR, +IDR 8.2 million NPV
Bioslurry as Fertilizer	Replaces 80% of chemical fertilizer usage	+3.2% IRR, +IDR 4.5 million NPV
Biogas Utilization	Reduces energy cost by 40–60% in milk and coffee processing	+5.8% IRR, +IDR 6.7 million NPV

Financial Feasibility

The processing of dairy cattle biomass demonstrates notable economic potential through income enhancement driven by product diversification and efficient waste utilization. The financial feasibility analysis evaluates cash inflows and outflows based on investment criteria such as the Net Present Value (NPV), Internal Rate of Return (IRR), Net Benefit-Cost Ratio (Net B/C), and Payback Period. Cash inflows originate from the sale of primary products, byproducts, and residual values. Both integration models, Type 1 and Type 2, produced similar main outputs, including coffee beans, ground coffee, fresh milk, and yogurt. However, they differ in terms of waste management. Type 1 generates only raw livestock manure, whereas Type 2 transforms waste into biogas and slurry.

In terms of benefits, the average annual income for the Type 2 coffee integration model with biogas management was IDR 1,023,690,968, which was considerably higher than the IDR 830,878,629 of Type 1. Hence, the difference in benefits is attributed not only to the quantity produced but also to the added value of the products. The income generated by Type 1 cow manure management process was IDR 19,552,448, whereas selling biogas and bioslurry yielded a higher added value and income of IDR 188,331,183 for Type 2. The income from waste management, along with the magnitude of the difference in income, demonstrates the efficiency of Type 2 as a circular model, thereby confirming the low risk and high value of return on investment in waste management systems. A detailed breakdown of the product revenues is presented in Table 3.

Table 3. Average income from products generated from each type of coffee and dairy cow integration. This table shows a comparison of average annual income obtained from two types of dairy and coffee integration farming on a scale of 6 dairy cows and 1 hectare of land per year. Type 1 is the existing integration model, and type 2 is the improved integration type. The results show that Type 2 has a significantly higher total income than Type 1 due to the optimisation of waste utilisation into value-added products from derivative products, namely the sale of biogas and bioslurry.

Product of integrated agriculture	Type 1	Type 2
Main Product		
Coffee Beans	IDR 90,552,241	IDR 101,767,930
Ground Coffee	IDR 103,488,295	IDR 116,306,210
Milk	IDR 249,887,889	IDR 249,887,889
Yogurt	IDR 367,397,756	IDR 367,397,756
Derivative Products		
Biogas	-	IDR 8,100,000
Bioslurry	-	IDR 180,231,183
Manure	IDR 19,552,448	-
Average total income	IDR 830,878,629	IDR 1,023,690,968

Notes:
#Business life: 10 years (economic lifepan of dairy cows)
#Types 1: integration of coffee farming and dairy + simple manure processing + simple coffee pulp feed production
#Types 2: integration of coffee and dairy farming + biogas plant management + coffee pulp concentrate processing

Although Type 2 requires a higher initial investment (IDR 2,172,256,544) than Type 1 (IDR 1,941,890,544) owing to the addition of biogas and concentrate feed systems, the efficient use of waste resources helps lower long-term operational costs. The capital expenditures in Type 2 include coffee cultivation, post-harvest handling, concentrate production, dairy farming, anaerobic digestion, and yogurt processing. Operating costs comprise both the variable and fixed components. Variable costs depend on the production scale and cover inputs such as fertilizers, feed, seeds, packaging, veterinary care, and artificial insemination. Feed costs, representing 60–70% of total variable costs, were significantly lower in Type 2 (IDR 172,845,312/year) than in Type 1 (IDR 215,835,450/year), largely due to the substitution of commercial feed with coffee pulp concentrate. The fixed costs of fuel, water, electricity, labor, and taxes were slightly higher in Type 1 (IDR 175,594,367/year) than in Type 2 (IDR 168,361,689/year), primarily because Type 1 still relies on LPG, whereas Type 2 benefits from biogas as an alternative energy source. Labor remains the largest fixed-cost component (IDR 51,100,000/year) across both systems.

The financial figures support the viability of both types of integration. At a discount rate of 6% (which is the BRI KUR interest rate), Type 1 integration has an NPV of IDR 1,225,662,343.36, while Type 2 has an NPV of IDR 1,714,402,922.83, meaning that Type 2 is financially superior. This is due to the input-output connectivity and optimisation of waste utilisation in Type 2. The Internal Rate of Return (IRR) for Type 2 is also higher, at 22%, compared to Type 1 at 16%. The IRR analysis results exceed the discount rate, meaning that the profits will be higher than standard savings interest rates or time deposits. These results are in line with several previous studies. Vinholis et al. [16] also reported that the application of integration between crops and livestock will reduce market and operational risks. Barbieri et al. [17] also stated that IRR increases with higher technology inputs into the system, while systems with low inputs provide returns of 9.2%, medium 11.4%, and high 20.9%, which is a reasonably wide range. In addition, excessive crop density, also reported by Trivelin et al. [18], also impacts the profitability and potential of the system to become more economically sustainable.

Furthermore, the B/C ratios also indicate that the project is financially viable, as Type 1 is 1.72, and Type 2 is 1.98. It shows that for every 1 IDR invested, the return is 1.72 IDR in Type 1 and 1.98 IDR in Type 2. In addition, the payback period is shorter in Type 2, taking 6 years and 8 months, as opposed to Type 1, which takes 7 years. This shows that capital is recovered quickly. All in all, this indicates a greater economic return from the combination of biogas and slurry processing in coffee-dairy farming, while also decreasing the reliance on fossil energy and synthetic inputs. A detailed comparison of the investment criteria, highlighting the economic performance of Type 1 and Type 2 systems, is presented in Table 4.

Table 4. Investment Criteria Values of each farming system. This table shows a comparison of investment criteria values for both types of coffee and dairy cattle integration: Type 1 (existing coffee and dairy cattle integration) and Type 2 (improved coffee and dairy cattle integration) on a scale of 6 cows and 1 hectare of coffee land. The financial feasibility indicators used are NPV, IRR, Net B/C, and payback period. The results show that Type 2 has advantages in all financial feasibility indicators, confirming the superior economic benefits of applying circular economy principles.

Investment Criteria	Type 1	Type 2
NPV (IDR)	1,225,266,234.36	1,714,402,922.83
IRR (%)	16	22
Net B/C	1.72	1.98
Payback Period	7 years	6 years 8 months

Notes:
#NPV : Net Present Value
#IRR : Internal Rate Return

Discussion

Agricultural systems that optimize the use of biomass from crops and livestock offer valuable opportunities to improve both the environmental sustainability and economic viability of the sector. When circular economy principles are applied to these systems, resource use efficiency increases, environmental pressures are reduced, and economic opportunities are created from the reuse of waste that was previously considered waste [19]. These benefits are more pronounced in improved integration (Type 2), which optimizes biomass use through biodigester technology and nutrient recycling, in line with the findings of Utami and Rangkuti [20], who emphasized increased productivity, reduced costs, and increased income through the efficient use

of manure and crop residues. Biodigester technology and bioslurry recycling at the farmer level are crucial contributors to the three main pillars of natural resource management.

Financial Benefits of Biomass Optimisation

Integrated agriculture that applies circular economy principles has been proven to increase financial profits. Model 2 (optimisation of waste utilisation with biodigester management) provides greater economic benefits with higher NPV and IRR values compared to Model 1 [21]. This significant increase in profits is due to the processing of waste that was previously only discarded, which has now become a source of income for farmers. The highest income contribution from waste utilisation comes from bioslurry and biogas, amounting to IDR 188,331,183 (10 times the income from selling dried manure). Reduced feed costs and the use of biogas as an alternative energy source also support efficiency in type 2. These results are in line with the research by Abbas et al. [22], which states that the utilisation of agricultural biomass waste into high-value products such as biogas, fertiliser, and feed can increase energy efficiency by up to 30%, and that the technology in the anaerobic process makes it possible to achieve a biomass conversion rate of up to 90% [22–25].

Climate Change Mitigation

Biodigester technology serves as a strategy for addressing environmental issues by reducing methane and other gas emissions and providing a source of renewable energy [26]. CH_4 emissions from untreated manure produce greater greenhouse gas emissions than the fermentation process with the help of anaerobic bacteria because of the conversion and decomposition of easily degradable materials [27]. Biodigesters effectively capture harmful gases and convert them into biogas, which can be used as a clean energy source. Maciel et al. [28] even mentions that livestock systems that utilize biodigesters can reduce the average environmental impact by 25–38% in acidification, eutrophication, climate change, energy use, photochemical oxidation, and ozone depletion.

Soil Improvement and Impact on Biodiversity

From a sustainability perspective, the use of bio-slurry goes beyond its function as a mere substitute for chemical fertilizers. Bio-slurry supports soil regeneration, reduces dependence on external inputs, and facilitates low-emission agricultural practices [3,28,29]. From an ecological perspective, the application of bio-slurry contributes significantly to mitigating greenhouse gas emissions, particularly by reducing CH_4 (methane) and N_2O (nitrous oxide) emissions from the soil. In addition, bioslurry is essential for improving soil and water quality because of its high content of macro nutrients such as nitrogen, phosphorus, and potassium, as well as humic acid [30–32] The increased availability of nutrients and organic matter directly promotes increased soil biodiversity, supporting a healthy microbial ecosystem vital for natural nutrient cycles and agroecosystem health [29]. The agronomic benefits of this practice are reinforced by studies showing that bio-slurry has been proven to increases crop yields beyond the performance of conventional chemical fertilizers [30].

Policy Implications

Although the research results produced excellent financial feasibility values, they still had several limitations. This study had projections based on the assumption of product price stability for 10 years without taking into account the inflation rate that could occur and affect operational cost differences. However, this condition is mitigated by reducing external inputs in Type 2. The financial analysis results provide empirical evidence of the financial superiority obtained by applying the coffee-dairy cow integration improvement type. Therefore, strategic policy interventions can be made with a focus on increasing profitability and business sustainability by offering affordable credit schemes for farmers, upstream sector subsidies, technological assistance, and training, as well as providing environmental service incentives (such as green subsidies and tax reductions) to reduce the initial investment burden to encourage farmers to adopt Type 2. This is because Type 2 requires a larger initial investment capital.

Conclusions

Financially and ecologically sounder systems of agriculture incorporate biogas into their systems. Their benefits can be seen in their higher NPV and IRR (IRR 22%) and in considerable operational cost savings (energy (40–60%) and concentrate feed costs (20–50%) reductions). From waste the system biogas and fertilizer recycle and renews elements in the system and enhances environmental sustainability. Using

biomass is economically and environmentally beneficial. However, supporting policies in the form of investment in guidance/outcome (technical) frameworks can drive system wider adoption.

Author Contributions

LH: Conceptualization, Data Curation, Formal Analysis, Methodology, Resources, Writing - Original Draft; **ER:** Conceptualization, Supervision, Writing - Review & Editing; **AMF:** Conceptualization, Supervision, Validation, Writing - Review & Editing; **RN:** Conceptualization, Validation, Writing - Review & Editing; **R:** Conceptualization, Supervision, Validation, Writing - Review & Editing.

AI Writing Statement

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Conflicts of Interest

There are no conflict of interest.

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