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Development of Sustainable Bioindustrial Agriculture Based on Crop-Livestock Integration to Achieve Food Security in Bengkulu Province, Indonesia

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ABSTRACT

The agricultural sector in Bengkulu Province faces challenges such as low productivity and product quality, underutilization of agricultural and livestock waste, high dependency on external (chemical) inputs, and subsistence farming practices that neglect economies of scale. Additionally, agricultural resource degradation, climate uncertainty, and population growth threaten food security in the province. To address these issues, the government is promoting the implementation of sustainable bioindustrial agriculture. This study aims to evaluate the adoption level, income, and cost efficiency of sustainable bioindustrial agriculture based on rice and cattle integration to enhance food security in Bengkulu Province. The research was conducted in Seluma and Rejang Lebong districts, involving 200 farmers selected through Accidental Sampling. Data was collected through interviews, observations, focus group discussions, and literature review. Analysis methods included Likert scale analysis, income analysis, and the Stochastic Frontier production function. The findings indicate that the adoption level of bioindustrial agriculture is low, with a score of 48.68 percent. The average annual income from bio-industrial activities is IDR 43,543,099, with a cost efficiency rate of 87.92 percent. In bio-industrial agriculture, the only variable found to significantly impact inefficiency is the farmer's age. Factors that significantly influence cost efficiency include

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income, seed prices, NPK fertilizer prices, and labor wages, while compost prices, calf prices, and feed prices do not have a significant effect on cost efficiency.

Keywords: Adoption; Bioindustry; Efficiency

1. Introduction

The agricultural sector in Bengkulu Province is a cornerstone of the local economy, employing nearly 60% of the productive workforce and contributing 28.42% to the province's Gross Domestic Product (GDP). Within this sector, food crops make up 32.08% of total agricultural output, underscoring agriculture's importance in sustaining the economy and ensuring food security in Bengkulu [1]. As a national strategic commodity, rice is especially critical to the food crop subsector and plays a vital role in achieving food security, a pressing issue for Indonesia and other developing countries. Sustainable food production hinges on the efficient use of all available resources, making rice a key focus for development given Bengkulu's agro-ecosystem and suitable land conditions [2].

Despite its potential, however, rice productivity in Bengkulu is relatively low, averaging 4.9 tons per hectare compared to the national productivity of 6 tons per hectare [1]. This disparity is largely due to factors such as the conversion of productive paddy fields to non-agricultural uses and the degradation of soil quality from excessive chemical use without conservation measures. Alongside rice production, the livestock sector—especially beef cattle—also plays a critical role in Bengkulu's agricultural economy. With a cattle population of 164,780, this sector is a primary income source for rural farmers and contributes significantly to meeting local demand for animal protein [1]. However, the expansion of rice cultivation and cattle production also results in an increase in biomass waste, which, if not properly utilized, poses environmental challenges.

Plant and livestock waste is actually a highly valuable resource. In addition to serving as organic material for plant growth and soil quality improvement, this waste can also be used as animal feed and an alternative household energy source to replace fossil fuels [3–5]. Therefore, it is essential to develop agriculture that optimizes land use and processes agricultural commodities and waste into food sources through sustainable bioindustrial agriculture based on rice-cattle integration.

Bioindustrial agriculture is a broader concept that encompasses the processing of agricultural and livestock resources with the aid of simple industrial technology to produce products with higher economic value. This processing is not limited to increasing agricultural yields but also includes managing agricultural products into more diverse and value-added commodities that can enhance farmers' economies [6]. For example, cattle waste such as feces and urine can be processed into compost and bio-urine, which can be further utilized as bioenergy in the form of gas. Meanwhile, plant waste such as straw, corn stalks, and vegetable waste can be used as animal feed [7, 8].

The basic principles of bioindustrial agriculture are waste minimization, reduction of imported inputs, processing of biomass and waste into new bioproducts, and integration between crops and livestock with the application of environmentally friendly technological innovations [9]. The development of bioindustrial agriculture is part of sustainable agricultural development, which prioritizes sustainability, community participation, environmental conservation, and orientation towards the development of local resource-based farming enterprises. The three main principles of the sustainability of the bioindustrial agriculture system are self-financing capability through mutually supportive farming activities, the application of small-scale business technology, and production cost efficiency [10].

Research on bioindustrial agriculture has shown promising results, demonstrating both productivity and economic benefits. For instance, a study in Lombok found that technology adoption and strengthened farmer institutions led to a 15% increase in rice productivity and a 17.71% rise in farmer income [11]. In the livestock sector, the cattle population saw a 13.72% annual increase, while waste utilization practices generated substantial additional revenue. Specifically, compost production contributed IDR 144,582,180, biourine sales yielded IDR 3,317,556, and biogas production provided household savings of approximately IDR 35,400,000 per year. Studies in West Java further support the economic feasibility of rice-cattle integration systems, showing a benefit-cost ratio (B/C) of 2.5, which enhances farmers' economic gains and the competitiveness of agro-industrial products [12, 13]. These findings highlight the potential of rice-cattle integration models to improve sustainability and profitability for small-scale farmers.

The current implementation of bioindustrial agriculture in various regions remains traditional and lacks sustainability. This study aims to address these limitations by examining bioindustrial agriculture through both economic and practical lenses, with a specific focus on rice-cattle integration in Bengkulu Province. The objectives of this research are threefold: (1) to assess the level of adoption of bioindustrial agricultural practices among local farmers; (2) to analyze income and cost efficiency associated with these practices; and (3) to develop a sustainable, environmentally friendly, zero-waste model for rice-cattle bioindustrial agriculture tailored to the conditions in Bengkulu. The expected outcome is a comprehensive set of recommendations that can enhance the sustainability and economic viability of bioindustrial agriculture in the region.

2. Materials and Methods

The study utilized a survey method conducted in two locations representing agricultural areas in Bengkulu Province: the lowland region of Seluma Regency and the highland region of Rejang Lebong Regency. These locations were purposively selected based on the consideration that both had previously implemented pilot projects for bioindustrial agriculture integrating rice-cattle, vegetable-goat, and corn-cattle systems.

The sampling method employed Accidental Sampling, where samples were chosen based on their relevance and suitability as data sources [14]. The research sample comprised 200 farmers who also raised cattle. This sample size was determined that if the sampling frame is unclear, the minimum sample size should be ten times the number of variables studied [15]. In Seluma Regency, 100 samples were taken from the districts of South Seluma, Semidang Alas Maras, and Sukaraja, while in Rejang Lebong Regency, 100 samples were taken from Curup, North Curup, and Bermani Ulu.

Data collection was carried out through observation and interviews. Primary data was gathered using questionnaires and direct interviews with farmers and livestock breeders, while secondary data was obtained from relevant institutions such as village officials, extension workers, and the Agriculture and Livestock Services that supported this research.

The first stage of the research involved analyzing the adoption level of rice-cattle-based bioindustrial agriculture. Data analysis was performed using the Likert Scale, with four indicators used to measure adoption levels: farm management, organic farming practices, waste processing, and waste utilization. The adoption level of rice-cattle integrated bioindustrial agriculture is categorized into three levels: low adoption (20%–46.66%), moderate adoption (46.67%–73.33%), and high adoption (73.34%–100%) [16, 17].

The second stage of the research analyzed income and cost efficiency in sustainable bioindustrial agriculture based on rice-cattle integration. The income for sustainable bioindustrial agriculture (Y) is calculated using the following formula [18–21]:

$$Y = TR - TC \tag{1}$$

Where Y is income from sustainable bioindustrial agriculture; TR (Total Revenue) represents the total income generated from all activities in the bioindustrial farming system; and TC (Total Cost) represents the sum of all expenses incurred in the bioindustrial farming system.

The analysis of cost efficiency in sustainable bioindustrial farming based on rice-cattle integration utilizes the Stochastic Frontier Cost function [22–24]. The equation is expressed as:

$$C_i = C(y_i, w_i) + (v_i, u_i) \tag{2}$$

The total production cost of bio-industrial agriculture, denoted as C_i, is influenced by the output produced (y_i) and the price of inputs w_i. Additionally, the model accounts for random errors through the distribution v_i and includes an error term u_i to capture the inefficiency effects within the system.

Cost efficiency analysis is conducted by deriving the dual cost function from the production function. The method involves minimizing the input cost function subject to the production function constraint, resulting in the dual frontier cost function as follows:

$$\begin{aligned} LnC_i = \beta o + \beta 1LnY + \beta 2LnW1 + \beta 3LnW2) \\ +\beta 4LnW3 + \beta 5LnW4 + \beta 6LnW6 + (v_i + \mu_i) \end{aligned} \quad (3)$$

In the model, LnC_irepresents the production cost of bioindustrial agriculture (IDR), while LnY denotes the revenue from bio-industrial agriculture (IDR year^{-1}). The input prices are captured by LnW1 for seed price (IDR kg^{-1}), LnW2 for NPK fertilizer price (IDR kg^{-1}), LnW3 for compost fertilizer price (IDR kg^{-1}), LnW4 for labor wage (IDR HKSP–1), LnW5 for calf price (IDR head–1), and LnW6 for feed price (IDR kg^{-1}). The model includes an intercept βo and estimated parameter coefficients β1 through β7. The error term, (v_i + μ_i) accounts for random errors and inefficiency effects, with μ_i specifically representing the inefficiency in the model.

Meanwhile, the parameter value of the distribution (μ_i) for cost inefficiency effects in this study is formulated as follows:

$$\mu_i = \delta 0 + \delta 1 \ \ Um + \delta 2 \ \ Jk + \delta 3 \ \ PgUt + \delta 4 \ \ PgS \quad (4)$$

The variables in the model include μ_i, which represents the cost inefficiency effects, and several factors influencing inefficiency: Um for the farmer's age (years), Jk for the number of family members (people), PgUt for farming experience (years), and PgS for livestock farming experience (years). The model also includes an intercept δ0 and estimated parameter coefficients δ1 through δ5.

The estimation of the model parameters above is carried out using the Maximum Likelihood Estimation (MLE) method with the Frontier 4.1 computational program [25]. The estimation of cost efficiency parameters and the inefficiency function is performed simultaneously in the following form [24]:

$$\sigma^2 \equiv \sigma^2 u \ + \ \sigma^2 v \text{ and } \gamma \equiv (\sigma u)/(\sigma v) \quad (5)$$

The model includes the following variances: σ^2 represents the variance of the normal distribution, $\sigma^2 u$ denotes the variance of the inefficiency term u_i, and $\sigma^2 v$ to the variance of the random error term v_i.

The current implementation of bioindustrial agriculture in various regions remains traditional and lacks sustainability. This study aims to address these limitations by examining bioindustrial agriculture through both economic and practical lenses, with a specific focus on rice-cattle integration in Bengkulu Province. The objectives of this research are threefold: (1) to assess the level of adoption of bioindustrial agricultural practices among local farmers; (2) to analyze income and cost efficiency associated with these practices; and (3) to develop a sustainable, environmentally friendly, zero-waste model for rice-cattle bioindustrial agriculture tailored to the conditions in Bengkulu. The expected outcome is a comprehensive set of recommendations that can enhance the sustainability and economic viability of bioindustrial agriculture in the region.

3. Results and Discussion

3.1. Characteristics of Respondents

A factor related to farmers' performance ability is age. Farmer's age affects work productivity [20]. The older the farmer, the more physically demanding the work feels, leading to a tendency for productivity to decline. However, on the other hand, as age increases, so does the farmers' experience in managing their farming activities. The respondents in this study were in their productive years, with an average age of 47.5 years.

In addition, experience in farming and livestock activities is also a factor that can increase labor productivity [19]. The respondents in this bioindustry agriculture study had heterogeneous backgrounds, with farming experience ranging from 2 to 48 years, with an average of 15.1 years. Meanwhile, experience in cattle farming ranged from 2 to 30 years, with an average of 7.9 years.

Farmers' education is also a management factor that can influence productivity levels in improving farming outcomes. Education provides farmers with the knowledge to better manage their farming and livestock activities. Proficiency in farming and increased labor productivity are influenced by the level of education and experience of farmers [26]. The average education level of the respondent farmers was completion of Junior High School (SLTP). Additionally, the average number of family members of the respondent farmers was 3.56 people. The number of family members affects the household head's responsibility in working to meet family needs and can also be a source of additional labor within the family.

3.2. Farmers' Adoption Rate of Sustainable Bio-Industrial Agriculture

The level of adoption of bioindustry agriculture by farmers was measured using a Likert Scale. This adoption level reflects the extent to which farmers have implemented bioindustry agriculture based on the integration of rice and cattle, assessed through four parameters: livestock management, organic farming, waste processing, and waste utilization.

Table 1 shows that 35% of farmers (71 respondents) are at a low adoption level, 56% of farmers (112 respondents) are at a moderate adoption level, and only 8.5% of farmers (17 respondents) are at a high adoption level.

In general, the level of adoption of bioindustry agriculture by farmers is at a moderate level, with a score of 48.68. Farmers in the study area have not fully implemented bioindustry agriculture, as they still use chemical inputs in managing their farming activities. Further details on the parameters of bioindustry agriculture adoption are presented in **Table 2**.

Table 1. Respondents based on the adoption level of bio-industrial agriculture (number of people).

No.	Adoption Category	Score	Sample (People)	Percentage (%)
1	Low	20.00–46.66	71	35.5
2	Moderate	46.67–73.33	112	56
3	High	73.34–100.00	17	8.5
Sum		**48.68**	**200**	**100**

Source: Processed primary data, 2024.

Table 2. Adoption parameters of farmers for bio-industrial agriculture.

No.	Parameter	Indicator	Score	Max Score	Index (%)	Adoption Level
1	Livestock Management	5	10.63	25	42.52	Low
2	Organic Farming	7	17.22	35	49.20	Moderate
3	Waste Processing	4	10.58	20	52.92	Moderate
4	Waste Utilization	4	10.25	20	50.12	Moderate
	Sum		**48.68**	**100**		Moderate

Source: Processed primary data, 2024.

3.3. Implementation of Farm and Livestock Management

To achieve optimal agricultural production, the implementation of farm management is crucial [27]. The farm and livestock management application index in the study area reached only 42.52 percent (**Table 2**), indicating a low level of application. Respondent farmers cultivate paddy fields with a semi-technical irrigation system, meaning that irrigation water is obtained on a rotational basis. The use of production inputs such as fertilizers, seeds, and pesticides is also below the recommended levels, resulting in rice production that remains below the national average productivity. The rice varieties planted by the farmers are Inpari, Sintanur, and IR. The average rice production in the study area is 5.2 tons per hectare per growing season, which is still lower compared to the research conducted in Indrapuri, Aceh Besar, where the productivity of the Inpari 32 rice variety can reach 6.01 tons per hectare per growing season [28]. Meanwhile, research by Balitbangtan Bogor showed that the productivity of Inpari rice varieties can reach 9.6 tons per hectare, and in Karawang, it can reach 9 tons per hectare per growing season.

The implementation of livestock management in the study area also remains in the low category. This reflects the farmers' limitations in applying livestock management as part of bioindustrial agriculture based on crop-livestock integration. In terms of housing, farmers have not fully implemented adequate standards related to the location, shape, size, and equipment of the livestock pens. Farmers tend to believe that housing does not have a significant impact on cattle growth. Feed provision for livestock is also minimal, with many farmers only providing grass or even allowing cattle to forage for their feed. Medicines are only administered when diseases strike, while preventive measures are still rarely taken by the farmers.

3.4. Implementation of Organic Farming

Bioindustrial agriculture based on crop-livestock integration aims to optimize the use of waste, where rice crop residues are used as cattle feed, while cattle manure and urine are utilized as organic fertilizers for rice plants. Additionally, bioindustrial agriculture encourages farmers to use organic fertilizers and pesticides derived from livestock, thereby reducing dependency on synthetic chemical fertilizers. The goal of this bioindustrial agriculture is to achieve chemical-free organic farming, where the higher the level of adoption, the closer the farming system gets to sustainable organic agriculture [29].

In an organic farming system, inputs such as organic fertilizers and pesticides originate from livestock and plant waste, eliminating the use of chemical fertilizers and pesticides. The seeds used must also be organic seed varieties that are responsive to organic fertilizers. The irrigation system must be separated from conventional paddy irrigation to prevent chemical fertilizer residues from flowing into fields that implement organic systems [30].

In the study area, the implementation of the organic farming system achieved a score of 49.20 percent (**Table 2**), which falls into the moderate category. Farming practices in the study area have not fully adopted a pure organic farming system. Farmers still use chemical fertilizers and pesticides because the response of crops to organic fertilizers tends to be slower, with results only visible in the following planting season. Moreover, the production of compost takes 3–4 weeks, which cannot quickly meet farmers' needs. These factors cause farmers to continue using chemical fertilizers, which provide a quicker response to crops and soil.

3.5. Processing of Rice and Cattle Waste

Research on bioindustrial agriculture on dry land in Bali demonstrated that this system integrates crops and livestock, where waste from crop products is used as livestock feed, and livestock waste is utilized as fertilizer to improve soil fertility and processed into fuel [31]. The foundation of bioindustrial agriculture is an integration system that creates synergy and mutual complementarity between crops and livestock, where waste from both sectors can be utilized reciprocally [32–34]. Livestock waste, such as cattle manure, is processed into compost and granular organic fertilizer, while liquid waste like cattle urine is used as liquid fertilizer. On the other hand, crop residues such as straw, leaves, and stems can be processed into livestock feed [7, 8].

The processing of rice and cattle waste in the study area showed a score of 52.92 percent (**Table 2**), which falls into the moderate category. The main obstacles faced by farmers in processing cattle urine waste include a lack of understanding of bio-urine processing techniques. In addition, farmers do not yet have adequate equipment to process the waste and face limitations in family labor. If they use outside labor, they incur additional costs. Furthermore, farmers also encounter difficulties in collecting cattle urine due to inadequate pen conditions. For processing rice waste, almost all farmers use leftover rice straw as supplementary cattle feed.

3.6. Utilization of Rice and Cattle Waste

Cattle produce feces and urine, where the feces can be utilized as organic fertilizer directly applied to rice plants. Another part of cattle waste, namely urine, can be processed into liquid fertilizer and organic pesticides that can be used on rice crops. On the other hand, rice plants produce agricultural waste such as straw, husks, broken rice, and bran, where rice straw and bran can be used as cattle feed [35].

The utilization of rice and cattle waste in the study area scored 50.12 percent (**Table 2**), falling into the moderate category. Although many farmers have processed cattle waste, some farmers in Rejang Lebong Regency do not use the processed waste products for their rice crops. They prefer to use the waste products on their vegetable crops. The farmers argue that compost and bio-urine are more effective when applied to vegetable crops because vegetables can be harvested faster than rice, allowing them to reap the benefits of cattle waste processing more quickly. Additionally, the high demand for compost in the market leads many farmers to choose to sell it rather than use it on their paddy fields. Meanwhile, bio-urine has not been widely utilized by farmers because they face difficulties in collecting cattle urine due to the lack of an intensive livestock management system.

3.7. Production, Revenue, and Income in Bio-Industrial Agriculture: Rice Farming

Rice farming is typically calculated based on two growing seasons per year, with an average land area of 0.69 hectares. The total production of dry milled rice (dry unhusked rice) is 7,143.50 kg per year, equivalent to 10,352 kg hectare^{-1} year^{-1} or 5.26 tons hectare^{-1} per growing season (**Table 3**). The average price of dry milled rice is IDR 6,162.50 per kilogram. Consequently, the total revenue from rice farming amounts to IDR 44,012,250 per year, calculated by multiplying the dry milled rice production by the price per kilogram. The total cost of rice farming is IDR 16,884,867 per year, resulting in a net income from rice farming of IDR 27,127,683 per year.

3.8. Cattle Farming

Income from cattle farming is calculated for one fattening period, which lasts between 8 to 12 months. The products from cattle farming include live cattle sold during religious holidays, such as Eid al-Adha, as well as compost and bio-urine. All respondent farmers process manure into compost; however, only about 24.5% or 49 farmers process urine into bio-urine. The low number of farmers processing bio-urine is due to challenges in collecting urine, because of inadequate pen systems and the fact that cattle are often kept outside the pen during the day. Additionally, urine processing requires extra technology and labor, which means that farmers must bear additional costs for labor beyond the cost of cattle maintenance.

The revenue from processing manure into compost and bio-urine is still relatively small, amounting to IDR 2,011,000 per year for compost and IDR 938,750 per year for bio-urine. These amounts only account for 3.5% and 1.7% of the total revenue from cattle farming, respectively (**Table 4**).

Table 3. Annual analysis of rice farming.

No.	Type	Minimum	Maximum	In a Year
1.	Production (kg)	2,000	30,000	7,143.50
2.	Price (IDR/kg)	6,000	6,500	6,162.50
3.	Revenue (IDR)	12,000,000	180,000,000	44,012,550
4.	Cost (IDR)	4,483,000	72,630.000	16,884.86
5.	Income (IDR)	3,093,000	107,910,000	27,127,683.00

Source: Processed primary data, 2024.

Table 4. Production and revenue from cattle farming (year).

No.	Production	Volume			Price (IDR)			Revenue (IDR)		
		Min	Max	Average	Min	Max	Average	Min	Max	Average
1.	Cattle (heads)	1	20	3,3	13,000,000	17,000,000	16,131,250	16,000,000	362,500,000	53,282,500
2.	Compost (kg)	100	10,000	1,883	800	3,500	1,178	100,000	10,000,000	2,011,000
3.	Bio-urine (liters)	0	1,000	84.63	9,000	35,000	11,524	0	17,500	938,750

Source: Processed primary data, 2024.

The sale of live cattle for *Eid al-Adha* remains the primary product of cattle farming. The income from cattle farming is calculated by subtracting the total production costs from the total revenue generated. Based on **Table 5**, the production costs for cattle farming amount to IDR 39,816,834 per year. With the total revenue from cattle sales, the net income earned is IDR 16,415,416 per year. On average, the number of cattle sold each year is 3.31 head.

3.9. Income from Sustainable Bio-Industrial Agriculture

Income from bioindustrial farming is calculated by summing the income from rice farming and cattle farming over a one-year period. For rice farming, income is calculated based on two growing seasons per year, while for cattle farming, it is calculated for one fattening period per year. The research findings show that the income from rice farming is IDR 27,127,683 per year, while the income from cattle farming is IDR 16,415,416 per year. Therefore, the total income from bioindustrial farming amounts to IDR 43,543,099 per year.

Farmers' income from bioindustrial farming reaches IDR 43,543,099 each year, or equivalent to IDR 3,628,591 each month. This amount is higher than the 2024 Provincial Minimum Wage (UMR) of Bengkulu, which is IDR 2,507,079 each month [36]. This indicates that rice and cattle farmers in the study area have already achieved a decent standard of living.

Table 5. Income from sustainable bio-industrial agriculture (IDR year^{-1}).

No.	Type	Minimum	Maximum	In a Year
1.	Production (head)	1	20	3.3
2.	Price (IDR)	13,000,000	17,000,000	16,131,250
3.	Revenue (IDR)	16,000,000	362,500,000	53,282,500
4.	Cost (IDR)	8,032,000	183,277,600	39,816,834
5.	Income (IDR)	1,046,850	351,493,300	16,415,416

Research on bioindustrial farming of salak (snake fruit) and goats in Yogyakarta showed a profit of IDR 22,150,000 per year, representing a 163% increase after the implementation of bioindustry practices [37]. The Benefit/Cost (B/C) ratio also improved from 2.11 to 3.18, thanks to compost processing and increased goat milk production.

Bioindustrial farming also provides significant benefits in terms of technology adoption and strengthening farmer institutions [11]. Over the past four years, rice productivity has increased by 15%, farmers' income by 17.71%, and the use of chemical fertilizers and rice seeds has decreased, while seed production has increased. In the livestock sector, there was an annual increase in the cattle population of 13.72% and the provision of 3,496.63 tons of dry matter fodder per year. In terms of waste utilization, compost production generated IDR 14,582,180, and income from bio-urine reached IDR 3,317,556. The strengthening of farmer institutions also brought additional benefits, including the provision of agricultural machinery services, rice milling facilities, production input kiosks, and organized planting and harvesting teams.

Consistent with studies that the integration of rice-cattle farming has been shown to increase farmers' income [38–40]. Farmers who use organic fertilizers from fermented cattle manure experienced an income increase of IDR 1.45 million each planting season compared to those who do not use organic fertilizers. The use of organic fertilizers reduces the need for inorganic fertilizers, leading to lower production costs. Research on dry land in Bali also demonstrated an increase in farmers' income and efficiency in bioindustrial farming [31].

3.10. Cost Efficiency in Sustainable Bio-Industrial Agriculture

Cost Efficiency (CE) is calculated as the ratio between the actual total production cost (C_i) and the minimum observed or expected total production cost (C_i) [41]. The efficiency value ranges from 0 to 1. Using the Frontier 4.1 program application will yield the Cost Efficiency (CE) value, which is the inverse of the cost function equation [42].

The efficiency level criteria are as follows: Efficiency in sustainable bio-industrial agriculture is categorized into three levels: Based on **Table 6**, the highly Efficient systems have an efficiency score of ≥ 0.90, Moderately Efficient systems have a score between 0.70 ≤ Efficiency < 0.90, and Inefficient systems score below < 0.70 [42–44].

In bio-industrial farming, the cost efficiency coefficient values ranged from a minimum of 77% to a maximum of 91%, with an average value of 87%, which falls under the moderately efficient category. This finding aligns with the research which reported that the cost efficiency of rice farmers who are members of farmer groups in Indonesia ranged between 70% and 90% [45]. In this study, 94.50% of the samples were categorized as moderately efficient, while 5.50% were highly efficient. The distribution of cost efficiency achievements can be seen in **Table 6**.

Table 6. Distribution of cost efficiency in bio-industrial agriculture.

Efficiency Index	Criteria	Sample	Percentage (%)
<0.70	Inefficiency	0	0
0.70–0.89	Moderate efficiency	189	94.50
0.90–1.00	High efficiency	11	5.50
Total		200	100
	Average efficiency		**0.87**

Source: Processed Primary Data, 2024.

Table 7 shows that the cost efficiency of bio-industrial agriculture in Bengkulu Province is at a moderately efficient level. This finding aligns with research indicating that the average cost efficiency of rice farming in Indonesia reaches 83 percent, as measured by the Cost Frontier model [46]. In contrast, other studies report that the cost efficiency of rice farming in the Mekong Delta, Vietnam, is higher, at around 90 percent [47].

Table 7. Stochastic frontier cost function in bio-industrial agriculture.

Variable	Coefficient	Standard Error	T-Ratio
Ln Constant (β0)	2.93	0.59	4.89
Ln Revenue (β1)	−0.0001	0.00003	−35.03**
Ln Seed Price (β2)	0.80	0.06	12.42**
Ln NPK Fertilizer Price (β3)	0.00006	0.00008	7.35**
Ln Compost Price (β4)	0.04	0.04	−1.05
Ln Labor Wage (β5)	−0.0003	0.00005	−2.50*
Ln Calf Price (β6)	0.096	0.14	0.64
Ln Feed Price (β7)	0.000007	0.00001	0.40
Sigma squared (σ^2)	0.986	0.019	5.14
Gamma (γ)	0.811	0.280	7.52
LR test of the one-sided error			17.22

Source: Processed primary data, 2024.
Note: ** Significant at α = 1%, t-table α = 1% = 3.118;
* Significant at α = 5%, t-table α = 5% = 2.371.

Cost efficiency was analyzed using the Stochastic Frontier cost function and the Maximum Likelihood Estimation (MLE) model. **Table 7** shows that the gamma (γ) coefficient in bio-industrial agriculture is significant at the 99 percent confidence level (α = 1%), with a gamma coefficient value of 0.811 or 81.1%. This indicates that 81.1% of the total variation in the cost of bio-industrial agriculture based on the integration of rice and cattle is influenced by independent variables such as income, seed prices, NPK fertilizer prices, compost prices, labor wages, calf prices, and feed prices. Meanwhile, the remaining 18.9% is attributed to the influence of inefficiency variables, such as age, number of family members, rice farming experience, and cattle farming experience.

The individual test results of the Stochastic Frontier show that four independent variables have a statistically significant effect on the production costs of bio-industrial agriculture, namely income, seed prices, NPK fertilizer prices, and labor wages. In contrast, the variables of compost prices, calf prices, and feed prices do not show a significant effect on the production costs of bio-industrial agriculture. The Stochastic Frontier production cost function in bio-industrial agriculture is presented in **Table 7**.

The income variable has a highly significant partial influence on the production costs of bio-industrial agriculture, with a negative sign, indicating that a 1 percent increase in income will reduce the production costs of bio-industrial agriculture by 0.0008 percent. This is due to the fact that higher income reflects increased production. Bio-industrial agriculture based on the integration of rice and cattle yields high production due to the combination of crop and livestock production which is more efficient in the use of production factors, thereby reducing production costs [29]. Additionally, farmers' ability to manage land with appropriate inputs without overuse also contributes. Affordable input prices and proper usage yield outputs that are proportional to the costs incurred, and adequate output prices have resulted in income above production costs. Farming is considered efficient when it generates profits, where the increase in output value exceeds the increase in input value.

The seed price variable has a significant impact on increasing the production costs of bio-industrial agriculture. This is reflected in the research findings, which show that the seed price variable has a very significant and positive effect on production costs. This means that when seed prices increase, the production costs of bio-industrial agriculture also increase. Most farmers plant Sintanur and Inpari varieties at a price of around IDR 12,500 kg^{-1}, but some use local seeds priced at IDR 6,000 kg^{-1}. Farmers with larger capital tend to use certified hybrid superior rice seeds, which can cost up to IDR 38,000 kg^{-1}. The higher the price of rice seeds, the higher the production costs of rice farming. The use of hybrid superior seeds is based on farmers' awareness of the seeds' superiority in terms of production and adaptation to the environment and pests. Seed price variation is also influenced by the source of purchase, whether directly from agricultural stores or at subsidized prices from farmer groups. The average seed usage by farmers is close to the recommendation for rice farming.

The NPK fertilizer price variable significantly affects the production costs of bio-industrial agriculture. All sample farmers still use NPK fertilizer in rice farming, although some combine it with cattle compost. The average price of subsidized NPK fertilizer is IDR 2,900 kg^{-1}, while non-subsidized fertilizer costs IDR 7,600 kg^{-1}. Farmers use NPK fertilizer because its effects are seen more quickly compared to cattle compost, which only shows effects in the next planting season. Additionally, NPK fertilizer is more readily available in stores or agricultural kiosks, while cattle compost requires time for processing. This is why farmers continue to use NPK fertilizer even though they have adopted a rice-cattle integration system. This finding is supported by research, which found that seed prices positively impact the increase in production costs [46].

The labor wage variable significantly affects the production costs of bio-industrial agriculture with a negative coefficient. This indicates that an increase in labor wages leads to a decrease in the production costs of bio-industrial agriculture. This result aligns with the study, which states that labor wages negatively impact the cost efficiency of rice farming [46]. Labor wages in the study area range from IDR 75,000 to IDR 100,000 per Full Workday (HKSP). In this study, although family labor is not paid in real terms, it is still considered an implicit cost. The labor used by farmers also works in both rice and cattle farming. The difference in economic performance, as reflected by the return on production costs in the form of income and relatively high labor productivity, can offset the negative impact of rising labor wages, thus reducing the production costs of bio-industrial agriculture.

Meanwhile, the other three variables—compost price, calf price, and feed price—do not significantly affect the cost efficiency of bio-industrial agriculture. The findings suggest that the relatively low price of compost and its usage below recommendations contribute to this outcome. Rice farmers tend to still use chemical fertilizers because they provide quicker visible results in plant growth and production, whereas compost takes longer to react as it functions to improve soil conditions.

Overall, the findings of this study show that in bio-industrial agriculture, cattle rearing can enhance production cost efficiency through diversified use of production resources, such as saving on chemical fertilizer costs by replacing them with organic fertilizers from cattle waste. Additionally, the use of chemical pesticides can be minimized by replacing them with cow bio-urine. The use of organic materials in farming will reduce the use of chemical inputs, leading to a more sustainable ecological system.

Research in Majalengka, West Java, on integrated farming shows an increase in rice production by 20–29 percent and a reduction in the use of inorganic fertilizers by 25–35 percent [48]. Fattening cattle using dry fermented straw and rice bran as the main feed results in an average weight gain of 0.7 kg per head per day. Adult cattle can produce 4–5 tons of wet manure per year, which is then processed into 2–2.5 tons of compost per head of cattle per year. The compost produced is reused in the rice fields, where 1 hectare of rice fields requires 1.5–2 tons of compost. The use of compost improves the physical properties of the soil while reducing the use of relatively expensive chemical fertilizers. Furthermore, research by the Bengkulu Agricultural Technology Assessment Center in 2016 shows that in a bio-industrial agricultural system with an integration system, a cow can produce 8–10 kg of manure daily. From this amount of cow manure, 4–6 kg of organic fertilizer can be produced per day. To achieve high productivity with organic cultivation technology, around 3.6 tons of organic fertilizer per hectare per season is needed, which can be met by 4 cows with a Planting Index (IP) of 200.

Furthermore, it is stated that the plant-livestock integration system has several advantages, including: (1) livestock can be used as labor, (2) helping to improve soil fertility due to continuous planting by using compost from livestock waste, and (3) crop residues from the harvest can be used as livestock feed [29]. This integration farming model can increase land productivity as an effort to achieve sustainable agriculture [49].

3.11. Cost Inefficiency in Bio-Industrial Agriculture

The analysis of cost inefficiency effects was conducted using the stochastic frontier analysis cost function with the maximum likelihood estimation (MLE) model. In bio-industrial agriculture, only one variable was found to have a significant impact on inefficiency, namely the farmer's age. In contrast, the other three variables—number of family members, experience in rice farming, and experience in cattle farming—did not significantly affect inefficiency (**Table 8**).

Table 8. Cost inefficiency in bio-industrial agriculture.

Variable	Coefficient	Standard Error	T-Ratio
Constant (σ^o)	−0.09	0.993	−0.094
Age (σ^1)	0.158	0.067	2.383*
Number of Family Members (σ^2)	0.00003	0.00005	0.538
Experience in Rice Farming (σ^3)	−0.10	0.214	−0.469
Experience in Cattle Farming (σ^4)	−0.00001	0.00007	−0.026

*: Significant
Source: Processed primary data, 2024.

3.12. Farmer's Age Variable

The farmer's age variable has a significant positive effect on the cost inefficiency of bio-industrial agriculture. This indicates that as farmers age, they tend to become more inefficient in managing farming costs. As farmers get older, their physical and managerial abilities to run their farms decline. The average age of farmers in the study area is 47.5 years, which is still considered productive but nearing older age, leading to a decline in their physical and management capabilities, thus contributing to inefficiency in the costs of bio-industrial agriculture.

The study also shows that the variables of family size, rice farming experience, and cattle farming experience do not have a significant impact on farming cost inefficiency. This suggests that these variables tend to support cost efficiency in bio-industrial agriculture. In the stochastic frontier production function, inefficiency effects are a function of socio-economic variables. There is a positive correlation between the level of technical inefficiency and farmers' age, farm scale, and the number of workers employed, and a negative correlation between technical inefficiency and producers' experience [50].

Based on studies of adoption rates and the economic feasibility of bio-industrial agriculture, a sustainable bio-industrial farming model based on rice-cattle integration has been developed, as illustrated in **Figure 1**.

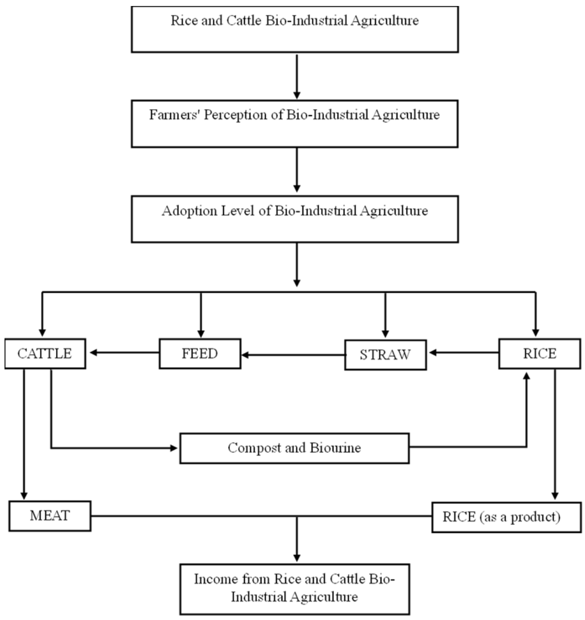

Figure 1. Sustainable bio-industrial agriculture development scheme.

4. Conclusions

Bio-industrial agriculture based on integration is a farming system that combines crops and livestock, founded on the concept of biological recycling. In bio-industrial agriculture, there is an interconnection of input-output among commodities, where each benefits from the other. This mutually beneficial concept enhances productivity and cost efficiency. The integration of rice and cattle in bio-industrial agriculture can increase farmers' income and create a sustainable farming system that is environmentally tolerable, socially acceptable, and economically feasible. The government should collaborate with agricultural extension workers and farmers to implement programs focused on education and training in integrated crop-livestock bio-industrial farming. These programs should cover farm and livestock management, waste processing technology, and processing technologies for agricultural and livestock products.

Author Contributions

N.K., conceptualization of ideas, data collection, data analysis, writing, and revision of the reviewer; H.D.P., conceptualization of ideas, data collection and analysis, manuscript review and literature review; J., conceptualization of ideas, reporting, editing and revision of reviewer comments.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of Research and Community Service Institute, Universitas Muhammadiyah Bengkulu (098.c/LPPM/II.3.AU/2024 and 1 July 2024).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data are available upon request from the corresponding author.

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Conflicts of Interest

The authors disclosed that they do not have any conflict of interest.

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