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ECONOMIC BENEFITS AND ENERGY EFFICIENCY OF USING SOLAR PANELS ENERGY FOR PADDLE AERATORS IN SHRIMP PONDS

KEUNTUNGAN EKONOMI DAN EFISIENSI ENERGI PENGGUNAAN ENERGI PANEL SURYA PADA KINCIR AIR DI TAMBAK UDANG

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ABSTRACT

Solar energy is a new innovation in aquaculture. The purpose of this study was to determine the economic benefits and energy efficiency of using solar panel energy on paddle aerator machines in shrimp ponds. The research method employed was a causal ex-post facto design. The variables observed were the electricity consumption of paddle aerators using solar energy compared to those using conventional energy sources. The research findings indicate that the oxygen production rates of paddle aerators were 2.04-2.77 mgO_2/hour (solar panel) and 2.02-2.89 mgO_2/hour (non-solar panel). Solar panels generated electrical energy in paddle aerators at rates of 8.34-8.75 watts. Electricity consumption by paddle aerators was recorded at 7.10-8.65 kW (solar panel) and 6.89-9.28 kW (non-solar panel). Quantitatively, the efficiency of electricity was found to be 0.10-1.24 watts when using solar panels. The use of solar panels is also considered more cost-effective for operational costs in intensive shrimp farming. Conclusion, the use of solar energy via solar panels for paddle aerators proves highly effective and economical compared to conventional electricity sources. Additionally, this system supports the operational effectiveness of the equipment throughout its technical lifespan.

Keywords: electricity, energy, cost, shrimp ponds.

ABSTRAK

Penggunaan energi panel surya adalah sebuah inovasi baru di bidang akuakultur. Tujuan dari penelitian ini untuk mengetahui keuntungan ekonomi dan efisiensi energi penggunaan energi panel surya pada mesin paddle aerator di tambak udang. Metode penelitian yang digunakan adalah riset dengan konsep desain kausal *ex-pose facto* dan pengambilan data secara *purposive sampling*. Adapaun peubah yang diamati adalah jumlah konsumsi energi listrik pada paddle aerator yang menggunakan energi panel surya dan yang tidak menggunakan. Hasil penelitian menunjukkan. Tingkat produksi oksigen oleh paddle aerator berkisar 2,04-2,77 mgO_2/jam (*use solar panel*) dan 2,02-2,89 mgO_2/jam (*non-solar panel*). Tingkat produksi energi listrik oleh panel surya di paddle aerator 8,34-8,75 watt. Konsumsi energi listrik oleh paddle aerator adalah 7.10-8.65 kW (*use solar panel*) dan 6,89-9,28 kW (*non-solar panel*). Dari konversi secara kuantitatif didapatkan tingkat efisiensi listrik 0,10-1,24 watt apabila digunakan panel surya. Penggunaan panel surya juga dinilai lebih hemat biaya untuk operasional biaya dalam budidaya udang intensif. Kesimpulan dari hasil penelitian ini adalah penggunaan energi panel surya sebagai energi alternatif untuk paddle aerator dinilai sangat efektif dan murah dibandingkan jika menggunakan sumber listrik komersial. Selain itu, sistem ini juga mendukung untuk efektifitas penggunaan alat selama masa umur teknis berlangsung.

Kata kunci: listrik, energi, biaya, tambak udang.

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INTRODUCTION

Aquaculture is an important fisheries industry activity that supports global food security efforts (Fong *et al.,* 2024). One of the most widely developed aquaculture activities in tropical waters in America and Asia is shrimp farming (Alamandoz *et al.,* 2019; Zulbainarni *et al.,* 2023). Shrimp farming has been extensively developed in South America and Southeast Asia since the 1970s with various cultivation patterns (Le *et al.,* 2024). The most cultivated species are *Litopenaeus vannamei* and *Penaeus monodon* shrimp (Ariadi *et al.,* 2023; Islam *et al.,* 2024). The advancement of shrimp farming correlates with the progress in science and technology (Alamandoz *et al.,* 2019). leading to increased shrimp production over time.

The progressive development of the shrimp farming sector correlates with the use of aquaculture engineering tools. One crucial tool used in shrimp farming activities is the paddle aerator. In shrimp farming, paddle aerators function as devices for dissolved oxygen supply engineering (Wafi and Ariadi, 2022). Additionally, paddle aerators serve to create currents to maintain homogeneous water conditions in ponds (Ariadi *et al.,* 2020). In intensive shrimp ponds, approximately 1 HP paddle aerator is required to manage shrimp biomass waste of 500 kg (Ariadi *et al.,* 2019). The use of paddle aerators is vital for maintaining stable shrimp pond ecosystems (Ramesh *et al.,* 2024).

One HP paddle aerator consumes electrical energy ranging from 0.97 to 1.07 kW (Wafi and Ariadi, 2022), which can be costly in intensive pond systems with multiple cultivation modules. One approach to minimize electricity consumption in ponds is the use of solar panels as an alternative energy source (Zheng *et al.,* 2021). Solar panel energy is still underutilized in shrimp farming activities but is considered more effective and environmentally friendly due to its renewable nature (Shi *et al.,* 2023). Solar energy has several advantages, including environmental friendliness, better efficiency compared to electric energy, long-term benefits, and relatively low maintenance costs (Nasir *et al.,* 2023; Zhang *et al.,* 2024; Zhou *et al.,* 2024). In industrial applications, solar panels are used to enhance the efficiency of electric energy use, which accumulates high power usage (Rodrygo *et al.,* 2024). This aligns with the use of paddle aerators in intensive shrimp farming, which increases operational costs by 5.22% (Ariadi *et al.,* 2023). Solar panel energy conversion is seen as an alternative technology that can be developed in aquaculture industries.

Based on the background above, the purpose of this study was to determine the economic benefits and energy efficiency of using solar panel energy on paddle aerator machines in shrimp ponds. This is crucial to inform stakeholders about the extent of solar energy utilization effectiveness in paddle aerators for intensive shrimp farming activities.

RESEARCH METHODS

This research was conducted in shrimp ponds in Ulujami Village, Pemalang, in July 2024, with sampling locations at two different sites. The first pond location utilized solar panels as an energy source to operate the paddle aerator. The second pond location was a conventional pond using electric energy to power the paddle aerator. The research design employed was a causal *ex-post*

facto design with data collection through purposive sampling. Sampling was conducted on five shrimp ponds using solar panels and five shrimp ponds not using solar panels. The research variables in each shrimp pond were equated in detail to facilitate research control.

The ponds used for the study were uniform, each measuring 2,000 m² with a stocking density of 120 shrimp/m². Structured data sampling was conducted at the pond edges and center. Parameters measured in this study included oxygen production data by the paddle aerator, solar panel energy production data, electrical consumption by the paddle aerator, and water quality parameters (pH, dissolved oxygen, salinity, temperature, and clarity). To calculate the oxygen production rate by the paddle aerator in the ponds, the formula by Boyd (1998) was utilized:

$$OTR = SOTR \times \frac{Cs-Cp}{9.09} \times 1{,}024^{T-20} \times \alpha \quad (1)$$

$$SOTR = (K_L\alpha) \times (Csat) \times (V) \times (10^{-3}) \quad (2)$$

$$K_L\alpha = K_L\alpha_T \div 1{,}024^{T-20} \quad (3)$$

$$\alpha = KL\alpha \text{ pond water} \div KL\alpha \text{ natural water} \quad (4)$$

Where: OTR = oxygen transfer rate (mg O_2/hour); 1,024T-20 = temperature correction factor; SOTR = standard oxygen transfer rate (mg O_2/hour); Cs = salinity value in the pond (ppt); Cp = saturated oxygen concentration in the pond (mg O_2/L); Csat = pond saturation percentage (%O_2); KLα = gass transfer coefficient (mg O_2/hour); α = balance coefficient (mg O_2/hour); V = water volume (m^3); KLα coefficient gas transfer pond temperature (7.24 mg O_2/hour).

To measure the level of electrical energy consumption for operating the paddle aerator, the following formula is used (Roy *et al.,* 2015) :

$$P_T(kW) = TOD\ (kgO_2/h) / AE\ (kgO_2/kWh) \quad (5)$$

Where: PT (kW) = Total electrical energy required by the paddle aerator; TOD (kgO_2/h) = Total oxygen demand in the pond; AE (kgO_2/kWh) = Efficiency of the paddle aerator usage rate in the pond.

The level of electrical energy production by solar panels can be estimated using the following equation (Ansori *et al.,* 2023):

$$E = h.c / ƛ \quad (6)$$

$$P_{out} = V_{oc} \text{ X } I_{sc} \quad (7)$$

Where: E = absorbed solar cell capacity; h = Planck's constant value (6.62 x 10-34 J.s); c = speed of light captured by the panel (3.00x108 $m.s^{-1}$); P_{out} = generated solar cell energy (watts); V_{oc} = electrical voltage value on the solar panel (volts); I_{sc} = electrical current flow on the solar panel (amperes).

Next, the data were collected and grouped according to the research variables. Following the data grouping process, descriptive analysis was conducted using Microsoft Excel 2021.The financial feasibility analysis of the shrimp pond is based on a business profitability analysis, which includes profit analysis, R/C Ratio, rentability, Net Present Value (NPV), Profitability Index (PI), Internal Rate of Return (IRR), and Payback Period. This financial analysis is used to determine the level of business feasibility from a financial perspective in the long term. The financial analysis formulas used in this study refer to the formulas developed by Primyastanto (2016), as follows:

1. Cost Benefit

   Cost benefit refers to the result of revenue from production costs subtracted by the continuous production process costs within a business unit.

   $$\Pi = \text{Total Revenue (TR)} - \text{Total Cost (TC)}$$

2. R/C Ratio

   R/C ratio represents the conversion value of total revenue (TR) divided by the production process cost (TC) within a unit of productive business activity.

   $$\text{R/C Ratio} = \frac{TR}{TC}$$

3. Rentability

   Rentability is the percentage value of production profit (L) divided by capital investment (M) within a production business unit.

   $$\text{Rentability} = \frac{\text{Profit}}{\text{Investment}} \text{ x } 100\%$$

4. *Net Present Value*

   Net Present Value (NPV) is a benchmark value used to determine whether a business project is feasible or not for a unit of productive business operation. The NPV is calculated as the difference between gross revenue and expenditure, divided by the discount factor, resulting in the net value presented in a business investment.

   $$\text{NPV} = \sum_{i=1}^{n} \frac{(Bt-Ct)}{(1+i)t} K_0$$

5. Profitability Index

   Profitability Index is a percentage value that compares the present value of net income with the investment expenditure during the business period.

   $$\text{Profitability Index} = \frac{\sum \text{Present Value of Net Cash Flows}}{\sum \text{Present Value of Investment}} \text{ x } 100\%$$

6. Internal Rate Return

   Internal Rate of Return (IRR) is a method used to assess the rate of return based on the Net Present Value and the current interest rate. Internal Rate of Return is calculated using the formula:

   $$\text{IRR} = i' + \frac{NPV}{NPV'-NPV"} (i" - i')$$

7. Payback Periods

The Payback Period (PP) is a calculation technique used to determine the period required to recover an investment, either in constant or non-constant cash flows.

$$PP = \frac{\text{Investment}}{\text{Annual Net Cash Flow}} \text{ x 1 year}$$

RESULT AND DISCUSSION

Oxygen Production Rate by Paddle Aerator

The estimated oxygen production rate by the paddle aerator in intensive shrimp ponds can be described in Figure 1. The oxygen production rate by the paddle aerator in ponds utilizing solar panel technology ranged from 2.04±0.28 to 2.77±0.41 mgO_2/hour (Figure 1, left). In ponds without solar panel technology, the oxygen production rate by the paddle aerator ranged from 2.02±0.33 to 2.89±0.29 mgO_2/hour (Figure 1, right). Overall, there were no significant differences observed in the oxygen production rates between the two research pond locations.

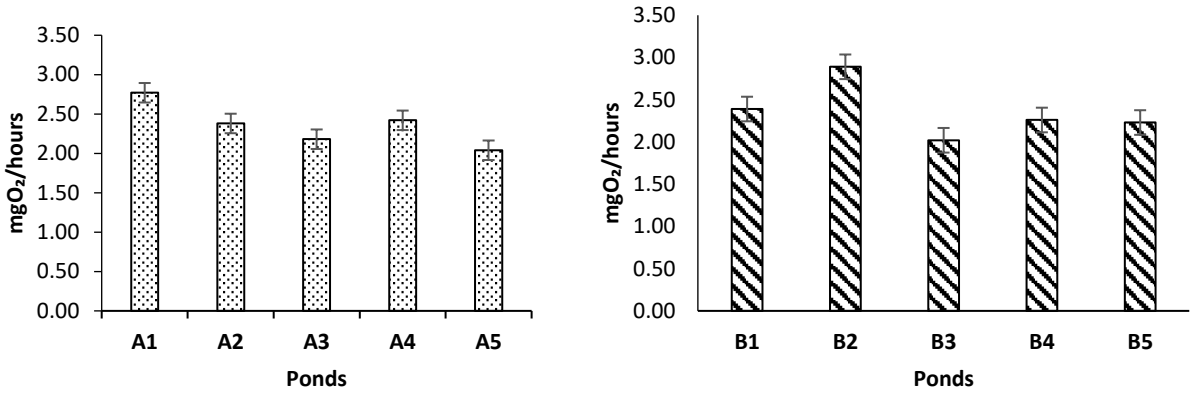

Figure 1. Dissolved Oxygen Production Rate by Paddle Aerator with Solar Panel Technology Applicant (Left) and Without Solar Panel Technology Applicant (Right)

Oxygen production rate by the paddle aerator is influenced by wind speed in the air and pond salinity levels (Jayanthi *et al.,* 2021). Low salinity levels and strong winds enhance the oxygen diffusion rate by the paddle aerator (Ariadi *et al.,* 2020). The oxygen solubility in ponds is also affected by water depth and temperature (Ariadi, 2024). Oxygen dissolves more easily at lower temperatures and in deeper pond depths (Linayati *et al.,* 2024).

Electric Energy Production by Solar Panels in Paddle Aerators

Solar panels are renewable energy sources being developed in aquaculture. The estimated electric energy production rate by solar cells in the paddle aerator at the research site is summarized in Figure 2. The electric energy production rate by solar panels in the paddle aerator ranges from 8.34±0.37 to 8.75±0.28 watts. Differences in energy production are possible due to variations in solar panel sunlight absorption capabilities.

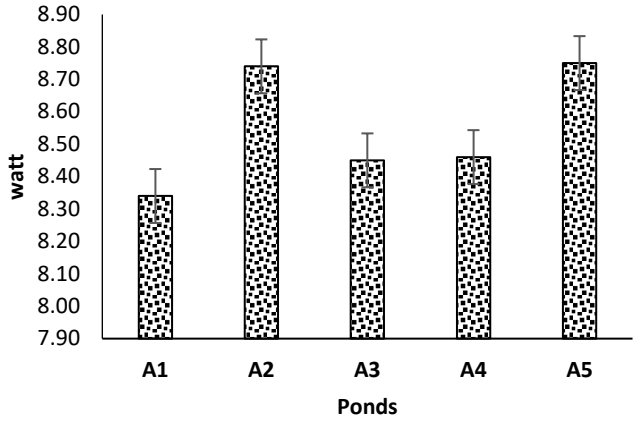

Figure 2. The Level of Electrical Energy Production by Solar Panels in Paddle Aerators

The positioning of solar panels is considered crucial in influencing the effectiveness of electrical energy conversion. Solar panels operate optimally in locations with environmental temperatures exceeding 25.00% intensity and constant sunlight exposure (Khwee, 2013). The use of solar panels on paddle aerators is expected to minimize the usage of electrical energy, which has a high consumption load (Ramesh *et al.,* 2024). In agricultural land irrigation activities, it can achieve a 23% efficiency in electrical energy usage for water irrigation (Marzouk *et al.,* 2024).

Electric Energy Consumption Rate by Paddle Aerators

The estimated electric energy consumption rate for operating paddle aerators in the research ponds is depicted in Figure 3. The electric energy consumption rate to operate the paddle aerator in Pond A ranges from 7.10±0.44 to 8.65±0.28 kW with oxygen production of 2.04±0.36 to 2.77±0.32 mgO_2/hour (left side of the figure). For Pond B, the electric energy consumption rate ranges from 6.89±0.30 to 9.28±0.18 kW with oxygen production of 2.02±0.25 to 2.89±0.35 mgO_2/hour (right side of the figure). Overall, the oxygen production rate by the paddle aerator influences the amount of electrical energy consumed for operationalizing the paddle aerator system.

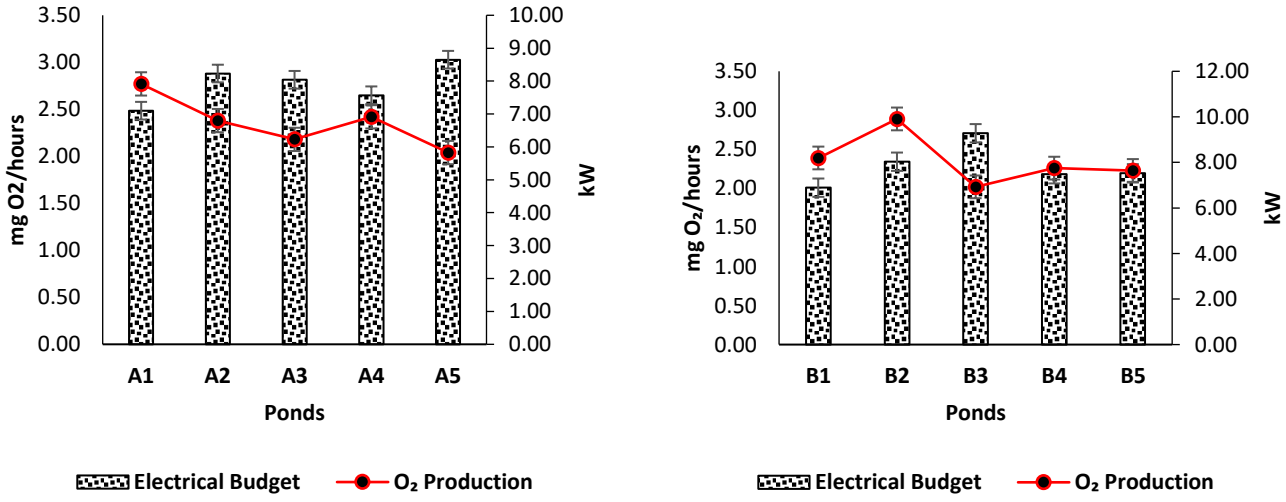

Figure 3. Level of Electric Energy Consumption by Paddle Aerators with Solar Panel Technology Applicant (Left) and Without Solar Panel Technology (Right)

The electrical energy required by the paddle aerator heavily depends on the specifications of the paddle aerator, the frequency of use, pond area, and the influence of abiotic factors (Moulick *et al.,* 2002). The longer the operational time of the paddle aerator, the greater the demand for electrical energy needed (Ariadi, 2020). The electrical energy consumption by the paddle aerator is dynamically calculated according to the dynamics of oxygen production generated by the paddle aerator (Ariadi *et al.,* 2021). Air pressure intensity and wind distribution patterns also affect the effectiveness of the paddle aerator's performance (Kumaran *et al.,* 2017).

Level of Solar Panel Energy Usage Conversion

The utilization rate of solar panel energy can be seen in Table 1. Based on mathematical analysis regarding solar energy usage efficiency, an efficiency rate ranging from 0.10 to 1.24 watts was obtained. This indicates that the use of solar panels is highly recommended as an alternative to electrical energy. The energy efficiency of solar panels can be further developed for the energy consumption of other devices in the pond.

Table 1. The Energy Efficiency of Resulting from Solar Panel Production by Paddle Aerators

Ponds	O_2 Production by Paddle Aerator (mg/l)	Electrical Budget (watt)	Solar Energy Production (watt)	Efficiency (watt)
A1	2.77	7.10	8.34	**1.24**
A2	2.38	8.23	8.74	**0.51**
A3	2.18	8.04	8.45	**0.41**
A4	2.42	7.57	8.46	**0.89**
A5	2.04	8.65	8.75	**0.10**

Solar panel energy is an alternative form of renewable energy that is more environmentally friendly (Erdemir and Dincer, 2024). In shrimp farming activities, the efficiency of energy usage affects the technical lifespan of equipment (Villar-Navarro *et al.,* 2021). Efficient energy consumption rates also impact the reduction of operational costs in farming. The consumption of electrical energy in aquaculture industries accounts for 5.22% of total production costs, necessitating innovations for efficiency (Ariadi *et al.,* 2023).

Financial Analysis of Intensive Shrimp Farming Using Solar Panel Technology

The financial feasibility analysis of using solar panels is based on the presence of fixed capital assets and working capital within the operational shrimp farming cycle. The details of the fixed capital and working capital components in the shrimp farming unit analyzed in this study are presented in Table 2. These capital values will then be used as variables to calculate the financial feasibility of the business.

Table 2. Fixed Capital and Working Capital in Vaname Shrimp (*L. vannamei*) Farming Using Solar Panel Technology

Component	Amount	Price ($)*	Technical Age	Total ($) (Non-Solar Panel)*	Total ($) (Make it Solar Panel)*
Investment Cost					
1. HDPE pond 3.000 m^2	3	7,576	10	17,273	17,273
2. Paddle wheel aerator	88	152	10	13,333	13,333
3. Water pump	6	1,939	10	11,636	11,636
4. Pand long pipe	21	9	10	191	191
5. Shrimp net	14	2	2	30	30
6. Motorcycle	1	909	10	909	909
7. Harvest scale	1	394	10	394	394
8. Laboartory facility (1 set)	1	727	10	727	727
9. Crustacide Protecting Device	7	8	1	53	53
10. Bird Security Device	7	8	1	53	53
11. Genset facility	2	4,242	15	8,485	8,485
12. Boreholes facilty	5	121	0	606	606
13. Solar cell panel technology	88	106	10	-	9,333
TOTAL INVESTMENT COST				**53,690**	**63,023**
Variable Investment Cost					
I. Fixed Cost					
1. Depreciation cost				2,113	2,113
2. Maintenance cost				1,275	1,275
TOTAL FIXED COST				**3,389**	**3,389**
II. Variable Cost					
1. Fry shrimp	1620000	0.014		4,704	4,704
2. Shrimp feed	24.341	0.882		17,702	17,702
3. Solar energy	158	46.17		107	107
4. Aquaculture facility	447	8		3,379	3,379
5. Labor	9	253		2,275	2,275
6. Harvest cost				205	205
7. Electricity cost				6,665	6,665
8. Healthcare facility	10	0.50		12	12
TOTAL VARIABLE COST				**35,049**	**35,049**
TOTAL VARIABLE INVESTMENT				***38,437***	***38,437***

1$ amount its IDR 17,000

Investment Costs of Using Solar Panels

The investment costs of using solar panels in shrimp ponds can be seen in Table 3. The investment cost of using a 1 HP paddle aerator is $499 with a technical lifespan of 5 years. For the investment cost of using a 1 HP paddle aerator with solar panels, it is $551. This means there is a difference of $52/1 HP for implementing solar panels in shrimp ponds, or if converted to solar panel usage costs, it amounts to $0.03/day or IDR 510/day. This value is economically viable when analyzed based on the energy output produced.

Table 3. Investment Costs for Using Solar Panel Technology on Paddle Aerators (Pond A) and Paddle Aerators Without Solar Panel Technology (Pond B)

Indicators	Pond A ($)	Pond B ($)
Gear	108	108
Machine	274	274
Wheel	65	65
Cable	20	20
Float	32	32
Solar panel	52	0
Total investment	**551**	**499**

1$ amount its IDR 17,000

The economic value of using solar panels for shrimp farming activities is highly advantageous. This investment is quite cost-effective compared to the daily electricity cost of $0.15 for 1 HP paddle aerator (Chen *et al.,* 2024). This investment value spans a long period, ensuring equipment durability and sustained usage. Through the use of solar panel energy, farmers can more easily participate in crucial electricity needs (Nunes *et al.,* 2022; Wafi and Ariadi, 2024).

Financial Analysis of Solar Panel Usage on Paddle Aerator

Based on the financial analysis, the use of solar panels on this paddle aerator can be very beneficial. This can be seen from the profit efficiency value of $52/1 HP or IDR 884,000/1 HP and the Net Present Value of $128 (Table 4.). This value was obtained from the conversion of shrimp harvest results of 22,754 kg/farm in 105 days of cultivation period. The productive results of the harvest are superior compared to ponds without solar panels which produce a shrimp harvest biomass of 20,958 kg/farm. This means that the use of solar panel equipment is highly recommended for aquaculture activities. The payback period also indicates a figure that is greater than the technical lifespan of the equipment (Table 4.). The return on investment for the equipment will be recovered before the solar panels require maintenance. The profitability and profitability index values are also quite similar to the feasibility assessment results of shrimp farming conducted by Muqsith *et al.,* (2021).

Table 4. Business Financial Analysis Results of Using Solar Panel Energy on Paddle Aerators

No.	Analysis	Value	Results	Criteria
1.	Cost Benefit ($)	52	Cost Benefit > Cost Production	Feasible
2.	R/C Ratio	1.15	R/C > 1	Feasible
3.	Rentability (%)	20%	R > i	Feasible
4.	Net Present Value ($)	128	NPV > 0	Feasible
5.	Profitability Index (%)	18	PI > 1	Feasible
6.	Internal Rate Return (%)	15	IRR > discount factor (10%)	Feasible
7.	Payback Periods (year)	3	PP > technical age	Feasible

The financial feasibility analysis results can serve as an economic reference for the implementation of solar panel technology on paddle aerators (Ariadi *et al.,* 2019). In addition to providing technical benefits, this equipment also offers economic advantages. If further developed, the use of solar energy could be integrated into shrimp pond systems. The financial value of the business represents the feasibility level of whether the technical unit of the business is viable (Wafi *et al.,* 2021). This applies to justifying the use of technology or a specific system within productive business activities (Ariadi *et al.,* 2021; Ramadhani *et al.,* 2024).

Pond Water Quality

The water quality parameters at the research pond locations are presented in Table 5. Overall, there were no significant differences observed in water quality parameters between ponds using solar panels and those that do not. Water quality parameters at the pond locations remain in good condition, with dissolved oxygen concentrations >4.00 mg/L, indicating sufficient oxygen availability in the pond ecosystem (Madusari *et al.,* 2024).

Table 5. Water Quality Profile at The Research Pond Location

Ponds	Parameters				
	pH	Salinity (gr/L)	Dissolved Oxygen (mg/L)	Temperature (^{0}C)	Brightness (cm)
A1	7.8±1.02	25±2.03	4.76±1.87	28.50±1.05	30±2.36
A2	7.7±1.57	25±2.18	4.82±1.93	28.25±1.62	30±2.11
A3	7.8±1.73	25±1.97	4.62±2.05	28.50±1.29	30±2.04
A4	7.8±2.02	25±2.01	5.13±2.01	28.25±1.60	25±2.42
A5	7.7±1.85	25±1.99	5.05±1.98	28.25±1.73	25±2.33
B1	7.8±1.84	27±1.89	4.83±1.78	29.00±1.02	30±2.18
B2	7.9±1.98	27±1.93	4.69±1.84	28.50±1.06	30±2.21
B3	7.9±2.07	27±1.99	5.10±1.53	28.50±1.41	30±2.07
B4	7.8±2.11	27±2.02	5.05±1.69	28.50±1.92	30±2.51
B5	7.7±2.03	27±2.01	5.12±1.70	28.25±1.61	30±2.11

Water quality parameters are crucial indicators for assessing the environmental conditions of pond water (Ariadi *et al.,* 2023). Good water quality parameters will impact the pond ecosystem balance and the condition of cultivated shrimp (Mardiana *et al.,* 2024). The dynamics of water quality in pond ecosystems are influenced by biotic and abiotic factors (Soeprapto *et al.,* 2023). The paddle aerator is one of the aquaculture engineering tools used to stabilize water quality conditions in ponds. Efforts are made to maintain water quality parameters in pond ecosystems stable and within the standards required for aquaculture activities (Mardiana *et al.,* 2024).

Overall, the oxygen production rate by the paddle aerator can provide sufficient dissolved oxygen production capacity in pond ecosystems. The quantitative oxygen production rate by the paddle aerator affects the amount of electrical energy consumption needed for the operational system of the paddle aerator (Nasir *et al.,* 2023). To enhance electrical energy usage efficiency in ponds, innovation in using alternative energy such as solar panels can be implemented. This research shows that electrical energy production by solar panels is capable of meeting the energy requirements for operating the paddle aerator. Additionally, the estimated use of solar panel energy is considered cost-effective for application in aquaculture industries (Ariadi, 2024).

CONCLUSION AND SUGGESTION

The use of solar panel energy as an alternative energy source for paddle aerators in shrimp ponds is considered highly effective and cost-efficient compared to using electricity as the main energy source for operating paddle aerators. Overall, the electricity usage in the operation of paddle aerators will affect the quantification of electrical energy needs, thus requiring a cheap and sustainable electricity source such as the use of solar panel technology.

For future research, a study on the effectiveness of converting energy produced by solar panels into profit should be conducted in detail. Additionally, for the development of future research it is necessary to examine the effectiveness of profit efficiency in intensive shrimp farming activities when applying the concept of green technology in its operational cycle.

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