Application of capacitor banks to enhance energy efficiency in aeration systems for fisheries cultivation

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ABSTRACT

Electrical energy consumption in aeration systems represents a major component of operational costs, primarily due to the low power factor of inductive equipment such as blowers. This study evaluates the effectiveness of capacitor banks in improving energy efficiency and their economic feasibility in small- to medium-scale aquaculture aeration systems. Over 90 days, measurements were conducted on energy consumption, current, voltage, and water quality parameters, including dissolved oxygen (DO) and pH in two systems: without and with capacitor banks. The results showed that the use of capacitor banks reduced daily energy consumption from 15.01 ± 0.45 kWh to 13.13 ± 0.45 kWh (savings of 12.51%), equivalent to approximately 56.4 kWh per month or 686.2 kWh per year. The average current decreased from 2.44 A to 1.88 A, while voltage, DO (6.50–6.64 mg/L), and pH (7.20–7.25) remained stable within the optimal range. Economic analysis revealed that an initial investment of IDR 1,500,000 has a payback period of 18 months, a net present value (NPV) of IDR 2.15–2.33 million (at 8% discount rate), and an internal rate of return (IRR) exceeding 50% per year. These findings demonstrate that the application of capacitor banks not only enhances energy efficiency and reduces power losses but is also highly feasible and profitable for practical adoption in aquaculture operations.

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1. INTRODUCTION

Intensive freshwater fish farming is increasingly developing as an effort to meet the increasing needs of the community for animal protein [1]–[3]. One of the widely used farming systems is the biofloc system, which relies on water quality management and the use of microorganisms to increase feed efficiency and maintain fish health [4], [5]. This system is considered environmentally friendly because it can minimize waste and reduce the need for water changes. In the biofloc system, aeration is an important component that functions to maintain dissolved oxygen (DO) levels in the water so that environmental conditions remain optimal for fish growth and microorganism activity [6]–[8].

However, the use of aerators and other supporting equipment requires quite large electricity consumption, which directly impacts the increase in operational costs, especially for small and medium-scale business units [9]–[11]. One of the main challenges is the low energy efficiency due to the use of inductive equipment, such as blowers and pumps, that produce a low power factor. The low power factor causes the electric current to flow beyond actual needs, thereby increasing the energy burden and costs without providing significant additional system performance [12]–[16].

A potential technical solution to increase electrical energy efficiency is to install a capacitor bank, which functions to improve the power factor, reduce reactive power losses, and reduce overall energy consumption [17]–[22]. Although this technology has been widely applied in the industrial sector, its application in fisheries cultivation systems, especially biofloc, is still limited and has not been comprehensively documented, both in terms of technical and economic aspects.

This research is relevant in the context of developing a blue economy, namely a sustainable development approach that integrates economic growth with the preservation of marine and inland water ecosystems [23], [24]. Within the blue economy framework, energy efficiency and carbon emission reduction are key strategies for improving productivity in the fisheries sector in a sustainable manner. However, despite the widespread application of electrical aeration systems in aquaculture, studies specifically addressing the utilization of capacitor banks to improve energy efficiency in biofloc-based cultivation systems remain limited and underexplored. Therefore, by analyzing the energy efficiency and economic feasibility of capacitor bank application in a biofloc aeration system, this research is expected to fill an existing knowledge gap and contribute scientific evidence to support more energy-efficient, low-cost, environmentally friendly, and resource-oriented aquaculture practices [25]–[30].

Through a comparative experimental approach between conventional aeration systems and systems equipped with capacitor banks, this study aims to measure the differences in electrical energy consumption, the quality of the cultivation environment (DO and pH), as well as the potential for saving electricity costs and the payback period. The results of this study are expected to be concrete technical and economic recommendations for freshwater fish farmers, while supporting the transformation of the fisheries industry towards a system that is in line with the principles of a blue economy.

2. METHOD

This study aims to evaluate the efficiency and economic feasibility of using capacitor banks to improve power factor and reduce daily electrical energy consumption in freshwater fish farming units (Figure 1). The research was conducted over a period of three consecutive months in 12 aquaculture ponds, each with a capacity of 3.14 m³ (2 meters in diameter and 1.04 meters in height). Each pond was equipped with an aeration and water circulation system operating continuously for 24 hours to ensure uniform oxygen distribution through 33 air outlets. The main equipment used in each pond included two aerators (blowers) with a power rating of 200 Watts each, one water circulation pump of 250 Watts, and two lamps of 20 Watts each, resulting in a total electrical load of approximately 690 Watts per unit (Table 1). To improve power efficiency, a 25 microfarad (μF) capacitor bank was installed in parallel with the main electrical panel of each pond. The capacitor bank was selected based on calculations of the system's reactive power needs, aiming to correct the lagging power factor caused by the inductive nature of the electric motors. Daily energy consumption was measured using a digital kilowatt-hour (kWh) meter, while current and voltage were monitored with a clamp meter. The research site was chosen based on the presence of a stable aeration and water circulation system, along with significant electricity usage for aquaculture operations.

This study used a comparative experimental method, with two treatments tested separately but under the same environmental and operational conditions. The first treatment was a pond system without the use of capacitor banks (as a control), and the second treatment was a pond system with the use of capacitor banks. Each system was run fully for a certain period, and measurements were taken daily to record electrical energy consumption (in kWh), current and voltage (Amperes and Volts), and power factor (cos φ) to see how much improvement in power quality was achieved after the installation of capacitors. In addition, a mitigation analysis was also conducted to address any harmonics that might occur in fish farming activities. The comparative analysis used is the unpaired T-test. This is done on the Kolmogorov-Smirnov normality test; the score obtained is more than 0.05, so that the data is normally distributed [23], [24].

Energy consumption data is converted into total daily electricity costs using the applicable non-subsidized household or small industry electricity rates. In addition, the initial investment costs for installing the capacitor are also recorded, including the price of the capacitor bank device, additional panels (if any), cables, and installation costs. Furthermore, the data is analyzed quantitatively to calculate energy efficiency and potential savings in electricity costs per month and per year.

Economic analysis was conducted using several approaches, including payback period (PP) analysis to determine the time required for electricity savings to cover the initial investment costs and include the capacitor's usage period and maintenance. In addition, a net present value (NPV) analysis was conducted to see the present value of future cost savings, as well as internal rate of return (IRR) calculations to evaluate the feasibility of the investment by comparing it to an assumed discount rate of 10% per year [24]. The system is declared economically feasible if it produces a positive NPV, an IRR greater than the discount rate, and has a payback period of less than three years. With this method, the study aims to provide a technical and financial overview of the application of capacitor banks as a relevant and sustainable energy efficiency strategy in small to medium-scale fish farming businesses.

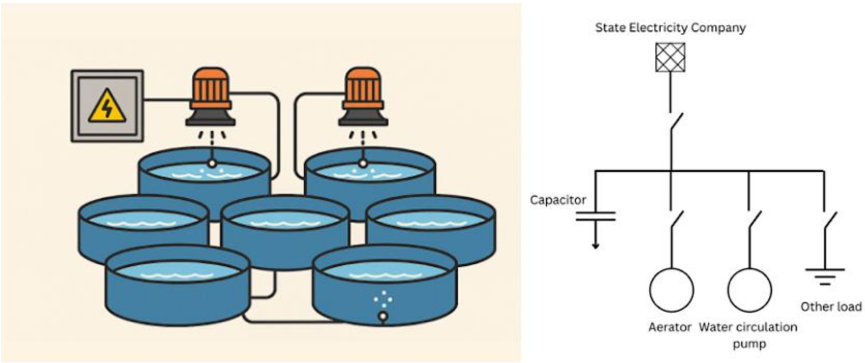

Figure 1. Electrical and aeration systems in fish farming ponds with capacitor bank installation

Table 1. Electrical system specifications

Electrical component	Power per unit (W)	Number of units	Operating time per day (hours)	Energy per day (kWh)
Aerator (blower)	200	2	24	12.00
Water circulation pump	250	1	24	6.00
Pond lights	20	2	12	0.48
Total				16.08

3. RESULTS AND DISCUSSION

3.1. The effect of using capacitor banks on energy efficiency and water quality

Based on the results of measurements carried out for 90 days, data were obtained regarding energy consumption, voltage, current, dissolved oxygen (DO) levels, and pH in the aeration system in fishery cultivation activities. Energy use was recorded at 15.01 ± 0.45 kWh in the system without a capacitor, and decreased to 13.13 ± 0.45 kWh in the system using a capacitor bank (Figure 2). The system voltage showed a value of 219.86 ± 1.01 V without a capacitor and 219.95 ± 0.92 V with a capacitor, which means there is no significant difference in practice (Figure 3). The electric current was recorded at 2.44 ± 0.05 A in the system without a capacitor, and decreased to 1.88 ± 0.04 A when the capacitor was used, showing how efficient the use of current is (Figure 4). For air quality parameters, DO levels were at 6.50 ± 0.12 mg/L in the system without a capacitor, and slightly increased to 6.64 ± 0.12 mg/L in the system with a capacitor (Figure 5). Meanwhile, the pH values were recorded at 7.20 ± 0.11 and 7.25 ± 0.11, respectively, both within the optimal range for cultivation activities (Figure 6).

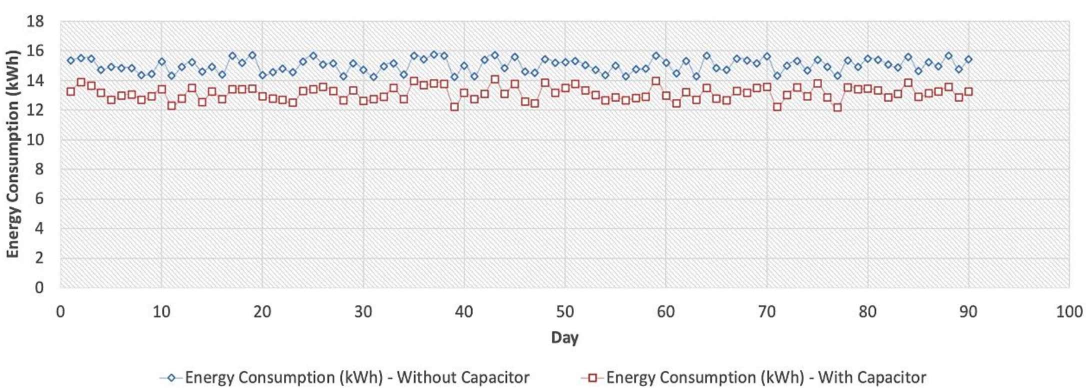

Figure 2. Daily energy consumption comparison of aeration systems

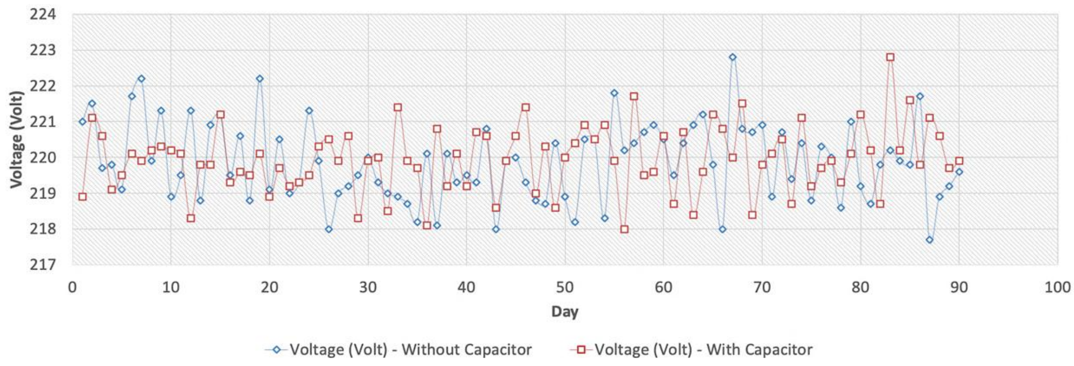

Figure 3. Daily voltage comparison of aeration systems

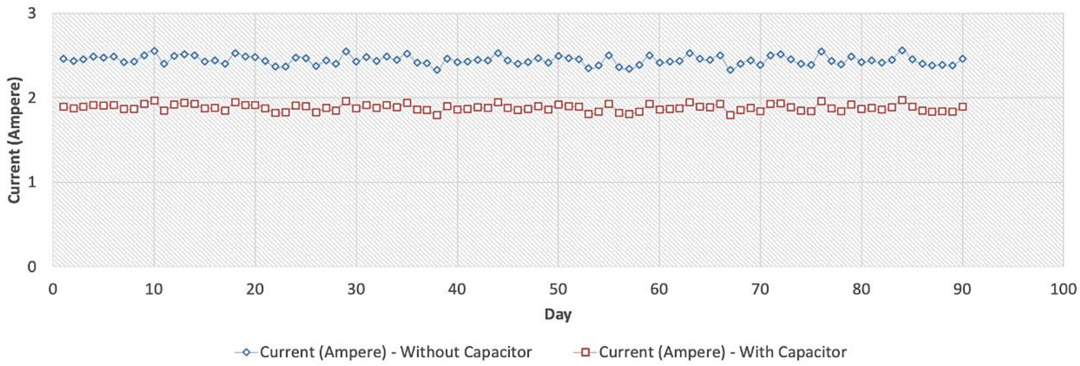

Figure 4. Daily ampere comparison of aeration systems

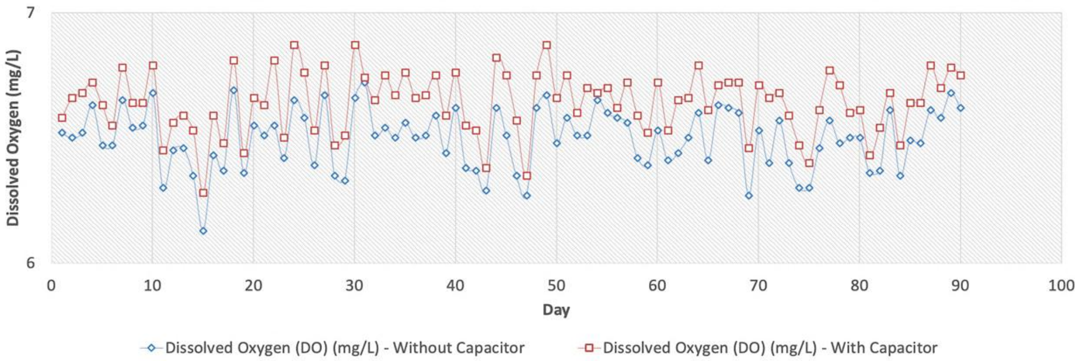

Figure 5. Daily DO comparison of aeration systems

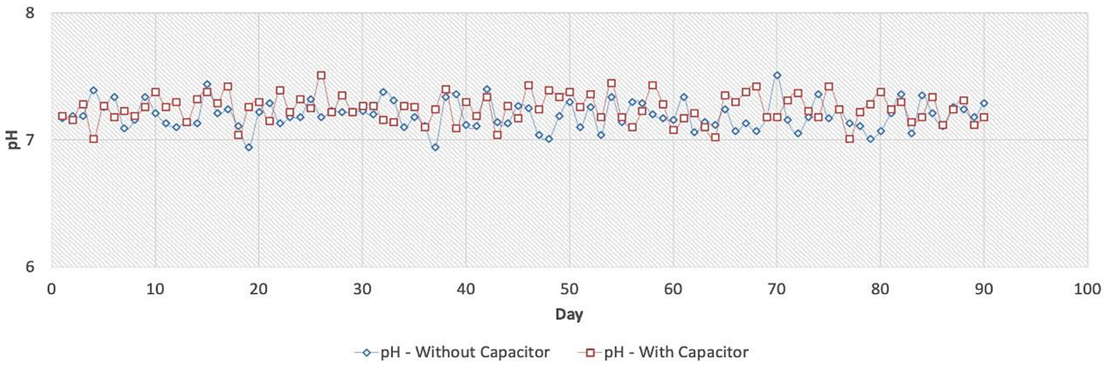

Figure 6. Daily pH comparison of aeration systems

Based on the results shown in Table 2, the installation of capacitor banks significantly increased the overall efficiency of the aeration system. Energy consumption decreased from 15.01 ± 0.45 kWh to 13.13 ± 0.45 kWh with a mean difference of 1.88 kWh ($p < 0.001$), in line with the decrease in electric current from 2.44 ± 0.05 A to 1.88 ± 0.04 A ($p < 0.001$), which is related to an increase in power factor from ±0.75 to ±0.87. Voltage did not show a significant difference between treatments ($p = 0.554$), so the increase in efficiency was mainly due to a decrease in current and power losses. Air quality parameters also showed statistically significant differences, with DO increasing from 6.50 ± 0.12 to 6.64 ± 0.12 mg/L ($p < 0.001$) and pH from 7.20 ± 0.11 to 7.25 ± 0.11 ($p < 0.001$), but all these values remained within the optimal range for the biofloc system, thus the application of capacitor banks was proven to increase energy efficiency without compromising operational stability or air quality.

Under varying load conditions, the system with a capacitor bank demonstrated more stable performance than the system without power factor correction. The capacitors maintained a high power factor when the load decreased, thus controlling current and reducing power losses. While under increased load, the capacitors dampened current surges and voltage fluctuations, allowing the equipment to operate more optimally. This demonstrates that power factor correction is effective not only under nominal conditions but also under dynamic load conditions commonly encountered in the field.

Besides conventional capacitor banks, there are other power electronics solutions that can improve power quality, such as static VAR compensator (SVC), active power filter (APF), and static synchronous compensator (STATCOM). These technologies offer more adaptive reactive power compensation, harmonic reduction, and faster response to non-linear load variations. However, their implementation in the aquaculture community faces challenges such as high initial investment costs, technical complexity, limited spare parts, and relatively small business scale. Therefore, capacitor banks remain the most practical and economical option for small- to medium-scale farmers, while advanced power electronics solutions are more suitable for large-scale industries or integration with automation systems.

Pond equipment such as aerators (blowers), water circulation pumps, pond lights, and capacitor banks generally operate with linear load characteristics, so the risk of harmonic distortion is relatively low. However, potential distortion can arise if some components use power electronics-based technology, such as inverters in high-efficiency pumps or blowers, and electronic ballasts in LED lamps. The current generated by these devices is non-sinusoidal and can trigger harmonic distortion, resulting in increased power losses, decreased power factor, and disruptions to capacitor bank performance, such as overheating or harmonic resonance. If harmonic distortion is not controlled, its impact can extend to reducing the efficiency of the electrical system and shortening the equipment's lifespan. To address this, several measures can be implemented, such as the use of passive harmonic filters (LC filters or detuned reactors) to suppress certain harmonic frequencies, as well as active harmonic filters that can dynamically balance the distortion. Furthermore, selecting capacitor banks equipped with harmonic protection, proper grounding, and cable layout, and regular power quality monitoring are important strategies for maintaining the stability and efficiency of the electrical system in aquaculture ponds.

From a sustainability perspective, implementing capacitor banks is a strategic step to reduce energy consumption, save operational costs, extend equipment lifespan, and reduce the carbon footprint of fossil-based energy. To maximize its benefits, an implementation roadmap is needed that includes load and harmonic analysis, capacity and protection design, phased system installation with phased switching, integration of sensor-based automatic controls, and ongoing evaluation. With this approach, the fisheries sector can not only improve energy efficiency but also has the potential to become a model for implementing sustainable energy technologies at the community level. Furthermore, the scalability of this technology allows for expansion into other sectors such as agriculture and wastewater treatment, extending its impact beyond technical improvements to support the broader sustainable development agenda.

Table 2. Results of the unpaired T-test for the whole system

Variable	Group	n	Mean ± s.d.	95% confidence interval	p-value
Energy consumption (kWh)	Without capacitor	90	15.01 ± 0.45	1.88 (1.75 – 2.01)	< 0.001
	With capacitor	90	13.13 ± 0.45		
Voltage (V)	Without capacitor	90	219.86 ± 1.01	-0.09 (-0.38 – 0.21)	0.554
	With capacitor	90	219.95 ± 0.92		
Current (A)	Without capacitor	90	2.44 ± 0.05	0.56 (0.55 – 0.58)	< 0.001
	With capacitor	90	1.88 ± 0.04		
Dissolved oxygen (mg/L)	Without capacitor	90	6.50 ± 0.12	-0.14 (-0.18 – -0.11)	< 0.001
	With capacitor	90	6.64 ± 0.12		
pH	Without capacitor	90	7.20 ± 0.11	-0.05 (-0.09 – -0.02)	< 0.001
	With capacitor	90	7.25 ± 0.11		

3.2. Economic feasibility analysis of capacitor bank application in aquaculture aeration systems

The application of capacitor banks in aeration systems significantly reduces electricity consumption and operating costs. Over a 90-day measurement period, average daily energy use decreased from 15.01 ± 0.45 kWh in the system without capacitors to 13.13 ± 0.45 kWh with capacitors, representing a saving of 1.88 kWh per day or approximately 686.2 kWh per year, which corresponds to cost savings of about IDR 81,385 per month or IDR 990,187 per year at an electricity tariff of IDR 1,443 per kWh. Statistical analysis using a t-test confirmed significant differences between the two systems ($p < 0.001$) in energy consumption and current, while changes in dissolved oxygen and pH, although statistically significant, remained within optimal ranges for biofloc systems and did not adversely affect water quality. From an economic standpoint, the initial investment of IDR 1,500,000 for a capacitor bank unit can be recovered within approximately 18 months, with five-year financial projections showing positive NPV values of IDR 2.15–2.33 million at an 8% discount rate and an IRR exceeding 50% per year, indicating that the application of capacitor banks is both economically feasible and highly profitable despite routine maintenance costs and an estimated economic lifespan of seven years.

From a technical standpoint, capacitor banks also improve operational stability under varying load conditions. When loads decrease, capacitors help maintain a high-power factor, keeping currents controlled and minimizing power losses. Conversely, when loads increase, capacitors dampen current surges and reduce voltage fluctuations, ensuring equipment operates under optimal conditions. Thus, power factor correction through capacitor banks is effective not only under nominal loads but also under dynamic load conditions commonly encountered in practice. To maintain optimal performance, regular maintenance such as visual inspection, terminal cleaning, and periodic capacitance measurement is recommended, with relatively low maintenance costs of about IDR 30,000–75,000 per year.

The application of capacitor banks in aquaculture aeration systems is economically advantageous due to their ability to improve power factor and reduce energy costs. During operation, aeration loads frequently fluctuate, resulting in dynamic variations in reactive power demand. Installed capacitor banks adequately respond to these fluctuations, maintaining a stable power factor and reducing current consumption, which directly lowers electricity costs.

However, capacitors can age over time due to thermal stress and dielectric degradation, gradually reducing their compensating capacity. Therefore, regular inspection and maintenance, such as capacitance testing and temperature monitoring, are essential to maintain performance. Although maintenance costs are small, the overall payback period remains short because the energy savings outweigh the initial investment and operating costs. Therefore, installing capacitor banks is a technically sound and economically feasible solution for small- to medium-scale aquaculture aeration systems.

Overall, the use of capacitor banks in biofloc aeration systems has been shown to improve energy efficiency, reduce operational costs, and maintain water quality stability, while offering strong economic feasibility with a short payback period and significant long-term benefits. With proper maintenance management and adequate risk mitigation, this technology is highly recommended for adoption by small- to medium-scale fish farmers, both as an energy-saving measure and as a step toward more sustainable aquaculture practices.

4. CONCLUSION

This study demonstrates that the application of capacitor banks in aeration systems provides clear benefits in terms of energy efficiency and economic feasibility. Over 90 days of observation, the system equipped with capacitor banks achieved an average reduction in energy consumption of 2.45 kWh per day (12.51%), equivalent to savings of approximately 56.4 kWh per month or 686.2 kWh annually. In addition, the electric current decreased from 2.44 A to 1.88 A without causing significant changes in voltage, while dissolved oxygen and pH remained within the optimal range for aquaculture operations. From an economic standpoint, an investment of IDR 1,500,000 for a capacitor bank unit can be returned within 18 months and generates a positive NPV of IDR 2.15–2.33 million over five years at an 8% discount rate. The internal rate of return (IRR) exceeds 50% annually, well above bank interest and inflation rates. These findings confirm that capacitor bank installation not only reduces energy consumption and enhances equipment performance but is also highly profitable, making it a recommended technology fsor small- to medium-scale aquaculture aeration systems.

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This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
I Made Aditya Nugraha	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
I Gusti Made Ngurah Desnanjaya		✓	✓		✓	✓		✓	✓	✓	✓	✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to animal use has been complied with all the relevant national regulations and institutional policies for the care and use of animals.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [IMAN]. The data, which contains information that could compromise the privacy of research participants, is not publicly available due to certain restrictions.

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