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The Preliminary Study of Electrigens Potential from Wastewater as The Manifestation Of "Khalifah Fil Tadbir" Conception

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ABSTRAK

Penelitian ini mengungkap bahwa limbah budidaya udang super intensif Punaga memiliki potensi sebagai sumber energi listrik melalui proses bioelektrogenik berbasis bakteri potensial indegenous dari limbah tersebut. Hasil penelitian menunjukkan bahwa empat jenis bakteri potensial yang diisolasi dari limbah budidaya udang super intensif, masing-masing memiliki kemampuan untuk menghasilkan power density rata-rata yang cukup signifikan. Isolat bakteri D (Bacillus sp) menunjukkan potensi elektrogenik tertinggi dengan rata-rata power density sebesar 38.55±0.87 mW/m2, diikuti oleh isolat bakteri B (Pseudomonas sp) dengan rata-rata power density sebesar 34.72±2.80 mW/m2, isolat bakteri C (Bacillus sp) dengan rata-rata power density sebesar 29.90±5.26 mW/m2, dan isolat bakteri A (Bacillus sp) dengan rata-rata power density sebesar 25.90±1.69 mW/m2. Penelitian ini menunjukkan bahwa limbah budidaya udang super intensif Punaga dapat dimanfaatkan sebagai sumber energi listrik melalui proses bioelektrogenik menggunakan bakteri potensial tertentu, seperti isolat bakteri Bacillus sp dan Pseudomonas sp. Selain itu, diperlukan penelitian lebih lanjut untuk mengoptimalkan potensi elektrogenik dari limbah budidaya udang super intensif dan meningkatkan efisiensi dan kinerja MFC yang digunakan dalam proses elektrogenik. Pengembangan teknologi pengolahan limbah menjadi sumber energi listrik melalui proses elektrogenik dari limbah budidaya udang super intensif dapat memberikan kontribusi yang signifikan dalam upaya mengatasi permasalahan energi dan lingkungan global.

Kata Kunci: *Bacillus*; Elektrigenik; MFC; *Pseudomonas*; Punaga

ABSTRACT

This study reveals that the super-intensive shrimp farming waste from Punaga can be used as a source of electricity through a bio-electrogenic process based on indigenous potential bacteria from the waste. The results show that four types of potential bacteria isolated from the super-intensive shrimp farming waste can each produce a significant average power density. Bacteria isolate D (Bacillus sp) showed the highest electrogenic potential with an average power density of 38.55±0.87 mW/m^2, followed by bacteria isolate B (Pseudomonas sp) with an average power density of 34.72±2.80 mW/m^2, bacteria isolate C (Bacillus sp) with an average power density of 29.90±5.26 mW/m^2, and bacteria isolate A (Bacillus sp) with an average power density of 25.90±1.69 mW/m^2. This study shows that the super-intensive shrimp farming waste from Punaga can be utilized as a source of electricity through a bio-electrogenic process using certain potential bacteria, such as Bacillus sp and Pseudomonas sp isolates. The development of waste treatment technology as a source of electricity through the bio-electrogenic process can provide a significant contribution to addressing global energy and environmental issues. This can be considered an implementation of the concept of "khalifah fil tadbir", in which humans act as stewards of the earth, responsible for using natural resources wisely and being accountable for the resulting environmental impacts.

Keywords: *Bacillus*; Electrigens; MFC; *Pseudomonas*; Punaga

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INTRODUCTION

Processing super-intensive shrimp culture waste into electricity is one of the sustainable solutions to address both environmental pollution and the growing need for renewable energy. The increasing scale of shrimp farming operations has led to a significant rise in organic waste, which, if not managed properly, can lead to eutrophication and degradation of aquatic ecosystems (Syah et al., 2017; Suwoyo et al., 2015), a Studies by (Balan, 2018) a highlight that shrimp pond sediments contain high levels of organic matter, including proteins, carbohydrates, and lipids, which serve as excellent substrates for microbial fuel cells (MFCs).

Early research by Dan et al. (2012) demonstrated that shrimp pond sediment could generate a peak current of 161.99 mA/m² and a voltage of 0.39 V using MFC technology. This finding underscores the potential of shrimp farming waste to be transformed into renewable electricity through the activity of electrogenic bacteria. Additionally, Ngurah et al. (2014) reported that sediment microbial fuel cells (SMFCs) using aquaculture waste as a substrate successfully reduced Chemical Oxygen Demand (COD) by 60%, improving water quality while generating electricity.

Processing super-intensively shrimp culture waste into electricity is one of the solutions that can be done to address environmental and energy issues. The waste produced in shrimp ponds has a high organic content (Balan, 2018; Syah et al., 2017; Suwoyo et al., 2015) and can be utilized as a renewable energy source (Dan et al., 2012; Ngurah et al., 2014; Parkash, 2016; Syahri et al., 2019).

An initial study on the electrogenic potential of super-intensive shrimp culture waste was conducted to determine its ability to generate electricity through the process of electrogenesis (Chaturvedi & Verma, 2016). Electrogenesis is a biological process in which microorganisms can produce electricity through the oxidation of organic matter contained in the waste (Artha et al., 2019). This process can be done using a microbial fuel cell (MFC), which is a device that can generate electricity from the activities of microorganisms inside (Bhusare et al., 2010; Dan et al., 2012; Pisciotta et al., 2012; Wang & Ren, 2013).

Several previous studies have been conducted to assess the potential of shrimp culture waste to generate electricity. One of them is a study conducted by Dan et al. (2012) that investigates the decrease in the accumulation of organic matter and electrical energy produced by shrimp pond sediments through Microbial Fuel Cells. The electric current generated by the shrimp pond sediment substrate in the MFC instrument reached a peak of ~161.99 mA/m2 and a voltage of ~0.39 V. This study indicates that shrimp culture waste has the potential to be a source of electricity through the process of electrogenesis.

The electrogenic mechanism involves the oxidation of organic matter by electrogenic bacteria such as *Bacillus* sp. and *Pseudomonas* sp. present in the shrimp pond sediments. These bacteria transfer electrons generated from their metabolic activity to the anode of the MFC, either directly through conductive pili and cytochromes or indirectly via soluble redox mediators. The electrons then flow through an external circuit to the cathode, producing an electric current. Meanwhile, protons generated in the process diffuse through the electrolyte towards the cathode, where they combine with electrons and oxygen to form water (Dan et al., 2012).

Operational parameters such as substrate concentration, pH, temperature, and electrode materials significantly influence the efficiency of the MFC. For instance, studies have shown that maintaining a neutral pH (around 7.0) and an optimal temperature range (25–35°C) enhances bacterial activity and electron transfer rates. Carbon-based materials like graphite or carbon felt are commonly used as anode electrodes due to their high conductivity and ability to support biofilm formation. In comparison, cathodes often utilize platinum catalysts to facilitate oxygen reduction reactions.

Although the potential of shrimp culture waste in generating electricity through the process of electrogenesis has been known, more research is still needed to improve the efficiency and performance of MFC which uses the waste as a source of organic material. Additionally, a study is needed to evaluate the environmental impact of using shrimp culture waste as a source of electricity. One of the efforts that must be done as a first step in the development of MFC is to explore various bioelectric agents, namely indigenous electronic bacteria that have the potential to be applied, including in super-intensive shrimp farming (Napitupulu et al., 2019).

In principle, processing the super-intensive shrimp farming waste into electricity through the electrogenic process is one of the solutions that can be implemented to address environmental and energy issues (Bhusare et al., 2010; Chaturvedi & Verma, 2016; Gude et al., 2013). Preliminary studies on the electrogenic potential of super-intensive shrimp farming waste have been conducted and have shown that shrimp farming waste has a significant potential to be converted into renewable electricity through the electrogenic process. The use of shrimp farming waste as a source of electricity can help reduce the amount of waste disposed of into the environment and provide clean and renewable energy. Studies by (Dan et al. (2012) and Ngurah et al. (2014) have shown that using shrimp pond sediment in Microbial Fuel Cells (MFCs) can significantly reduce Chemical Oxygen Demand (COD) by up to 60–70%, thereby minimizing the pollutant load released into surrounding water bodies.

However, to fully utilize this potential, further research is needed to improve the efficiency and performance of MFCs that use shrimp farming waste as a source of organic matter. In addition, the economic and environmental aspects of using shrimp farming waste as a source of electricity also need to be further evaluated. In the context of shrimp farming, processing waste as a source of electricity through the electrogenic process can also provide added value for shrimp farmers and the shrimp farming industry. By generating electricity from waste, shrimp farmers' operational costs can be reduced, and it can also help improve the sustainability of the shrimp farming industry. In research reported by (Pham et al., 2021) on the ability of Membrane-less Microbial Fuel Cells (MFCs) to treat wastewater for shrimp aquaculture wastewater recirculation, and improve the performance of Penaeus vannamei. This study compared shrimp farming without MFC and with MFC models. The results obtained in this study show that MFC circulates shrimp aquaculture wastewater and increases the growth increase of *Penaeus vannamei* (Pham et al., 2021).

In the long term, developing waste processing technology into a source of electricity through the electrogenic process from super-intensive shrimp farming waste can make a significant contribution to efforts to address global energy and environmental issues, thus avoiding violent activities against the universe as termed by (Napitupulu et al., 2019).

In the context of renewable energy research, Islamic values provide a foundational framework for addressing environmental challenges, particularly through the principle of "khalifah fil tadbir." This concept emphasizes the role of humans as stewards of the earth, entrusted with the responsibility to use natural resources wisely, avoid wastefulness, and prevent environmental harm (Kementerian Agama Republik Indonesia, 2022). In this study, the development of Microbial Fuel Cell (MFC) technology for converting shrimp farming waste into electricity is guided by the ethical and practical imperatives of khalifah fil tadbir.

Shrimp farming, while economically valuable, generates significant organic waste that, if not managed properly, contributes to water pollution and ecosystem degradation. By utilizing MFC technology, this research aims to transform waste into a renewable energy source, thereby aligning technological innovation with environmental stewardship. The principle of khalifah fil tadbir guides this approach by ensuring that waste management practices are not merely driven by efficiency but are also ethically responsible and environmentally sustainable. This study embodies khalifah fil tadbir in several critical aspects: 1) Resource Optimization: The conversion of organic waste into electricity exemplifies the wise and efficient use of available resources, reducing reliance on fossil fuels and minimizing environmental pollution; 2) Environmental Preservation: By lowering Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) in shrimp farming effluent, the research mitigates the harmful impacts of aquaculture waste on surrounding ecosystems; and 3) Sustainability and Equity: The technology promotes long-term sustainability and supports the economic well-being of shrimp farmers by lowering energy costs and providing a cleaner production process.

Incorporating khalifah fil tadbir into renewable energy research ensures a holistic perspective that balances scientific innovation with ethical responsibility. This study seeks to contribute not only to the advancement of MFC technology but also to the broader goal of achieving ecological shalehan (Fua, 2014)—a form of piety that reflects care for the environment and future generations. By framing the research within this ethical context, the findings offer a sustainable solution to waste management challenges while upholding the moral duty to protect and preserve the natural world.

METHODS

Isolation was initiated by preparing the bacterial growth media, namely Luria-Bertani. Then, sediment samples were collected from the wastewater of super-intensive shrimp farming in Punaga, Takalar Regency, South Sulawesi. The sediment samples were taken from the pond and the shrimp farming waste disposal site. To prevent contamination during sample collection, enrichment, and isolation, several aseptic procedures were implemented. Samples were collected using sterilized metal spoons or sampling tubes autoclaved at 121°C for 15 minutes. Researchers wore sterile latex gloves and face masks to avoid contamination from external sources. The samples were immediately placed in sterile, sealed containers and transported at 4°C to minimize microbial growth during transit. During the enrichment process, sterilized media such as Luria-Bertani were prepared, and inoculation was carried out under a laminar air flow (LAF) cabinet to ensure aseptic conditions. All instruments, including pipettes and inoculation tools, were sterilized by flaming or autoclaving prior to use. For bacterial isolation, the spread plate method was conducted under LAF conditions using sterile agar plates. Inoculation loops were sterilized by flaming until red-hot before each use, and plates were incubated in an inverted position to prevent contamination from condensation. Negative controls, consisting of uninoculated media, were included to verify the absence of contamination. These measures ensured the validity and reliability of the research results.

Enrichment culture was then carried out by cultivating the sediment samples on a Luria-Bertani (LB) broth medium containing tryptone (10 g/L), yeast extract (5 g/L), NaCl (10 g/L), and sodium acetate (5 mM) as a source of nutrition for the electrogenic bacteria. The medium was adjusted to a pH of 7.0. To maintain anaerobic conditions, the inoculated media were placed in anaerobic jars with gas-generating sachets and resazurin (0.0025%) as an oxygen indicator. The jars were flushed with 99.9% nitrogen gas for 5 minutes before being tightly sealed. The culture containing sediment samples and organic materials was then incubated at a temperature and anaerobic conditions suitable for the needs of the electrogenic bacteria from the pond, namely at 30°C for 2 x 24 hours (Bhusare et al., 2010; Du et al., 2007). This ensured optimal growth of the electrogenic bacteria while preventing contamination from aerobic microorganisms.

The initial detection of the electrogenic power of the isolates grown on the isolation media was done by testing with a carbon electrode. The carbon electrode, which was connected to an ammeter, was used to test the redox potential produced by bacteria in the medium containing energy sources (Aziz et al., 2013). The redox potential observed indicates the electrogenic ability of the bacterial isolate. The selected isolate was then characterized by colony morphology, cell characteristics, and physiological properties based on biochemical tests. The isolate was then tested in a miniature MFC reactor to measure its electrogenic ability (Aiyer, 2020). The miniature MFC consisted of an anode, cathode, and electrolyte to measure the electric current produced by bacteria in the medium containing energy sources (Logan et al., 2006; Pisciotta et al., 2012). The bacterial isolate culture was prepared in a volume of 100 ml with a bacterial cell count of 10^7 cells/ml. The miniature MFC is an instrument consisting of two electrodes (anode and cathode) connected by a wire and placed in a tube with electrolytes inside. In the miniature MFC, the anode is placed in a medium containing electrogenic bacteria in the predetermined volume, while the cathode is placed in a medium containing platinum as an electron acceptor. Each electrode of the miniature MFC is connected to a copper wire by alligator clips connected to a digital multimeter, with the positive pole on the cathode and the negative pole in the anode space to show the voltage and current strength produced. The voltage and electric current readings were recorded, and from this data, the power density value (W/m^2) could be obtained.

To validate the results, negative controls using media without bacterial inoculation and non-electrogenic bacterial controls (e.g., Escherichia coli) were included. These controls were processed under the same conditions to ensure that any observed electrogenic activity was due to the isolated bacteria and not abiotic reactions or background electron transfer. This data provides initial information about the electrogenic ability of the isolated electrogenic bacteria, ensuring that the results are accurate and reliable. (Bhusare et al., 2010; Ram Prasad et al., 2018; Santoro et al., 2014, 2017b, 2017a).

RESULTS AND DISCUSSION

The isolation of bacteria from the sediment of Punaga's super-intensive shrimp farming waste, carried out using the spread method on Luria-Bertani media, showed diverse bacterial colony growth. Based on the initial detection of electrogenic activity of the growing isolates, four isolates were identified as potential electrogenic bacteria, which were subsequently characterized as shown in Table 1. Based on the characterization, the four selected isolates were identified as bacteria from the genus *Bacillus* and *Pseudomonas*.

Table 1. The Characteristics of electrigens bacteria from Punaga super-intensive shrimp farming waste sediment

Characteristic	**Waste sediment electrigens bacterial isolate code**			
	A	**B**	**C**	**D**
Colony	Circular, undulate, umbonate, opaque, non-translucent, diameter 2-4 mm	Circular, entire, convex, glistening, semi-translucent, diameter 1-2 mm	Circular, undulate, umbonate, dull, opaque, diameter 2-4 mm	Circular, undulate, convex, dull, opaque, diameter 2-4 mm
Gram	Positive	Negative	Positive	Positive
Cell Shape and arrangement	Bacil, mono/ diplobacil	Bacil, diplobasil	Bacil, streptomycin	Coccobacil, strepotobacil
Endospore	+ (Central ellipse/terminal)	-	+ (Ellips central)	+ (Ellips, central)
Growth nature	Anaerobic	Anaerobic	Anaerobic	Anaerobic
MIO Test	-	+	-	-
Citric test	+	-	-	+
Glucose test	+	+	+	+
MR test	-	+	+	+
VP test	+	-	-	-
Genera	***Bacillus* sp.**	***Pseudomonas* sp.**	***Bacillus* sp.**	***Bacillus* sp.**

Notes:

+ = Positive reaction in the conducted test
- = Negative reaction in the conducted test

The analysis of electrogenic capability level towards characterized and prepared electrogenic bacteria was conducted using a miniature MFC instrument to show the magnitude of voltage and electric current as shown in Table 2, w2, which were averaged as shown in Figure 1. These data indicate the amount of electrical power produced by electrogenic bacteria per unit surface area of the electrode in the miniature MFC. The higher the power density, the more effective and efficient the MFC is in generating electric energy from organic waste.

Based on these findings, it can be said that super-intensive shrimp farming waste has the potential to be generated as a renewable source of electricity through bioelectrogenic processes. Four potential types of bacteria can bed as electricity producers through MFC, namely bacterial isolates A, B, C, and D, each recognized as *Bacillus* and *Pseudomonas* genus bacteria. Each bacterial isolate has a different power density. Bacterial isolate D has the highest power density of 38.55±0.87, while bacterial isolate A has the lowest power density of 25.90±1.69. This indicates that bacterial isolate D has the greatest potential to be used as a source of electricity from shrimp farming waste.

Table 2. The measurement of electrical voltage data generated by bacterial isolates from the waste sediment of Punaga's super-intensive waste

NO	Isolate A			Isolate B			Isolate C			Isolate D		
	V (Volt/m²)	I (A/m2)	P (Watt/m2)	V (Volt/m²)	I (A/m²)	P (Watt/m²)	V (Volt/m²)	I (A/m²)	P (Watt/m²)	V (Volt/m²)	I (A/m²)	P (Watt/m²)
1	157.167	0.156	24.388	184.834	0.175	30.567	175.167	0.182	23.623	198.834	0.199	39.535
2	165.834	0.166	27.501	191.000	0.191	36.481	171.667	0.172	29.469	197.000	0.197	38.809
3	165.000	0.165	27.225	190.500	0.191	36.290	173.334	0.173	30.045	196.000	0.196	38.416
4	159.500	0.157	24.492	188.500	0.189	35.531	176.000	0.197	36.481	193.500	0.194	37.441

The miniature MFC experiments demonstrated that the highest power density was produced by Bacillus sp. (Isolate D), yielding 38.55±0.87 mW/m², followed by Pseudomonas sp. (Isolate B) with a power density of 34.72±2.80 mW/m². Other isolates, such as Bacillus sp. (Isolate C) and Bacillus sp. (Isolate A), generated power densities of 29.90±5.26 mW/m² and 25.90±1.69 mW/m², respectively. These results indicate that Bacillus sp. and Pseudomonas sp. have significant potential for bioelectricity generation through electrogenesis in MFCs using shrimp pond sediment as a substrate.

To better contextualize these findings, a comparative analysis with previous studies is essential. The power density of 38.55±0.87 mW/m² obtained from *Bacillus* sp. (Isolate D) in this study aligns closely with the findings of Dan et al. (2012), who reported a maximum power density of ~39.5 mW/m² using shrimp pond sediment. This consistency suggests that shrimp culture waste is a reliable substrate for bioelectricity generation. However, the results are lower compared to the study by Kaoplod & Chaijak (2022), where *Bacillus* sp. generated a power density of 94.09 mW/m² using cellulose as a substrate. The differences in power output may be attributed to variations in substrate composition, bacterial strain efficiency, and the surface area of the electrodes used.

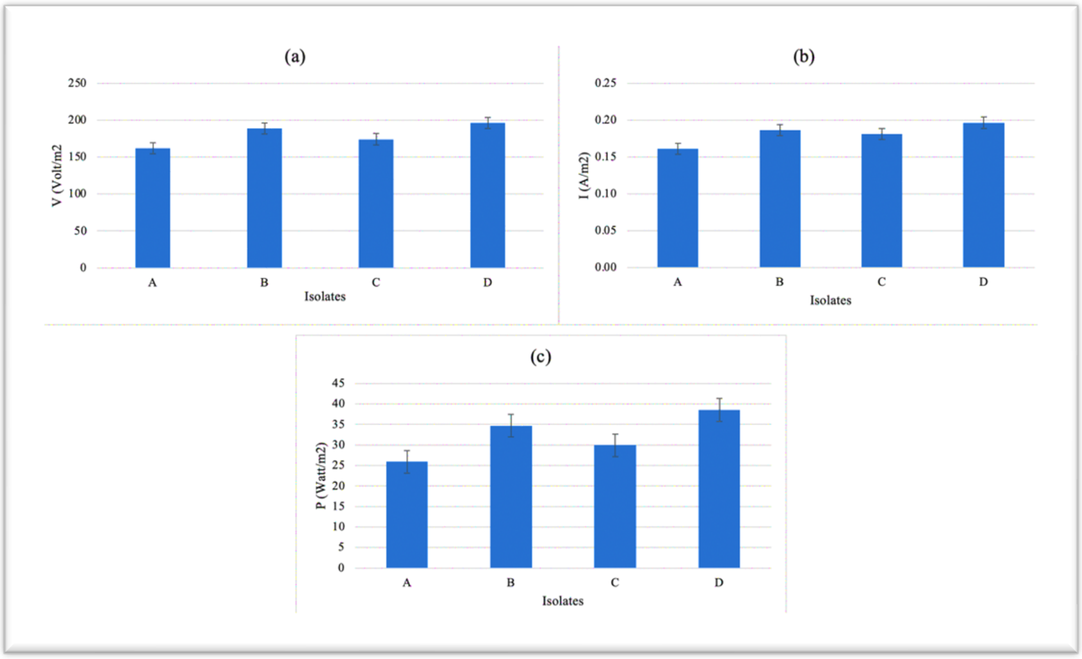

Figure 1. The average value of voltage (a), electric current strength (b), and power density (c) on MFC system with four bacterial isolates from Punaga shrimp farm waste sediment as electrigens.

Similarly, the power density produced by *Pseudomonas* sp. (Isolate B) in this study, 34.72±2.80 mW/m², surpasses the 22.9 mW/m² reported by Ilamathi et al. (2019) using Pseudomonas sp. in dye wastewater. This indicates that shrimp pond sediment provides a richer nutrient profile, enhancing bacterial electrogenic activity. These comparisons highlight the importance of substrate type and environmental conditions in determining the efficiency of MFC systems.

The differences in the potential of each bacterium can be caused by genetic variation factors or differences in the ability of bacteria to oxidize organic materials contained in shrimp waste (Sandeep S, 2015). The genetic variations between different bacterial isolates can affect their electrogenic potential. In addition, factors such as substrate type, temperature, pH, and metal ion concentration in the environment can also affect the electrogenic ability of bacteria (Logan, 2009).

As a bacterium that shows good electrogenic potential, *Bacillus* sp. is one type of bacteria that has the potential as a potential electrogene (Kaoplod & Chaijak, 2022; Treesubsuntorn & Thiravetyan, 2021; Gomaa et al., 2021). Several studies with similar results have been conducted to evaluate this potential, including research by (Aravindavall2012), which shows that *Bacillus* sp. can generate electricity through electrogenic processes using MFC. The results of this study indicate that

Bacillus sp. indeed can make materials and generate electrical currents. Research by Kaoplod & Chaijak (2022) also shows that *Bacillus* sp. can generate a relatively high power density through bioelectrogenic processes. In this study, *Bacillus* sp. managed to generate a power density of 94.09 mW/m2. Research by Treesubsuntorn & Thiravetyan (2021) also shows that *Bacillus* sp. can be used as a source of electricity through electrogenic processes. In this study, *Bacillus* sp. managed to generate a voltage of 0.62 V and a current of 50-60 mW/m2 using MFC.

The potential of *Bacillus* sp. as a potential electrigens may be influenced by several factors such as the type of substrate used, environmental conditions, and the type of MFC used. therefore, further research is still needed to optimize the potential of *Bacillus* sp. as a potential electrigens. *Pseudomonas* sp. bacteria, which also have the potential as a potential electrigens, are also supported by several studies. For example, a study conducted by (Ai et al., 2019; Ilamathi et al., 2019) showed that an isolate of *Pseudomonas* sp. isolated from organic waste can generate electricity through MFC. The study showed that the use of *Pseudomonas* sp. isolates in MFC produced a power density of 22.9 mW/m2 and a voltage of 4.4 V. In addition, another study conducted by Virdis et al. (2011) also showed that several strains of Pseudomonas sp. can produce electricity in MFC.

However, to optimize this potential, further research is needed to improve the efficiency and performance of MFCs that use shrimp farming waste as a source of organic material. In addition, the economic and environmental aspects of using shrimp farming waste as a source of electricity also need to be further evaluated. Preliminary calculations indicate that converting shrimp pond sediment into electricity using MFCs could reduce waste treatment costs by up to 20–30% compared to conventional aerobic treatment methods. This is due to the dual benefit of waste reduction and electricity generation, which can offset energy costs for shrimp farmers. For instance, a shrimp farm producing 1 ton of waste per month could generate approximately 3–5 kWh of electricity, which can partially power aeration or lighting systems, thereby reducing operational expenses.

From an environmental perspective, the use of MFCs for shrimp waste treatment has the potential to reduce Chemical Oxygen Demand (COD) by 60–70% and Biological Oxygen Demand (BOD) by 50–65% (Dan et al., 2012; Syah et al., 2017). This reduction in organic pollutants helps mitigate the environmental impact of shrimp farming, preventing eutrophication in surrounding water bodies. Additionally, greenhouse gas emissions from traditional waste treatment methods can be minimized, contributing to more sustainable aquaculture practices.

These quantitative insights support the feasibility of integrating MFC technology into shrimp farming operations, highlighting its potential to provide economic savings and significant environmental benefits. In the long run, the development of waste processing technology as a source of electricity through the electrogenic process of super-intensive shrimp farming waste can make a significant contribution to addressing global energy and environmental issues.

These findings underscore the potential of *Bacillus* sp. and *Pseudomonas* sp. for sustainable energy generation from aquaculture waste. To further improve the efficiency of MFCs, future research should focus on optimizing parameters such as substrate concentration, electrode surface area, and the configuration of the MFC. Incorporating different electrode materials or enhancing the biofilm formation process could also increase power output. Additionally, long-term studies assessing the stability and scalability of this system in real-world aquaculture settings are necessary to validate its practical applications.

The development of microbial fuel cell (MFC) technology for waste treatment and energy generation can be considered as an implementation of the concept of "*khalifah fil tadbir*" in Islam. This concept refers to the belief that humans are the stewards or managers of the earth, responsible for utilizing natural resources wisely and being accountable for the environmental impact they create. In the context of waste treatment, MFC offers an attractive solution as it can convert organic waste into electrical energy through the chemical reactions that occur within bacterial cells.

The process of treating waste with MFC involves the colonization of bacteria within the cell, which can oxidize organic matter in the waste (Bahartan et al., 2012; Mishra et al., 2017; Wang & Ren, 2013). These bacteria produce electrons and protons as by-products of their metabolism, which can be directed through the electrodes and converted into electric current (Aziz et al., 2013; Parkash, 2016). In the context of the "khalifah fil tadbir" concept, the development of MFC technology for waste treatment and energy generation has positive implications for the environment, as it can reduce organic waste that can pollute the environment and produce electrical energy that can be used as an alternative energy source.

The development of MFC technology for waste treatment and energy generation can be considered a practical implementation of the concept of “khalifah fil tadbir” in Islam, which emphasizes the responsibility of humans as stewards of the earth to use natural resources wisely and minimize environmental harm. This research, by converting shrimp farming waste into renewable electricity, directly embodies the principle of responsible resource management. Rather than allowing organic waste to contribute to environmental degradation, the findings demonstrate a sustainable approach to waste utilization, reducing pollution and promoting energy self-sufficiency for aquaculture operations.

The study’s outcomes align with the ethical mandate of khalifah fil tadbir by addressing two critical aspects: environmental preservation and economic benefit. Environmentally, the reduction of Chemical Oxygen Demand (COD) by 60–70% and Biological Oxygen Demand (BOD) by 50–65% mitigates the risk of water pollution, protecting aquatic ecosystems and surrounding communities. Economically, the generation of 3–5 kWh of electricity per ton of waste offers shrimp farmers a means to reduce operational costs and reliance on fossil fuels, fostering long-term sustainability.

Furthermore, this research highlights the ethical responsibility to seek innovative solutions that balance technological advancement with environmental stewardship. By adopting MFC technology, shrimp farmers not only improve waste management practices but also contribute to the broader goal of ecological sustainability and social welfare, reinforcing the Islamic value of maintaining harmony between human activity and the natural world. This approach exemplifies the essence of khalifah fil tadbir—ensuring that human actions benefit both present and future generations while safeguarding the integrity of the environment. One of the most relevant verses related to the concept of "khalifah fil tadbir" is the Quranic verse Surah Al-Baqarah verse 30, which states:

وَاِذْ قَالَ رَبُّكَ لِلْمَلٰۤىِٕكَةِ اِنِّيْ جَاعِلٌ فِى الْاَرْضِ خَلِيْفَةً ۗ قَالُوْٓا اَتَجْعَلُ فِيْهَا مَنْ يُّفْسِدُ فِيْهَا وَيَسْفِكُ
الدِّمَاۤءَۚ وَنَحْنُ نُسَبِّحُ بِحَمْدِكَ وَنُقَدِّسُ لَكَ ۗ قَالَ اِنِّيْٓ اَعْلَمُ مَا لَا تَعْلَمُوْنَ

Translation: Remember when your Lord said to the angels, "Indeed, I will make upon the earth a khalifah." They said, "Will You place upon it one who causes corruption therein and sheds blood, while we declare Your praise and sanctify You?" Allah said, "Indeed, I know that which you do not know." QS. Al-Baqarah (22): 30 (Kementerian Agama Republik Indonesia, 2022).

This verse illustrates that Allah SWT has appointed humans as the khalifah on earth to protect and manage the earth and its contents. As khalifah, humans are responsible for preserving nature and using natural resources wisely, as well as being accountable for the environmental impact they produce.

According to the Tafsir Tahlili in the original Quran published by the Ministry of Religious Affairs, this verse explains that when Allah SWT informed His angels that He would make Adam the khalifah on earth, the angels asked why Adam, who would later cause destruction and shed blood on earth, was chosen. The angels considered themselves more worthy of holding that position, as they are creatures who always glorify and sanctify Allah SWT. Allah SWT did not accept their assumption and answered that He knows what the angels do not know. Everything Allah SWT does is based on His knowledge and wisdom, even if it cannot be known by them, including the appointment of Adam as khalifah on earth. The meaning of Adam's khalifah on earth is his position as a khalifah on earth to carry out His commands, develop the earth, and make use of everything in it (Kementerian Agama Republik Indonesia, 2022).

In the context of developing MFC as a waste-to-energy technology, the concept of "khalifah fil tadbir" can be realized by using environmentally friendly technology to process waste and generate renewable energy. This is in line with the principles of Islam, which teach us to preserve the environment and respect the creation of Allah SWT (Hartini, 2013; Rodin, 2017). By utilizing waste as a source of energy, humans can reduce their dependence on limited fossil energy sources and their negative impact on the environment. Therefore, the development of MFC in the processing of waste into a source of energy can be considered a real implementation of the concept of "khalifah fil tadbir".

CONCLUSION

Bacillus sp. and *Pseudomonas* sp. have the potential as potential electrigens, which can be used as a source of electricity through the bioelectrogenic process in MFC. Further research is needed to optimize this potential. This potential can also be utilized to address global energy and environmental issues through the development of waste treatment technology as a source of electricity through the electrogenic process of super-intensive shrimp cultivation waste. However, the economic and environmental aspects of using shrimp farming waste as a source of electricity also need to be further evaluated, which overall is our responsibility as human beings who must hold firmly to the concept of "khalifah fil tadbir".

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