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Tofu Wastewater Treatment and Bioelectricity Production Potential by Combining Anaerobic Baffled Reactor and Microbial Fuel Cells

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ABSTRAK

Sistem Anaerobic Baffled Reactor (ABR) selama ini dimanfaatkan untuk penurunan senyawa polutan dalam air limbah saja. Kondisi anaerob pada ABR dapat berfungsi ganda sebagai ruang anoda pada Microbial Fuel Cells (MFCs) yang sama membutuhkan kondisi anaerob. Penelitian ini bertujuan untuk menguji kemampuan penyisihan COD dan TSS pada air limbah tahu dan menguji potensi listrik yang dihasilkan dari unit kombinasi ABR dan MFCs. Percobaan dilakukan skala laboratorium menggunakan system kontinyu selama 96 jam. Reaktor ABR dibuat terdiri dari 5 kompartemen, dimana kompartemen kedua dipasang anoda untuk MFCs. Ruang katoda sistem MFCs dibuat terpisah dari reaktor ABR dan diisi dengan larutan elektrolit. Ruang anoda pada ABR dan ruang katoda dihubungkan dengan jembatan garam. Elektroda yang digunakan pada MFCs yaitu zinc sebagai anoda dan tembaga sebagai katoda. Penyisihan polutan pada air limbah tahu mencapai 55,85% untuk COD dan 88,68% untuk TSS. Potensi listrik dari MFCs meningkat seiring dengan peningkatan penyisihan bahan organik dalam air limbah. Tegangan listrik yang dihasilkan mencapai 0,94 V dan arus listrik 0,40 mA. Power density yang dihasilkan pada sistem MFCs ini mencapai 94 mW/m2.

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Anaerobic baffled reactor, Bioelectricity, Electrical potential, Microbial fuel cells

ABSTRACT

Anaerobic Baffled Reactor (ABR) systems have only been utilized to reduce pollutant compounds in wastewater. Anaerobic conditions in ABR can double as an anode chamber in Microbial Fuel Cells (MFCs) which require anaerobic conditions. This study aims to test the ability of COD and TSS removal in tofu wastewater and the potential electricity generated from a combination unit of ABR and MFCs. The experiment was conducted on a laboratory scale using a continuous system for 96 hours. ABR reactor was made consisting of 5 compartments, where the second compartment was installed anode for MFCs. The cathode chamber of the MFCs system was made separate from the ABR reactor and filled with electrolyte solution. The anode chamber in the ABR and the cathode chamber are connected by a salt bridge. Copper serves as the cathode and zinc as the anode in MFCs. Pollutant removal in tofu wastewater was 88.68% for TSS and 55.85% for COD. As the amount of organic matter removed from MFCs increases, so does their electrical potential. wastewater. Electric current of 0.40 mA and electric voltage of 0.94 V were produced. This MFC system produced a power density of 94 mW/m2.

1. INTRODUCTION

Tofu wastewater contain high suspended solids (TSS) and organic matter as COD, so that if it is disposed of directly into water bodies without prior processing it will be able to reduce the quality of environment. The organic matter in the form of carbohydrates, proteins and fats can be used as a substrate by microorganisms. In the initial wiring conducted in this study, tofu wastewater had a COD content of 7,987 mg/L. The high organic compounds in tofu wastewater make it more optimal to be processed using an anaerobic processing system (Diah Syafaati et al., 2019).

Like other anaerobic technologies, ABR is specifically designed for the treatment of wastes that hinder the activity of aerobic microorganisms. As noted by Ahamed et al. (2015), the advanced anaerobic baffled reactors increase the efficiency of organic matter degradation and enhance the stability of processes. Trihidayanti et al. (2021) conducted research that showed ABR achieving up to 85% COD reduction in food industry wastewater due to the anaerobic microorganisms responsible for complex organic matter breakdown. Moreover, as pointed out in the earlier work of Mutsvene et al. (2023), the adaptable anaerobic baffled reactors respond to various organic load to effortlessly treat industrial and domestic wastewater, making it a reliable buffer tank. Lau and Trzcinski (2022) stated ABR technology has also gained popularity due to low operating costs and maintenance in comparison to other technologies, making it applicable in various industries and on a larger scale.

Anaerobic baffled reactors (ABR) treat wastewater by passing it through a series of compartments partitioned with baffles. Baffle separators help the wastewater move in a zigzag manner, which maximizes the treatment time by anaerobic microorganisms. ABRs are usually combined with filtration systems, rotating biological contactors (RBC), or hybrid systems. (Mohammed & Sills, 2022)(Khan et al., 2023). ABR is used as an initial stage to decompose most of the organic matter through anaerobic processes, followed by filtration to remove suspended particles and further reduce the organic load. In the combination of ABR and RBC, the remaining organic matter is degraded through aerobic processes in the RBC by utilizing rotating media that provides a large surface for microbial biofilm growth (Mohammed & Sills, 2022). Some of these ABR combinations focus on the removal of pollutants in wastewater only.

Microbial Fuel Cells (MFCs) is one of the technologies that can be used to generate electrical energy by utilizing organic materials in waste. MFCs are designed to convert chemical energy from organic compounds into electrical energy directly through the catalytic activity of microorganisms (Do et al., 2020). In general, the MFCs design consists of two main compartments: the anode chamber and the cathode chamber, which are separated by a proton exchange membrane (PEM). In the anode chamber compartment, microorganisms oxidize organic substrates (e.g. wastewater), releasing electrons and protons. The anode collects electrons, which are transferred and travel through an external circuit to the cathode, generating electrical current. Protons, on the other hand, PEM is permeable to protons which travel towards the cathode chamber. At the cathode, electrons, protons, and acceptors of electrons which is generally oxygen react to form water (Rahimnejad et al., 2020). This not only generates electricity, but also reduces the organic load of wastewater treated. Efficiency of MFCs has been shown to depend on the type of microorganism used, the nature of the organic substrate, the design of the electrodes, and the operating conditions. All in all, MFCs offer a very promising technological approach towards sustainable wastewater treatment and renewable energy production. I combined ABR and MFC systems to analyze the COD and TSS removal efficiency from tofu wastewater and to study the amount of electricity that could be produced during treatment. While ABR is renowned for its anaerobic organic matter degradation potential, and MFCs for their ability to convert organic matter to electricity, the integration of these two systems creates a novel synergy that is lacking study in relation to tofu wastewater. The second compartment of the ABR acts as an anaerobic reaction chamber as well as an anode of the MFC system. This dual use optimizes space and operational efficiency, reducing the need for separate systems.

2. METODH

2.1 Reactor Design

The reactor utilized for the study is an Anaerobic Baffled Reactor (ABR) composed of acrylic blocks with internal baffles. This particular ABR has five compartments and a total volume of 6815.3 cm^3. An ABR is an anaerobic reactor, meaning it operates in oxygen-free environments. The MFCs system is made up of an anode and a cathode chamber. The second compartment of ABR serves as an anode chamber in the MFCs system, while the cathode chamber is externally placed, separate from the structure of ABR (Arvin et al., 2019). The cathode chamber is constructed from acrylic and has a volume of 678 m3 containing an electrolyte solution. The anode used is zinc and the cathode used is copper. Between the anode and cathode chambers is connected by a salt bridge. The salt bridge is made from a mixture of 100 ml of boiling distilled water, 11.099 grams of KCl and 2.5 grams of nutrient agar. The mixture was stirred until homogeneous and thickened and then put into a 1-inch diameter clear pipe with a length of 10 cm (Trihidayanti et al., 2021). A digital Avo-Multimeter was installed on the MFCs system to measure the voltage and current strength produced. The design of the ABR-MFCs combination reactor can be seen in Figure 1

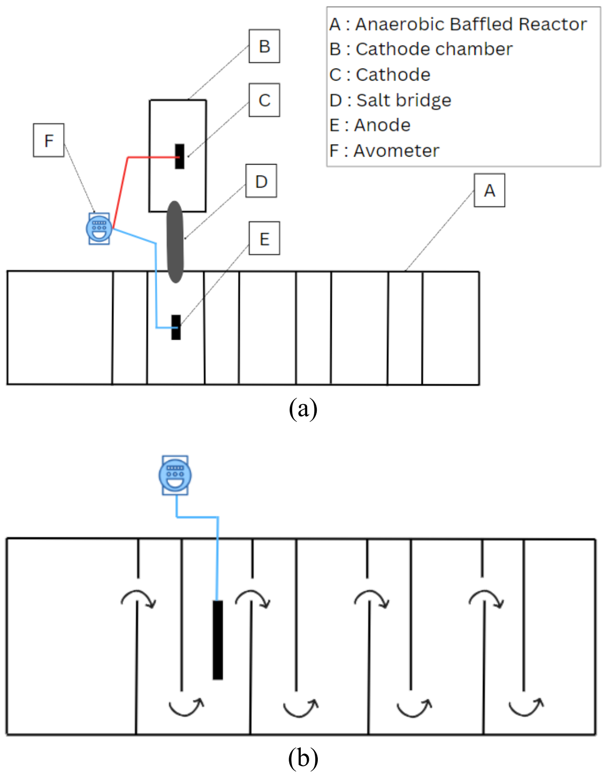


Figure 1. Research reactor design, a) Top view plan; b) Side view reactor

2.2 Research Procedure

2.2.1 Seeding and Acclimatization

Seeding is done by adding nutrients to the wastewater. The wastewater used for this study was obtained from a tofu home industry in Sidoarjo Regency, East Java Province, Indonesia. MLSS testing is done to measure the growth of microorganisms, when MLSS is more than 2,000 mg/L then the seeding target is achieved and the acclimatization process is continued. The working principle of acclimatization is to introduce tofu wastewater into the reactor gradually, the aim is to stabilize the performance of microorganisms.

2.2.2 Running Experiment

The research experiment was conducted after the target seeding and acclimatization process was achieved. Tofu wastewater flowed into the reactor with a discharge of 0.01 L/min. The experiment was conducted for 96 hours with 5 measurements of COD and TSS parameters.

2.3 Laboratory Analysis and Data Processing

2.3.1 Test Methods of MLSS, COD, and TSS

The COD test method follows SNI 6989.2.2009, namely reflux (spectrophotometry) and TSS follows SNI 06-6989.3:2004 (gravimetry).

2.3.2 Pollutant Removal Efficiency

Pollutant removal efficiency was calculated for COD and TSS parameters using Equation 1.

Removal = $\frac{Cin-Cout}{Cin}$ ×100%……………………………(1)

Information:

C_{in}= parameter concentration before treatment (mg/L)

C_{out}= parameter concentration after treatment (mg/L)

2.3.3 Power Density

The data required for power density analysis are the voltage (V) and amperage (mA) values measured using a digital Avo-Multimeter. Calculation of power density using Equation 2.

P = $\frac{v\ x\ I}{A}$ ………………………………………………(2)

Information:

P = Power density (mW/m2)

v = Voltage (V)

I = Strong Current (mA)

A = Electrode Surface Area (m2)

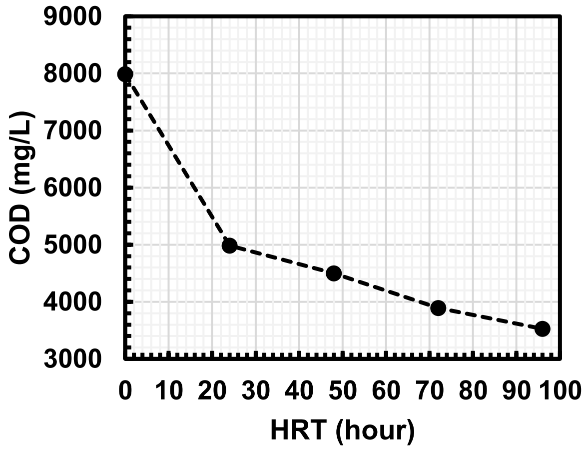
3. RESULTS AND DISCUSSION

3.1 Seeding and acclimatization results

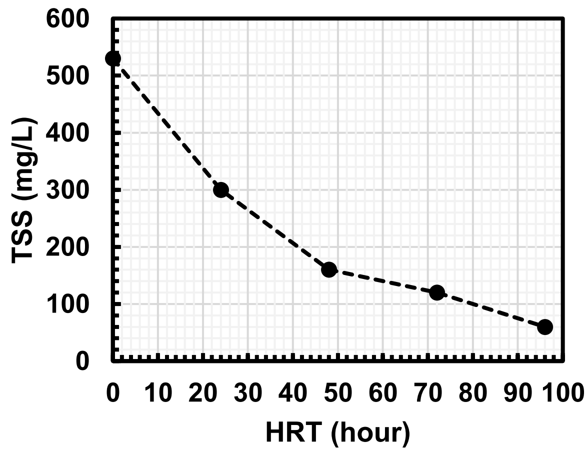
The seeding process was achieved after 15 days, with an MLSS value of 2,140 mg/L. After seeding, the acclimatization process was carried out by adding tofu wastewater. The acclimatization stage involves the adaptation of bacteria to wastewater that requires treatment. The acclimatization process was carried out 2 times in stages. The first acclimatization with the composition of 50% seeding isolates and 50% tofu wastewater and the second with 100% tofu wastewater. Wastewater was provided gradually to avoid a significant decrease in COD removal efficiency and to prevent shock loading of bacteria. During the acclimatization process, COD levels were tested and COD removal was calculated every day. In this study, it was found that the acclimatization process lasted up to 6 days. The completion of the acclimatization process is marked by stable COD removal, or indicated by the difference in removal with the previous day less than 10%. This shows that the microorganisms in the reactor are stable and ready for running tofu wastewater treatment.

3.2 Pollutant removal

Tofu wastewater treatment in the ABR-MFCs system can be run after the acclimatization process reaches stability, which is indicated by the level of COD removal efficiency. Running was carried out for 96 hours, with measurements of COD and TSS parameters every 24 hours. The decrease in COD and TSS for 96 hours can be seen in Figure 2.



(a)



(b)

Figure 2. Measurement of pollutant parameters every 24 hours; a) COD, b) TSS

Linear COD and TSS removal occurred as the running time progressed. The percentage of COD removal was 37.58%, 43.67%, 51.28%, and 55.85% for HRT 24 hours, 48 hours, 72 hours, and 96 hours, respectively. The TSS resulted in greater removal every 24 hours consecutively, ranging from 43.40%, 69.81%, 77.36%, and 88.68%. The reduction of organic content is carried out by anaerobic microorganisms in the ABR.

ABR works by passing waste through a series of compartments separated by Baffles. Wastewater entering the reactor undergoes a zigzag flow change, hence extending the contact time between organic compounds and anaerobic microorganisms. Anaerobic microorganisms in ABR decompose complex organic compounds into simpler compounds (Rivera et al., 2022).

Organic compounds that have been broken down by anaerobic microorganisms into simpler ones are converted by Electroactive Bacteria into electrons and protons in the anode chamber (Mohyudin et al., 2022). The anode chamber needs to be in a condition without oxygen. Electroactive Bacteria will metabolize in anaerobic conditions by decomposing organic matter into protons, electrons (e) and, carbon dioxide (CO2). Electrons and protons are then transferred to the cathode chamber, where in the presence of oxygen they will be converted to water (Wang et al., 2023). This conversion reaction follows Equations 3 and 4, while the overall process in MFCs follows Equation 5 (Satar & Permadi, 2022)

$$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^- \quad (3)$$
$$8H^+ + 8e^- \rightarrow 2O_2 + 4H_2O \quad (4)$$
$$CH_3COO^- + 2O_2 \rightarrow 2HCO_3^- + H^+ \quad (5)$$

3.3 Power Density

Power density is a measure of the amount of electrical power that can be generated per unit volume or per unit area of a system or device (Saravanan et al., 2022). Data on voltage and current strength are processed to calculate power density. Based on the experiment, the voltage and current generated from the MFCs system increased along with the increase in the removal of organic load in wastewater, which in this case is characterized by COD removal. Data on voltage and current strength for 96 hours can be seen in Table 1.

Table 1. Results of voltage, current strength, and COD removal

HRT (hour)	Voltage (V)	Current strength (mA)
24	0,35	0,20
48	0,41	0,22
72	0,73	0,30
96	0,94	0,40

The process of forming electricity in the MFCs system begins when microorganisms that are usually in aerobic conditions use oxygen and nitrate as electron acceptors, but in this case the electron acceptor in the process of degrading organic matter used is the anode. This anode is also a medium for biofilm growth (Novriandy et al., 2021). In addition to electrons, another result of the organic matter degradation process is protons that will flow to the cathode through the salt bridge. Electrons attached to the anode electrode then flow through an external circuit to the electrode on the cathode. The meeting between electrons and protons is what causes the potential difference between the two ends of the electrodes (cathode and anode) to produce electricity (Rahimnejad et al., 2020).

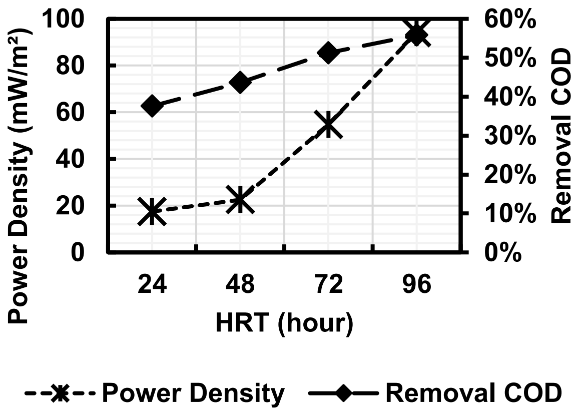


Figure 3. Relationship between power density and COD removal by time

Power density is affected by factors such as the type of microorganisms used, operating conditions such as pH and temperature, and electrode design. Increasing power density can be achieved through design and material optimization, as well as improving the efficiency of biological and electrochemical processes. In this case study, copper and zinc were the electrodes utilized. Zinc is an example of a material that can be used as an anode. What makes zinc favorable as anode is the fact that both electrochemical and biochemical reactions can be used (Çek, 2017). The reason why zinc works so well is because of its good adsorption ability which allows microbes to populate the surface of the electrode (Radi et al., n.d).

This power density achievement shows that the ABR-MFC system is not only effective in reducing pollutant loads, but also has the potential as a renewable energy source from organic waste. Application in small-scale tofu industry allows for practical application. The reactor unit can be designed in a modular and compact form, so that it can be integrated directly with the waste disposal channel from the production process. The electrical potential generated from this MFCs system allows it to be used as a source of electrical energy for light purposes, such as lighting systems, automatic sensors, or simple monitoring systems (Jadhav et al., 2021). On the other hand, the challenges of implementing the ABR–MFC system in the small-scale tofu industry need to be considered. The need for a fairly long retention time, where during the test time of 96 hours, the COD removal efficiency was still below 70%. The electricity output generated is still relatively small so that it is not sufficient for a larger energy load without combining several MFC units .

CONCLUSION

The integration of Anaerobic Baffled Reactors (ABRs) with Microbial Fuel Cells (MFCs) provides a new and more efficient mechanism for treating wastewater that has a high organic matter content. This integration has a positive effect on the recovery of energy and removal of contaminants in the treatment of wastewater such as tofu. The results from the ABR-MFC systems were impressive with COD and TSS removal efficiencies of 55.85% and 88.68%, respectively. The efficiency of the MFCs partition is the function of the degree of organic reduction from the ABR. As the ABR reduces organic matter, the electric potential of the MFC increases leading to a power density of 94 mW/m². These results demonstrate the potential of these integrated systems not only for the reduction of pollution in wastewater but also for the generation of clean energy contributing to more sustainable wastewater management systems.

The ABR-MFCs combination system exhibits significant promise for use as an energy-producing, environmentally friendly waste processing technology in the small-scale tofu business. This strategy firmly backs the idea of an environmentally responsible industry, notwithstanding operational and technical difficulties. This system can serve as an integrated solution to manage waste and use renewable energy in the traditional food business sector with the right design optimization and implementation approach.

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