

Article

Organic Waste for Bioelectricity Generation in Microbial Fuel Cells: Effects of Feed Physicochemical Characteristics

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Abstract: Food waste (FW), piggery waste (PW), and activated sludge (AS) were investigated as potential organic feeds for bioelectricity generation in laboratory-scale microbial fuel cells (MFCs). The MFCs fed by FW gained the highest maximum power density at 7.25 W/m^3 , followed by those fed by PW at 3.86 W/m^3 and AS at 1.54 W/m^3 . The tCOD removal in the FW-, PW-, and AS-MFCs reached 76.9%, 63.9%, and 55.22%, respectively, within a 30-day retention time. Food waste, which resulted in the highest power density and tCOD removal, was selected for a series of following tests to investigate the effects of some physicochemical properties of organic feed on the performance of MFCs. The effect of feed particle size was tested with three controlled size ranges (i.e., 3, 1, and <1 mm) in MFCs. A smaller feed particle size provided a higher power density of 7.25 W/m^3 and a tCOD removal of 76.9% compared to the MFCs fed with organic waste with a larger particle size. An increment in feed moisture from 70% to 90% improved the maximum power density from 7.2 to 8.5 W/m^3 , with a 17.5% enhancement, and improved the tCOD removal from 75.8% to 83.3%, with a 10.0% enhancement. A moderate C/N ratio of approximately 30/1 maximized the power density and COD removal (7.25 W/m^3 and 81.73%) in the MFCs compared to C/N ratios of 20/1 (4.0 W/m^3 and 64.14%) and 45/1 (4.38 W/m^3 and 71.34%).

Keywords: microbial fuel cell; organic wastes; feed physicochemical characteristics; bioelectricity generation; COD removal



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1. Introduction

Ever-accelerating urbanization and population growth have exacerbated the world-wide crisis of waste generation, natural resource depletion, and energy shortage [1]. According to [2], worldwide solid waste generation has grown to 2.3 billion tons in 2023 and is expected to reach 3.8 billion tons by 2050. Approximately 70% of human-derived solid waste is subject to organic solid waste, which refers to discarded solid materials containing high amounts of organic components [3]. The improper and/or inefficient treatment and management of such organic solid waste can cause a series of problems, including environmental quality and ecosystem deterioration, as well as considerable human welfare issues and economic losses [4]. In particular, organic solid wastes are conventionally collected and treated together with mixed municipal solid waste in landfills or via incineration, which may lead to greenhouse gas emissions, leachate generation, air pollution, and bad odors, among others. However, organic solid waste is a valuable resource that can be recycled in various ways, including energy generation and agricultural applications [5]. The physicochemical properties of organic solid waste vary highly depending on its origin and composition, making it suitable for different types of recycling and valuation options. In terms of energy recycling, several organic-rich solid wastes such as food waste, agricultural and livestock waste, and sewage waste, which contain high amounts of biopolymers such as proteins, carbohydrates, and lipids, can potentially be applied to provide highly efficient chemical energy, given proper technology and management.

Currently, two main biological technologies, namely anaerobic digestion and aerobic composting, are widely employed for energy and resource recovery from solid organic waste. Anaerobic digestion, particularly prevalent in managing food waste, effectively breaks down organic materials through anaerobic microbial metabolism and produces biogas, which has diverse applications such as cooking fuel and electricity generation [6]. However, this method has certain drawbacks, including its limited processing capacity, restricted requirements regarding optimal environmental conditions, a narrow pH range, a limited presence of competitive electron acceptors, and difficulty in efficiently purifying and applying the produced biogas. The inadequate management of the generated biogas can lead to the release of greenhouse gases, further exacerbating global climate change [7]. On the other hand, composting, as an aerobic process that naturally transforms organic waste into beneficial soil amendment or mulch [8], also faces some limitations, such as the large footprint of the composting site, extended treatment periods, and environmental challenges related to odors and dust [9].

Microbial fuel cells (MFCs) offer a promising approach for harnessing chemical energy from organic-rich waste in the form of bioelectricity [10]. They are bio-electrochemical systems that oxidize organic-rich substances and release electrons through exoelectrogens [11,12]; the released electrons are transferred to the anodes and flow through the external circuits to generate an electric current [13]. In the past decades, MFCs have been extensively tested for bioelectricity generation from various waste streams such as municipal wastewater and agro-food industrial wastewater [14]. The MFCs treating different types of wastewater have exhibited tremendous diversity in maximum power density, and high COD removal rates were frequently attained [15]. Research has been conducted on utilizing waste materials like blueberry and banana waste, which have demonstrated significant power generation in single-chambered MFCs [16,17]. Although the MFC system has advantages such as direct energy generation and COD elimination, it also faces some of the same difficulties as other technologies, including complexity and technical difficulties, a lengthy startup time, and susceptibility to environmental factors [18]. Nonetheless, there is a lack of comprehensive research investigating the use of solid organic waste as a viable feedstock in MFCs [19]. The specific physical and chemical properties of organic solid waste, as opposed to waste streams, can hinder the efficient passage of electrons from organic substrates to the electrode [20]. Despite these challenges, previous studies have demonstrated encouraging results in terms of substrate oxidation and bioelectricity generation. The maximum power density using various organic feeds ranged from 2.06 to 8.1 W/m³ in different research studies [21,22]. To optimize the performance of MFCs in treating organic solid wastes, it is crucial to expand our understanding of how the physical and chemical properties of organic feeds influence the MFC's overall efficiency and effectiveness.

Consequently, there is a major knowledge gap concerning the treatment of organic substrates in MFCs and the influence of their physicochemical properties on MFC performance. Hence, this study investigated the performance of selected organic solid wastes, including food waste (FW), piggery waste (PW), and activated sludge (AS), as the feeds of MFCs for bioelectricity generation and organic elimination in laboratory-scale systems. In addition, the effects of a few physicochemical properties, including the feed particle size, moisture content, and C/N ratio, were studied for potential performance enhancement in the application of MFCs for organic solid waste treatment.

2. Materials and Methods

2.1. Organic Solid Waste Collection and Preparation

Three typical organic solid wastes, namely food waste (FW), piggery waste (PW), and activated sludge (AS), from local sources were chosen for the present study. The FW and AS were collected separately from the student canteen and wastewater treatment plant, respectively, at an educational institute in Pathum Thani, Thailand; PW was collected from a piggery farm in the same province of Thailand. The collected waste samples were characterized and/or processed for a designed laboratory experiment. To investigate the

effects of the feed physicochemical properties on bioelectricity generation in MFCs, the maximum particle size, moisture content, and C/N ratio of the collected organic waste samples were modified before specific tests. The organic waste's particle size was regulated using a mincer (OEM, Bangkok, Thailand) equipped with 3 and 1 mm sieves, respectively. The maximum sieve sizes for each were 3 and 1 mm, and the <1 mm size was achieved by blending the 1 mm particle size in a blender. The moisture content of the organic waste was adapted to approximately 70%, 80%, and 90% using distilled water. The C/N ratio of the organic waste was controlled at 20/1, 30/1, and 45/1 using analytical-grade starch and ammonium nitrate (NH_4NO_3).

2.2. Laboratory-Scale MFC Setup and Operation

Figure 1 shows the schematic diagram of the single-chambered air cathode MFC used in the present study. The MFC reactor had an effective volume of 0.7 L, with dimensions of 10 cm in width, 10 cm in height, and 7 cm in length. Two cylindrical carbon brushes (Tongfuyu Industry, carbon brush electrode, Shenzhen China), each measuring 4 cm in diameter and 10 cm in length and with a total surface area of approximately 220 cm^2 , were inserted into the anode chamber. A piece of cation exchange membrane with a surface area of 70 cm^2 (Ionsep, Ionsep-AM, Nantong China) was used to separate the anode chamber and the air cathode. A low-cost air cathode was fabricated on a stainless-steel mesh by covering one side with a diffusion layer and the other with a catalytic layer. The mesh was initially immersed in acetone for 24 h and subsequently heated at 90°C for 2 h. The catalytic layer comprised 10% carbon black and 90% activated carbon and PTFE, while the diffusion layer consisted of PTFE and carbon black [23]. This assembly was supported on a stainless-steel mesh measuring $7 \text{ cm} \times 10 \text{ cm}$ with an effective area of 70 cm^2 . Copper wires were used to link the electrodes to a 200Ω external resistance during operation. With the use of a data logger and the Picolog6beta program (ADC-20 Terminal Board, Pico Technology Co., Ltd., Eaton Socon UK), voltage generation was observed. This configuration achieves high oxygen mass transfer coefficients and water pressure tolerance, resulting in increased current densities and power output. Furthermore, the activated carbon combined with carbon black improves the conductivity and efficiency of the cathode, boosting overall MFC performance [24].

Anaerobic sludge collected from an up-flow anaerobic sludge blanket (UASB) reactor in a local brewery wastewater treatment plant was seeded into the anode chambers. To prevent the growth of methanogens, the sludge was pre-treated at 100°C for 30 min before being incubated in MFCs for approximately 14 days [25,26]. A synthetic feed composed of 500 mg/L of acetate together with vitamins and minerals was provided during the start-up of the MFCs [27]. Once the open-circuit voltages of the MFCs reached stable levels, the selected organic wastes were gradually fed into the reactors to acclimate the microorganisms to a new environment. The inoculum was fed into the anode chambers for biofilm formation.

For each waste type, one reactor was operated in duplicate to compare bioelectricity generation using different organic solid wastes as the feeds of the MFCs. The organic solid waste providing the best bioelectricity generation was further examined for the effects of different feed physicochemical properties, as mentioned above in Section 2.1. A solid retention time (SRT) of approximately 30 days was set for all batch tests. Following this time, all of the reactor's contents were swapped out before it was fed for the following cycle. A room temperature of approximately 35°C and a neutral pH of ~ 7 were maintained using a phosphate buffer solution in all MFCs during operation.

2.3. Laboratory Analysis

The collected organic solid waste samples were characterized for total solids, volatile solids, moisture content, tCOD, total Kjeldahl nitrogen (TKN), and total organic carbon (TOC). The total solid, volatile solid, and moisture contents were determined following the US EPA standard method 1684 [28]. The tCOD was measured according to the standard

titration method [29], and the TOC was analyzed following the modified Walkey and Black method [30]. The TKN was analyzed using the Kjeldahl method [30]. The C/N ratio of the organic feed was determined by dividing the TOC by the TKN [31].

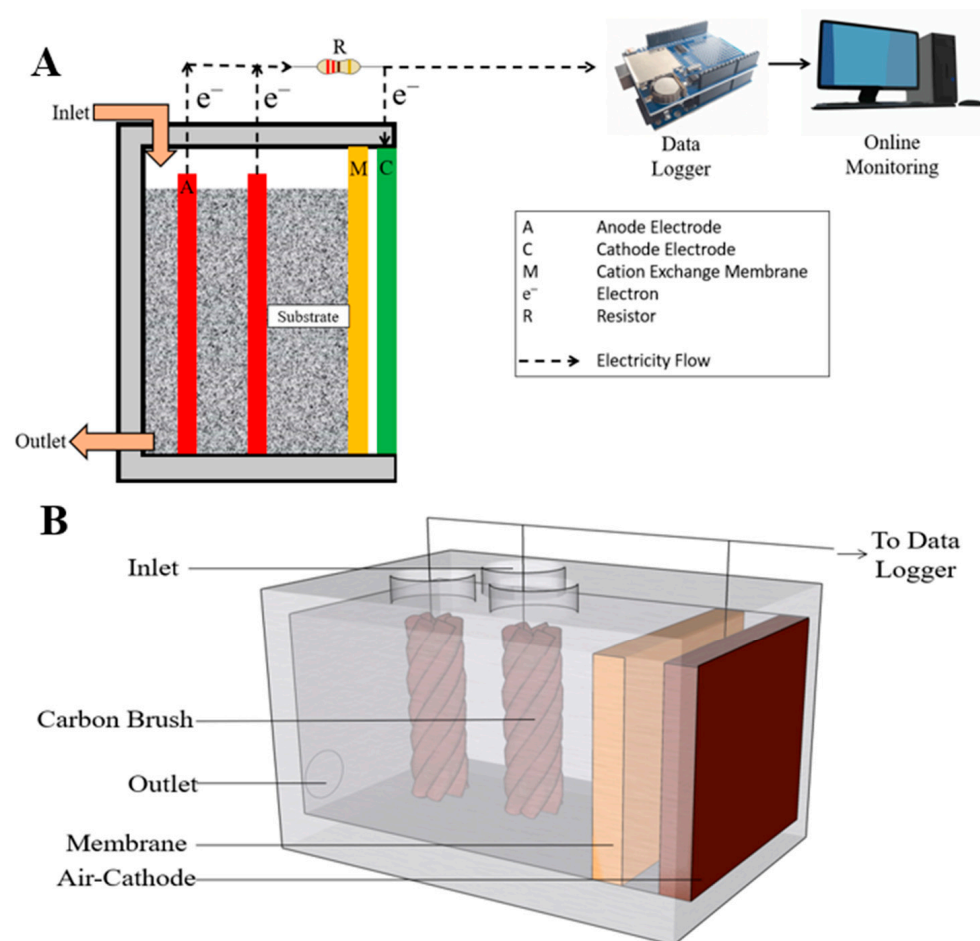


Figure 1. (A) Schematic diagram of the single-chambered MFC used in this study; (B) MFC system setup.

The polarization curve was depicted at the beginning of each reactor operation to determine the maximum power density and internal resistance of the MFCs at a steady state. The curve was plotted for power density (W/m^3) and current density (A/m^3) at different external resistance levels ranging between 1000 and $10\ \Omega$ [32].

2.4. Data Analysis

The power density and internal resistance of the MFC were determined using Equations (1) and (2), respectively, as follows [32]:

$$P = \frac{V^2}{V_A \times R_{\text{ext}}} \quad (1)$$

$$R_{\text{int}} = \frac{V_{\text{OC}} - V}{I} \quad (2)$$

where P is the power density, W/m^3 ; R_{int} and R_{ext} are the internal and external resistances, Ω ; V is the cell voltage generation, V ; V_{OC} is the open-circuit voltage, V ; I is the electric current, A ; and V_A is the volume of the anode chamber, m^3 .

The coulombic efficiency (CE) was calculated based on the tCOD removal in the MFCs as follows [33]:

$$CE = \frac{\sum (I \times \Delta t)}{F \times \text{sCOD}_{\text{removed}} \times 4} \times 100\% \quad (3)$$

where F is Faraday's constant (i.e., 96,485 C/mol) and $\text{tCOD}_{\text{removed}}$ is the total COD removed within a time interval of t , mol.

A one-way analysis of variance (ANOVA) was adopted to compare the performances of MFCs fed with organic feeds possessing varied physicochemical properties, i.e., organic feed type, particle size, moisture content, and C/N ratio.

3. Results and Discussion

3.1. Characterization of Selected Organic Wastes

The physical properties and chemical compositions of organic solid wastes were heterogeneous, depending on their specific sources. Table 1 summarizes the physicochemical characteristics of organic solid wastes selected in this study in comparison with previous findings. All selected solid food wastes originally had a moisture content of around 70%, which was, in general, comparable with those measured in similar types of organic solid wastes [34]. The FW had the highest solid content of 27.5%, followed by PW (17.6%) and AS (4.8%). The FW contained a higher volatile proportion of up to approximately 93.5% compared with a comparable proportion at approximately 87–88% in PW and AS. The total COD values measured in the three organic solid wastes were 226.5 ± 32.1 , 26.2 ± 8.1 , and 48.1 ± 11.3 g/L, respectively, at the same order of magnitude with a few previous studies [35]. According to [36], the C/N ratio of organic waste affects the microbial community and rate of electron transfer, which may result in different performance levels in biological treatment processes. In the current study, the C/N ratios of the FW and AS were similar to those found in the works of the literature shown in Table 1, whereas a slightly low C/N ratio of 9.8% in the PW was noted due to the relatively high nitrogen content in the raw waste. In summary, the organic solid wastes had a composition similar to those of other types of organic wastes reported previously, which implies a good generalizability of the results obtained from this study.

Table 1. Characterizations of selected organic solid wastes and their comparison with previous findings.

Waste Type	pH	TS (%)	VS/TS (%)	MC (%)	COD (g/L)	TOC (%)	TN (%)	C/N	References
Food waste	6.5	27.5 ± 3.3	93.5 ± 1.2	72.5 ± 3.3	226.5 ± 32.1^a	52.4 ± 3.8	1.9 ± 0.2	28.0 ± 3.8	This study
Piggery waste	8.2	17.6 ± 2.6	88.7 ± 1.5	82.4 ± 4.0	26.2 ± 8.1^a	46.3 ± 2.1	4.7 ± 0.2	9.8 ± 2.1	This study
Activated sludge	7.1	4.8 ± 2.0	87.2 ± 1.6	95.2 ± 3.3	48.1 ± 11.3^a	38.2 ± 2.2	2.9 ± 0.2	13.2 ± 2.0	This study
Food waste	n.a.	12.9	88.2	87.1	117 ^a	49.8	4.0	12.5	[35]
Food waste	n.a.	17.5	0.94	82.5	n.a.	51.2	2.8	18.3	[34]
Cattle manure	n.a.	29.3	n.a.	70.7	n.a.	42.6	1.5	28.4	[37]
Raw piggery waste	7.9	n.a.	n.a.	n.a.	$19.3^a/7.0^b$	n.a.	n.a.	n.a.	[38]
Composting product	6.5	39.0	62.0	61.0	n.a.	38.0	1.7	22.4	[39]
Wastewater	n.a.	15.67 g/L	10.5 g/L	n.a.	11.4 ^a	n.a.	n.a.	n.a.	[40]
Activated sludge									

^a total COD; ^b Soluble COD; n.a., not available.

3.2. Performance of Selected Organic Solid Wastes as the Feed of MFCs

The performance of the MFCs fed with three different organic solid wastes, i.e., FW, PW, and AS, is shown in Figure 2. With a fixed external resistance of 200 Ω , the MFCs fed with FW generated a voltage output of 0.72 ± 0.2 V compared with that obtained in the MFCs fed by PW (0.55 ± 0.2 V) and AS (0.28 ± 0.1 V). The polarization curves in Figure 2B indicate that a P_{max} up to 7.25 ± 1.4 W/m³ was obtained in the FW-MFC, surpassing those observed in the PW-MFC (3.86 ± 1.2 W/m³) and AS-MFC (1.54 ± 1.2 W/m³); although, comparable internal resistances were measured in the three MFCs. The good performance regarding bioelectricity generation in the FW-MFC can be explained by the fact that the FW was much richer in biodegradable organic contents compared with PW and AS. This can be

corroborated by the tCOD removal results in Figure 2D, showing that approximately 76.9% of the tCOD could be eliminated in the FW-MFC after the 30-day batch test, exceeding the values obtained in the other two reactors despite their lower initial tCOD in the corresponding organic waste feeds. The FW's volatile composition allows for rapid breakdown and uptake by anaerobic microbes [41]. In addition, [42] suggested an optimum C/N ratio of organic feed for anaerobic digestion of 25–30. The presence of easily biodegradable organics, as well as the suitable C/N ratio for the anaerobic microbial metabolic degradation of the FW, may be responsible for the higher bioelectricity generation in the corresponding MFC. A higher CE of up to 5.9% was observed in the PW-MFC, compared with the values of 1.9% and 0.8% observed for the AS-MFC and FW-MFC, respectively. This may be attributed to the high moisture content of AS and PW, which resulted in a higher mobility of ions and, hence, an enhanced electron transfer rate to the anode electrode.

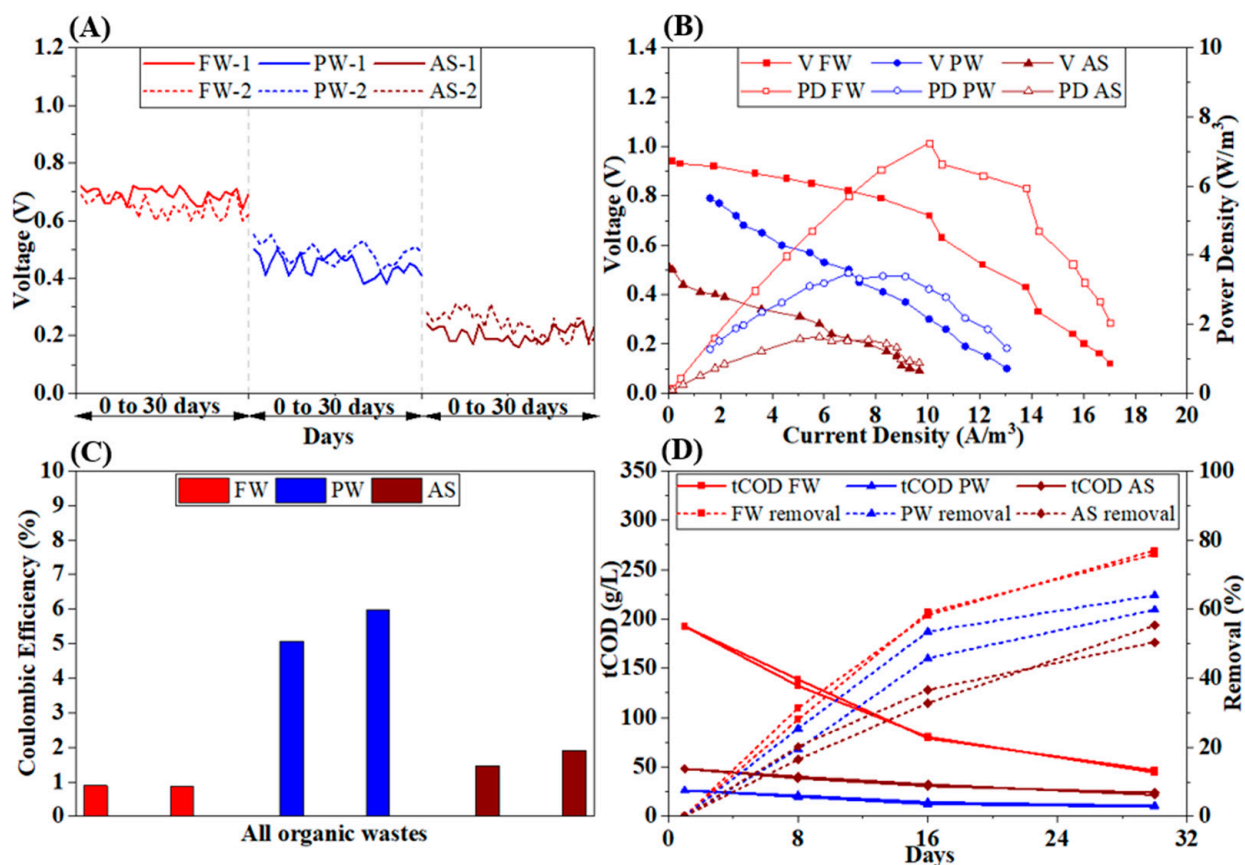


Figure 2. Performance of the MFCs with different organic solid wastes as feed: (A) voltage generation, (B) polarization curve, (C) coulombic efficiency, and (D) tCOD removal.

3.3. Effect of Particle Size on MFC Performance

A one-way analysis of variance (ANOVA) was adopted to compare the performances of MFCs fed with organic feeds possessing varied physicochemical properties, i.e., organic feed type, particle size, moisture content, and C/N ratio.

The effect of the maximum particle size of organic feed was investigated by mincing the FW and sieving it through a mesh sieve with a size of 3 mm, 1 mm, and <1 mm before feeding the FW into the MFCs. Figure 3 shows the voltage generation, $P_{\max}$, tCOD removal, and CE among the MFCs fed with FW with different particle sizes. Reducing the feed particle size from 3 to <1 mm significantly increased voltage generation by 38.5%, from 0.52 ± 0.1 to 0.72 ± 0.2 V, at an external resistance of 200Ω and enhanced the $P_{\max}$ by 73.9%, from 4.17 to 7.25 W/m^3 ($p < 0.05$). Such an increment in bioelectricity generation was especially observed when the particle size was decreased from 3 to 1 mm, whereas a slight improvement was observed when the particle size was further decreased to <1 mm.

In addition, a smaller feed particle size (i.e., ≤ 1 mm) in the MFCs resulted in a slightly higher COD removal (76.9%) and CE (0.8%) in comparison with a particle size as large as 3 mm (i.e., COD removal at 55.5% and CE at 0.4%). Table S2 shows the performance improvement in terms of the TOC and TN removal. The advancement in bioelectricity generation and pollution removal in MFCs that were fed compounds with a smaller particle size is probably due to the greater surface area of organic feed available for microorganisms. According to [43], it is easier for microorganisms to hydrolyze and ingest the organics when the particle size is reduced.

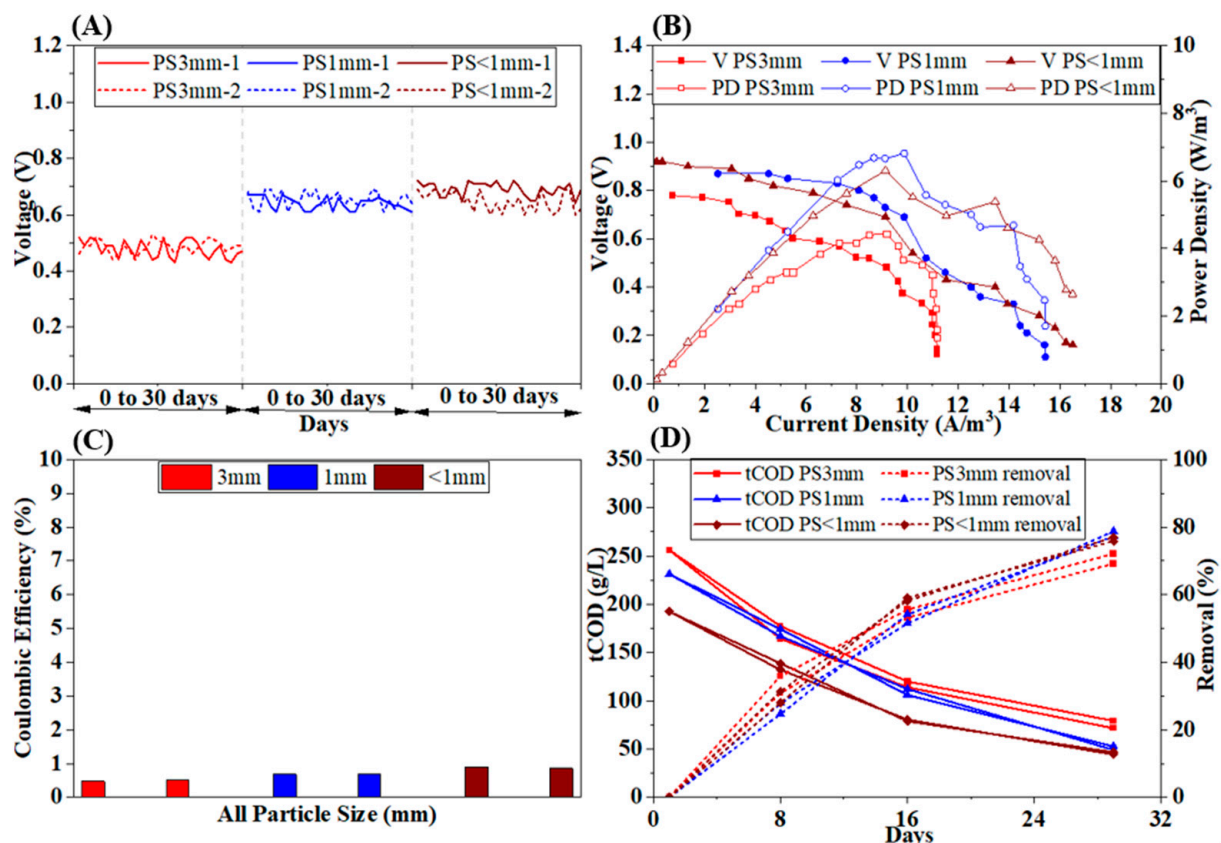


Figure 3. Performance of the MFCs depending on the feed particle size of food waste: (A) voltage generation, (B) polarization curve, (C) coulombic efficiency, and (D) tCOD removal.

3.4. Effect of Moisture Content on MFC Performance

The effect of food waste with a moisture content of 70%, 80%, and 90% on MFC performance was studied. Figure 4 shows the variations in the voltage output, polarization curve, coulombic efficiency, and COD removal in MFCs fed with food waste with different moisture contents. Increasing the moisture content of food waste from 70% to approximately 90% resulted in an increase in voltage generation from 0.69 ± 0.2 to 0.92 ± 0.1 V, accounting for a 33.3% increment despite the slightly diluted tCOD in the organic feed. Similarly, a maximum power density of up to 8.5 W/m^3 was obtained in the MFC fed with food waste with a moisture content of 90%, followed by 7.7 and 7.2 W/m^3 obtained in those fed with food waste containing 80% and 70% moisture, respectively. A tCOD removal ranging from 75.8% to 83.3% was observed in three parallel MFCs, with a slightly higher tCOD removal for the MFCs fed with food waste with a higher moisture content. This was in agreement with the findings regarding the TOC and TN removal (Table S3). For the CE, there was no such clear trend. As shown in Figure 4D, the CE of the tested MFCs increased from 0.85% to 1.46%, increasing by approximately 58.2%, as the feed moisture increased from 70% to 90%.

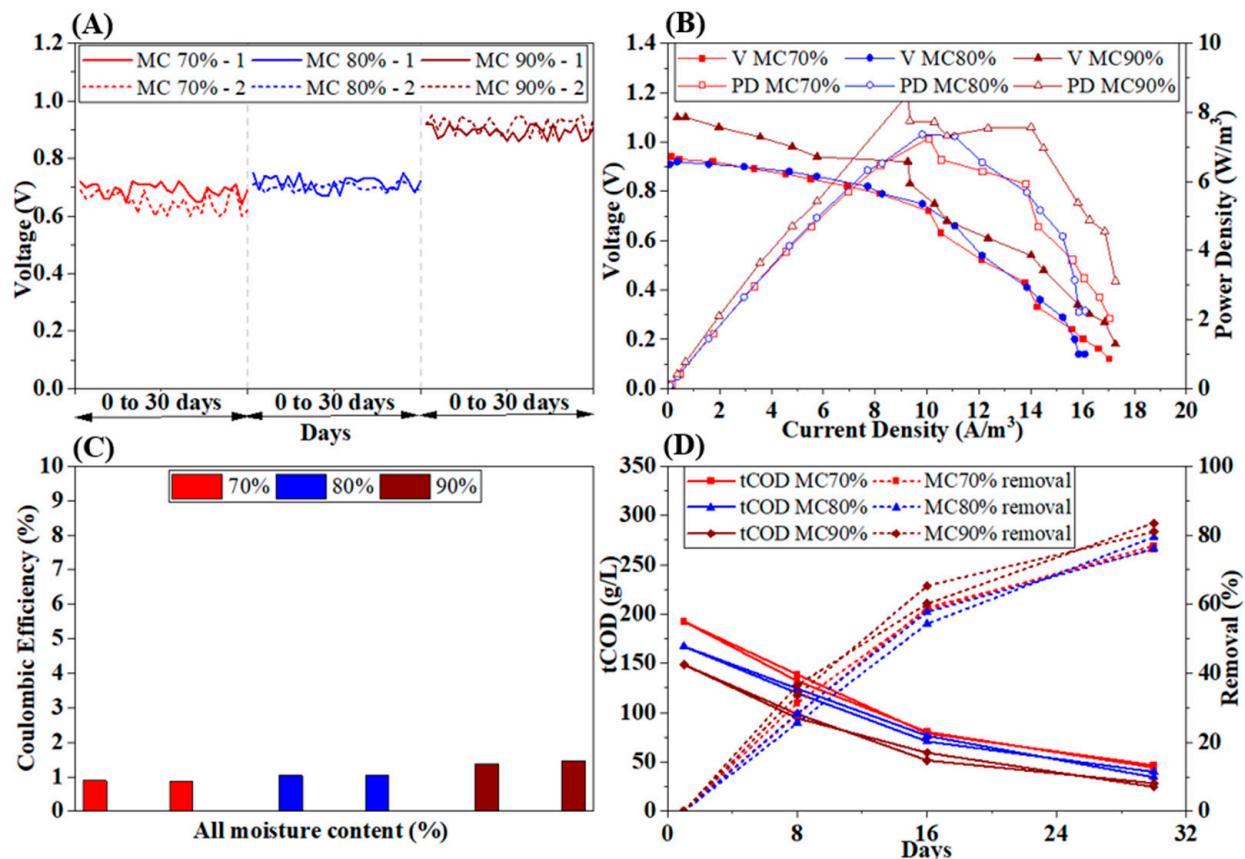


Figure 4. Performance of the MFCs with different feed moisture contents of food waste: (A) voltage generation, (B) polarization curve, (C) coulombic efficiency, and (D) tCOD removal.

These results indicate that increasing the feed water content in a solid MFC can significantly enhance its bioelectricity generation performance. A similar observation has been reported previously [44] for anaerobic digesters treating organic solid waste, where an increased moisture content in organic feed tended to result in higher methane production. The authors of a previous study [45] have also pointed out that moisture is necessary for microorganisms to remain alive and active and facilitates the effective transfer of electrons from the microorganisms to the electrode in the anode chamber of an MFC. Also, according to [46], the moisture content in microbial fuel cell air cathode affects the CE by influencing oxygen penetration, which is critical for supporting effective cathodic reactions and maximizing electron transmission. The continuous increase in the CE with an increase in the feed moisture content, as shown in Figure 4D, supports this assumption. In addition, high moisture accelerated the physical and chemical breakdown of organic substances in the organic feed, making them easily available to microorganisms.

3.5. Effect of C/N Ratio on MFC Performance

The effects of food waste with C/N ratios of 20/1, 30/1, and 45/1 on the performance of the MFCs are shown in Figure 5. A moderate feed C/N ratio of 30/1 resulted in the highest voltage output and maximum power density of 0.72 ± 0.1 V and 7.25 W/m^3 , respectively, outperforming those obtained for the C/N ratios of 20/1 (0.56 ± 0.08 V and 4.07 W/m^3) and 45/1 (0.64 ± 0.1 V and 5.22 W/m^3). A C/N ratio outside the ideal range produces comparatively less power compared to that in the ideal range, i.e., C/N ratios at 25–30 [42]. With a much higher C/N ratio in the organic feed, insufficient nitrogen is available to sustain the anabolism of exoelectrogens. Therefore, the rates of organic carbon consumption and electron generation may decline [47]. However, a lower-than-necessary C/N ratio in the organic feed can cause ammonia accumulation in the anode chamber,

which in turn results in toxicity to the exoelectrogens and reduces the electricity generation efficiency in the MFCs [48]. The best COD reduction at 75.8% in MFCs fed with FW at a C/N ratio of 30/1 revealed that the most active organic consumption occurred at a moderate C/N ratio, in line with the observation for electricity generation. A comparable CE was observed in the MFCs operated under varied feed C/N ratios, as the CE is mainly determined by the extracellular transmission of electrons and is not affected by the nutrient availability in the organic feed [49].

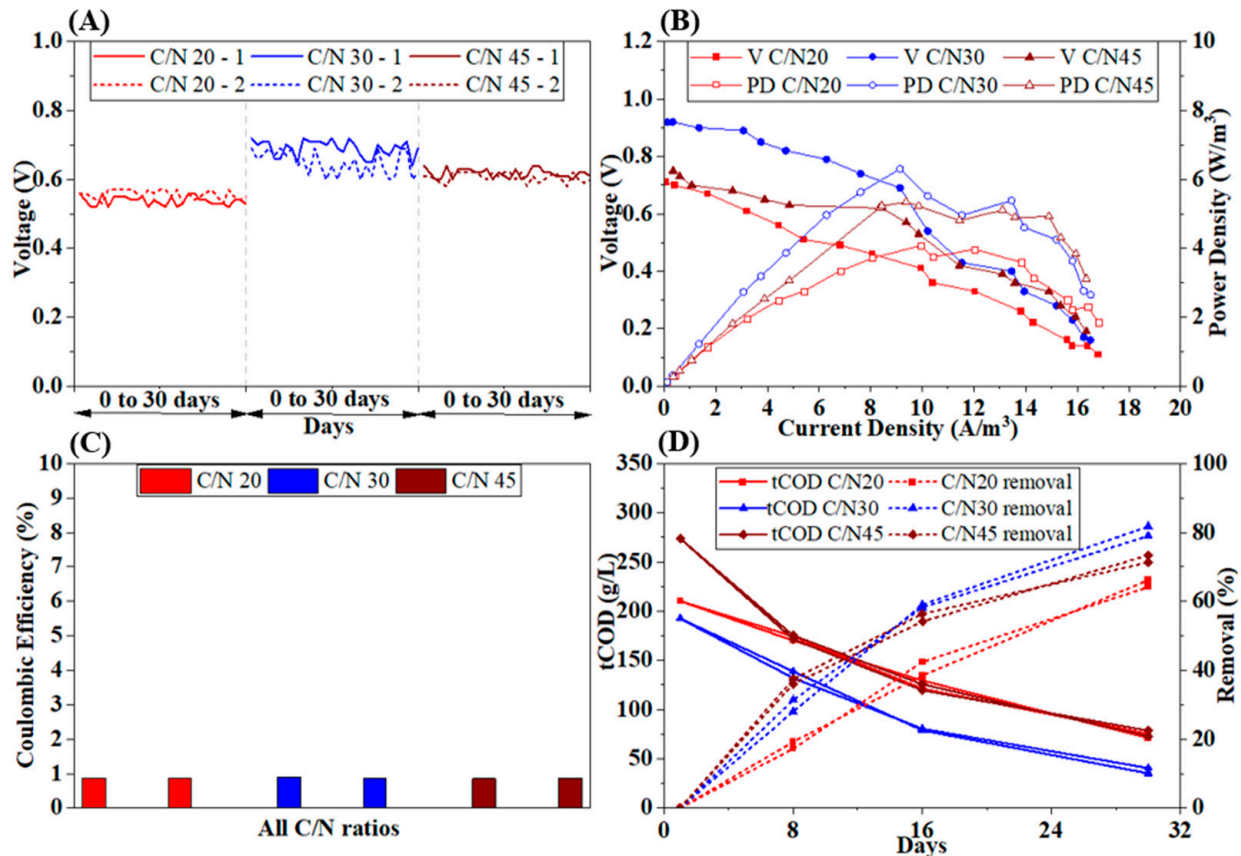


Figure 5. Performance of the MFCs with different feed C/N ratios of food waste: (A) voltage generation, (B) polarization curve, (C) coulombic efficiency, (D) tCOD removal.

3.6. Long-Term Operation of MFCs Connected in Series

The long-term operation of MFCs connected in series with food waste as the feedstock is depicted in Figure 6. During this long-term operation, the MFCs exhibited a consistent performance, achieving a peak voltage of 3.5 ± 0.1 V when all four reactors were operated in series. This increase in voltage occurs because the voltage across each cell in a series connection is additive, resulting in a higher overall voltage for the connected MFCs. However, it is important to note that the internal resistance of each cell also accumulates, which affects the total resistance of the circuit. The PD_{max} and tCOD removal achieved was 9.7 W/m^3 and 80%, respectively. The COD removal rate remained stable because all four reactors operated under identical conditions and utilized the same feed characteristics, as shown in Figure 2D. The coulombic efficiency (CE) was consistently around 10% throughout all phases. This consistency in the CE is attributed to the fact that the CE is primarily governed by the electrochemical processes within each MFC, which are not inherently altered by series connections. The internal reactions and microbial activities within each cell remain consistent, dictating the total charge produced through microbial metabolism and electron transfer processes. Consequently, while the cumulative voltage increases the total current output, the CE remains unaffected by the series connection.

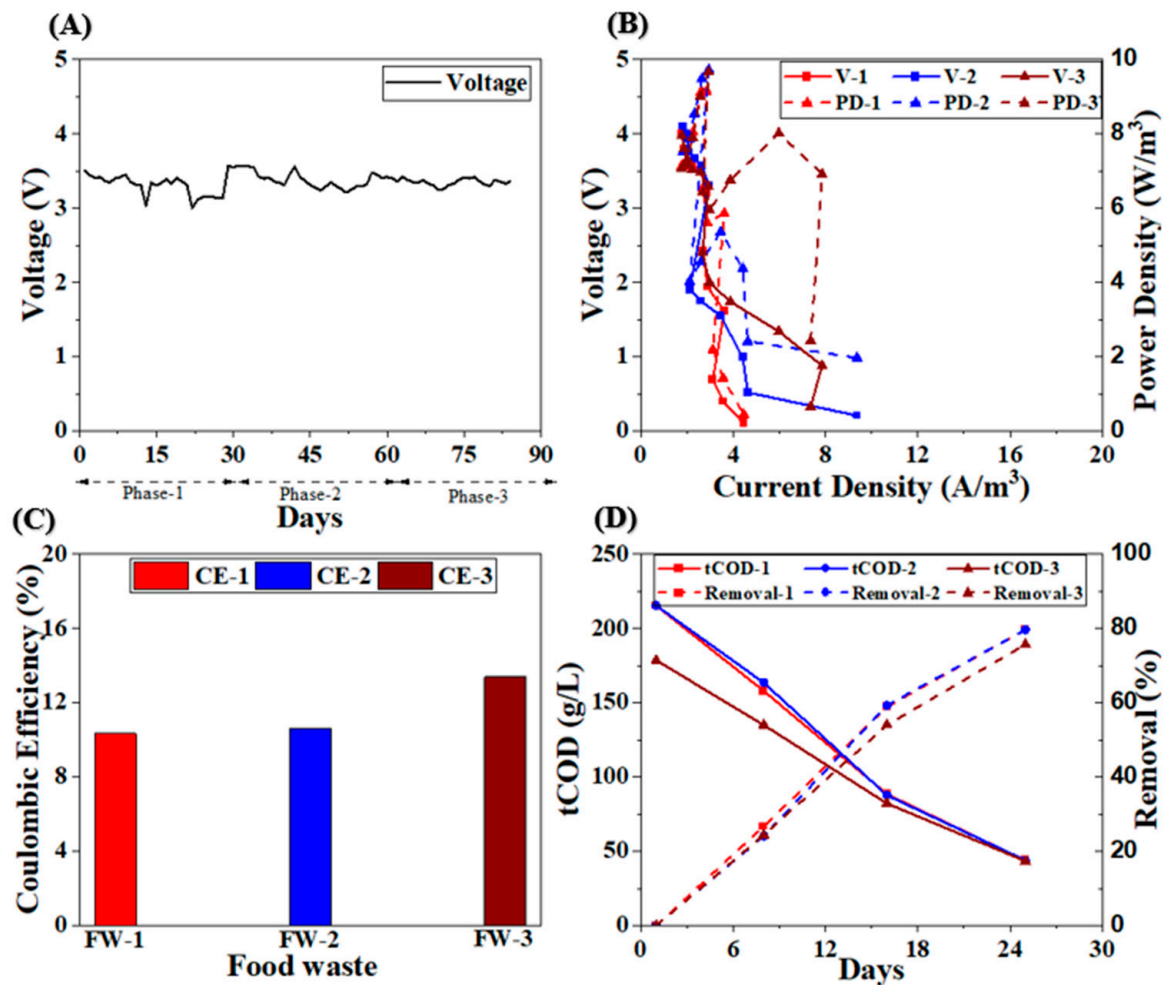


Figure 6. Long-term operation of the MFCs connected in series with food waste as the feed: (A) voltage generation, (B) polarization curve, (C) coulombic efficiency, and (D) tCOD removal.

3.7. Implications of the Present Study

Despite a good number of studies that have been conducted using various organic feeds in MFCs, only a few have looked into the use of various high-organic substrates as feeds in MFCs (Table 2). The current study demonstrates a superior voltage and power density production compared to most of its counterparts. MFC power generation has shown significant progress in small-scale systems, becoming an emerging power source. However, the practical applications of MFCs remain restricted due to challenges such as expensive materials, e.g., membranes and electrodes. To address these issues, more research is required, focusing on low-cost materials for electrodes and membranes.

Currently, only a few applications, such as micro-DC motors, LED lamps, and low power-demand clocks, can effectively use the low voltage produced by MFCs [50]. To enhance energy generation, it is imperative to expand the investigation to specific microbes responsible for substantial power output. This expansion would not only facilitate high power generation but also assist in identifying the most suitable microorganisms for improved performance.

Moreover, the current study only examined a limited range of solid organic wastes. To broaden the scope, further research is essential, encompassing various types of solid wastes and investigating their physicochemical properties to determine their potential for MFC applications.

Table 2. Bioelectricity generation performance of MFCs fed with different solid organic wastes in previous studies.

MFC Type	Organic Feed	Maximum Power Density (W/m ³)	Reference
Single-chambered air-cathode MFC	Food waste	7.25	This study
Single-chambered air-cathode MFC	Piggery waste	3.86	This study
Single-chambered air-cathode MFC	Anaerobic sludge	1.5	This study
Single-chambered air cathode	Household Food waste	7.7–8.1	[22]
Two chambered	Boiled solid potato	1.4	[51]
Single-Chambered	Landfill leachate	6.82	[52]
Two Chambered (H-type)	Landfill leachate	2.06	[21]
Single-chambered MFC	Cattle manure	0.02	[53]
Single-chambered air cathode MFC	Cattle manure	0.02–0.1	[38]
Two chambered MFC	Waste activated sludge	0.1	[40]
Single Cassette-electrode air cathode MFC	Cattle manure	16.3	[37]

4. Conclusions

The performance values of various organic solid wastes, i.e., FW, PW, and AS, as feed for MFCs were investigated in laboratory-scale systems. The maximum power density obtained in an MFC fed with FW was 7.25 W/m³, outperforming those with PW (3.86 W/m³) and AS (1.54 W/m³). The highest tCOD removal was obtained in the FW-MFC at 76.9%, compared with those observed for the PW-MFC (63.9%) and the AS-MFC (55.2%), after a 30-day operation cycle. This was attributed to the high content of easily biodegradable organics in the FW. Therefore, the FW was selected to further investigate the effects of various physicochemical properties (i.e., particle size, moisture content, and C/N ratio) of organic feed on the performance of MFCs. The highest maximum power density of 7.25 W/m³ and the maximum tCOD removal of 76.9% were observed for the smallest feed particle size (i.e., <1 mm), probably due to the high absorbability of smaller organic particles by exoelectrogens. Increasing the feed moisture from 70% to 90% resulted in an improved maximum power density by 17.5%, from 7.25 W/m³ to 8.52 W/m³, and a 10% higher tCOD removal, from 76.97% to 83.49%, respectively. Most likely, this occurred because the electron transmission in the cathode chamber was enhanced by increasing the feed water content. Furthermore, a moderate organic feed C/N ratio of approximately 30/1 facilitated bioelectricity generation and tCOD removal compared with a relatively low (20/1) or high (45/1) feed C/N ratio, suggesting the importance of the feed nutrient balance in bioelectricity generation in solid MFCs. In the long-term operation of MFCs using food waste, a peak voltage of 3.5 V was observed. This rise in voltage was due to the additive nature of voltages across individual cells in a series connection, leading to an increased overall voltage for the interconnected MFCs. Throughout all phases, the CE remained consistently around 10%. This steady CE was attributed to the electrochemical processes within each MFC, which are unaffected by series connection.

This work is novel since it investigates the performance of MFCs in comparison to several high-organic solid substrates. The top-performing substrates were then chosen for further study to figure out how the physicochemical characteristics of the substrate impact MFC performance. Furthermore, this study was carried out with the custom reactor's design and dimensions considering the organic solid substrates as the feed in MFCs.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr12061110/s1>, Table S1: Characteristics of different organic waste before and after the reactor operation; Table S2: Characteristics of food waste with different particle sizes before and after the reactor operation; Table S3: Characteristics of food waste with different moisture content before and after the reactor operation; Table S4: Characteristics of food waste with different C/N ratios before and after the reactor operation.

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