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Sustainable Bioenergy Generation from Organic Waste: Harnessing the Bioelectric Potential of Combined Mango and Orange Peel Substrates in Microbial Fuel Cell Systems

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The utilization of agricultural residues as renewable energy feedstock offers a sustainable approach to mitigating environmental degradation and improving energy security. In the Philippines, yellow mango peel waste (YMPW) and orange peel waste (OPW) are abundant organic byproducts often improperly disposed of, contributing to ecological pollution and resource inefficiency. This study explores the potential of converting YMPW and OPW into electricity using microbial fuel cells (MFCs)—bio-electrochemical systems that employ electrogenic microorganisms to oxidize organic substrates and facilitate electron transfer. Focusing on the synergistic effects of combined fruit peel substrates, experiments were conducted using a dual-chamber MFC across substrate masses of 50 g, 150 g, and 300 g. Results showed that a 1:1 mixture of YMPW and OPW at 300 g yielded the highest power output of 0.28554 W, with a power density of 528.05 W/m³ and energy efficiency of 0.6225%. Individually, OPW and YMPW produced 0.21633 W (400.06 W/m³, 0.4732%) and 0.17501 W (323.65 W/m³, 0.4248%). Statistical analysis (ANOVA) confirmed significant differences among treatments ($F = 314.5888$, $P < 0.05$), highlighting the enhanced performance of the mixed substrate. These findings validate the viability of fruit peel waste as a feedstock for bioelectricity generation and underscore the potential of MFCs for decentralized, low-cost, and sustainable energy solutions. The research supports waste valorization within a circular economy and contributes to the advancement of clean, renewable energy technologies.

1. Introduction

The global shift toward renewable energy has advanced MFC technology, which converts organic matter into electricity through microbial action (Chen et al., 2019). MFCs offer a sustainable solution by generating power while treating organic waste (Sindhu et al., 2020). Recent attention has shifted toward agricultural residues such as YMPW and OPW, particularly in tropical countries like the Philippines (Sonawane et al., 2022). Mango output in the Philippines reached 596.34 thousand metric tons in early 2023, contributing to waste generation (Philippine Statistics Authority, 2023). Similarly, citrus waste from oranges continues to accumulate due to both local production and imports (Philippine Statistics Authority, 2021). These organic by-products, rich in fermentable sugars, hold untapped potential for clean energy (Sindhu et al., 2020).

Most studies have focused on single substrates. Orange peel generated the highest voltage among bananas and mangoes in one study, but mixtures were not examined (Rahman et al., 2021). Mango peel has been tested for heavy metal removal, but not for energy when blended with other materials (Aleid et al., 2023). Electricity was generated from mango waste supplemented with Spirulina; however, no microbial characterization was performed (De La Cruz Noriega et al., 2022).

Other works tested fruit peels individually. Orange peel was evaluated for energy harvesting in hybrid piezoelectric systems (Gaur et al., 2020). Tomato, banana, and pineapple peels were used to generate power in a single-chamber setup (Kalagbor et al., 2020). Electricity was also produced from banana and orange peels (Elviliana et al., 2018). Tangerine peels have demonstrated potential as a bioelectric fuel source (Rojas-Flores et al., 2023). Organic feedstocks were emphasized for their role in MFC output (Moradian et al., 2021).

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Recent advancements in MFC technology have focused primarily on enhancing system efficiency through material and design innovations. Adebule et al. (2018) demonstrated improved power output from kitchen waste using redox mediators, while Gajda et al. (2020) enhanced anode performance through activated carbon modification. Rafieerad et al. (2021) investigated the potential of MXene and modified graphene for advanced electrode applications, and Flimban et al. (2019) discussed cost and scalability challenges in MFC deployment. Breheny et al. (2019) examined biocatalytic electrode designs to boost performance, yet such efforts often prioritize electrochemical components over substrate optimization. In parallel, Solangi et al. (2021) reviewed fruit waste primarily as a bio-adsorbent for environmental remediation rather than as an energy substrate. Studies by Wongkaew et al. (2021) linked mango peel composition to microbial fermentation behavior but did not assess its electrochemical energy potential. Capul et al. (2023) demonstrated sustainable system integration using solar-powered humidity control but did not address biomass-based electricity generation.

Fruit waste shows potential as an energy substrate. Still, most studies focus on single types, overlooking benefits of combining wastes with complementary nutrients that enhance microbial activity and electron generation. Microbial community dynamics are crucial for MFC efficiency, highlighting the need to understand their response to varied substrates and conditions. This study examines the combined electrochemical performance of yellow mango and orange peel wastes in single-chamber MFCs, optimizing feed concentration and temperature while analyzing microbial communities. This approach supports low-cost, sustainable energy from local waste in the Philippines and advances decentralized bioelectrochemical power systems.

2. Methodology

This study explores the conversion of combined YMPW and OPW into electricity using MFCs. A fixed 1:1 ratio of YMPW to OPW was maintained in the combined substrate group across all tests to evaluate potential synergistic effects. MFCs were constructed using locally sourced materials, and key parameters such as substrate concentration and electrode configuration were optimized to assess their impact on electricity generation. The following methodology was used for the experiments.

2.1 MFC Design and Construction

The MFC consists of a single-chamber unit that contains both the anode and cathode. The system includes the blended fruit peel substrate, electrodes, and container. The anode sits submerged at the bottom, creating an oxygen-free zone for microbial activity, while the cathode is positioned at the top, exposed to oxygen to enable reduction reactions. This setup optimizes microbial activity and electricity generation.

2.2 Preparation of Electrodes

Stainless steel wire mesh was cut into circular shapes to fit the containers and vertically split to serve as electrical connections. Heat shrink tubes (black for the anode, red for the cathode) distinguished the electrodes. Activated carbon was evenly glued onto the mesh to increase surface area, promoting bacterial colonization and biofilm formation, thereby enhancing microbial interaction and improving MFC electricity generation efficiency.

2.3 Preparation of the Substrate

YMPW and OPW were each processed into a homogeneous slurry using a 1:2 substrate-to-water ratio, with every batch prepared by mixing 50 g of peel with 100 mL of distilled water. The slurry was consistently measured and layered in the container in the following sequence: substrate, anode, additional substrate, and cathode on top, to maximize microbial interaction and enhance electricity generation.

2.4 Assembly of the Microbial Fuel Cell

MFCs were assembled by placing the prepared electrodes into containers, ensuring they were fully submerged in the substrate. The anode and cathode were connected to an external circuit to measure voltage and current. The setup was maintained under controlled conditions for consistency.

2.5 Automated Data Collection

A computerized monitoring system was developed using an Arduino Uno microcontroller, a MAX471 current sensor, and a desktop computer to enable continuous real-time monitoring of MFC performance. The sensor was connected to the MFC to measure current and voltage, with a 1 kΩ resistor placed at the V_{out} terminal to facilitate current measurement. The Arduino Uno, coded using the Arduino IDE, managed live data collection, with measurements automatically sent to the computer for documentation over 30 test runs.

Automation improved measurement accuracy and efficiency. Collected voltage and current data over time allowed for the precise calculation of power output and total energy generation.

2.6 Monitoring and Measurement

Voltage and current were periodically recorded throughout the two-hour experiment using automated Arduino sensors for continuous data collection. Power output was calculated from these measurements, and the accumulated data were saved for analysis.

2.7 Computation of Key Metrics

The following formulas were used to compute key metrics related to the MFC performance:
Power Density Eq(1): This section discusses the power density of the microbial fuel cell (MFC), a key parameter for evaluating energy generation efficiency relative to system volume. Power density, defined as the electrical power output (P, in watts) per unit volume (V, in cubic meters), enables direct comparison across different MFC designs and configurations and is expressed in watts per cubic meter (W/m³).

$$Power\ Density = \frac{P\ (W)}{V\ (m^3)} \tag{1}$$

To calculate the internal volume of the MFC chambers, cylindrical containers were used. Volume was determined using the formula in Eq(2):

$$V = \pi r^2 h \tag{2}$$

The radius (r) was fixed at 0.045 m, while the height (h) varied depending on the substrate mass: 0.0142 m for 50 g, 0.0425 m for 150 g, and 0.085 m for 300 g. These dimensions resulted in calculated chamber volumes of 9.03365×10^{-5} m³, 2.70373×10^{-4} m³, and 5.40747×10^{-4} m³.
Power output values measured at each substrate level were then divided by the corresponding volumes to determine power density and assess the efficiency of organic material conversion into electrical energy within the MFC system.
Energy Efficiency Eq(3): This metric represents the ratio of power output (P_{out})over the power input (P_{in}), expressed as a percentage. It was calculated as follows:

$$Energy\ Efficiency = \frac{P_{out}}{P_{in}}\ x\ 100\ \% \tag{3}$$

Power Eq(4): Power is calculated by multiplying the measured current (I, in amperes) by the measured voltage (V, in volts), resulting in power measured in watts (W).

$$Power = I\ x\ V \tag{4}$$

Running Energy Generation Eq(5): This metric represents the total energy generated during the experiment and is calculated by multiplying the power output (P, in watts) by the total operation time (T, in seconds), resulting in energy measured in joules (J).

$$Running\ Energy\ Generation = Power\ (W) x\ Time(s) \tag{5}$$

The collected data were analyzed to assess MFC performance under various substrate and electrode conditions. Power density, energy efficiency, and total energy output were systematically quantified and analyzed across multiple trials to optimize the operational parameters for electricity generation from combined yellow mango and orange peel waste.

3. Results and Discussion

This section presents the study's findings and their interpretation, including statistical analysis. ANOVA was used to assess significant differences among three groups—YMPW, OPW, and their combination—tested at substrate volumes of 50 g, 150 g, and 300 g.

3.1 ANOVA Test

As presented in Tables 1, 2, and 3, the results of the ANOVA tests for each substrate mass (50 g, 150 g, and 300 g) indicate that the computed F-statistics (58.4494, 42.2114, and 314.5888) all exceed the F-critical value of 3.1013, with P-values (8.1198×10^{-17}, 1.5385×10^{-13}, and 1.49875×10^{-40}) well below the significance threshold ($\alpha = 0.05$). These findings reject the null hypothesis and confirm statistically significant differences in mean power output among YMPW, OPW, and combined groups. Each treatment included 30 observations, ensuring strong statistical reliability.
YMPW consistently showed the lowest variance, followed by OPW, while the combined group had the highest. This trend suggests that YMPW offers more stable electrochemical performance, while the combined substrate

introduces greater variability, likely due to interactions affecting microbial activity or substrate degradation within the MFC system.

Table 1: ANOVA test Results between YMPW, OPW, and the combined peel waste of 50 g

Groups	*Sum*	*Average*	*Variance*	*Source of Variation*	*SS*	*df*	*MS*
YMPW	*0.2827*	*0.0094*	*8.5909E-07*	*BETWEEN GROUPS*	*0.0071*	*2*	*0.0035*
OPW	*0.7094*	*0.0236*	*6.76357E-05*	*WITHIN GROUPS*	*0.0053*	*87*	*6.0562E-05*
COMBINED	*0.9227*	*0.0308*	*0.0001*	*TOTAL*	*0.0123*	*89*	

Table 2: ANOVA test Results between YMPW, OPW, and the combined peel waste of 150 g

Groups	Sum	Average	Variance	Source of Variation	SS	df	MS
YMPW	1.5362	0.0512	2.6322E-05	BETWEEN GROUPS	0.06996	2	0.03498
OPW	2.9762	0.0992	0.0012	WITHIN GROUPS	0.0721	87	0.0008
COMBINED	3.5184	0.1172	0.00013	TOTAL	0.1421	89	

Table 3: ANOVA test Results between YMPW, OPW, and the combined peel waste of 300 g

Groups	Sum	Average	Variance	Source of Variation	SS	df	MS
YMPW	5.2505	0.1750	0.0001	BETWEEN GROUPS	0.1871	2	0.0936
OPW	6.49	0.2163	0.0006	WITHIN GROUPS	0.0259	87	0.0003
COMBINED	8.5662	0.2855	0.0002	TOTAL	0.2130	89	

3.2 Power versus Time Analysis

Power-versus-time analysis recorded MFC power output every 15 min over 120 min to assess performance. Figure 1a compares the power outputs of YMPW, OPW, and their combined mixture at masses of 50 g, 150 g, and 300 g. The highest output was observed with 300 g of combined waste, followed by 300 g of OPW and 300 g of YMPW, which exhibited slightly lower but comparable peaks.

The lowest outputs were observed for 50 g YMPW, followed by 50 g OPW and 50 g combined waste, indicating that power output increases with substrate mass. Across all masses, combined peel waste outperformed individual substrates, suggesting a synergistic effect enhancing microbial activity and electron transfer.

3.3 Percent Increase Graph

Figure 1b presents a percentage increase graph illustrating the relative rise in power output of the microbial fuel cell (MFC) as the substrate mass increases. The graph compares power outputs across three different raw material weights: 50 g, 150 g, and 300 g. By visualizing the percent change, the figure effectively demonstrates the direct relationship between substrate volume and power generation efficiency. This analysis is critical for optimizing MFC performance, as it provides insights into how variations in substrate quantity affect overall energy output and system efficiency.

3.4 Energy Efficiency

This section evaluates the energy efficiency of MFCs using fruit peel waste as substrate, focusing on how effectively chemical energy (in calories) is converted into electrical energy (in watt-hours). For YMPW, energy output increased with substrate mass: 0.00601 Wh (50 g), 0.05003 Wh (150 g), and 0.11597 Wh (300 g). With a carbohydrate content exceeding 9%, the estimated energy inputs were 4.55 cal, 13.65 cal, and 27.3 cal, resulting in efficiencies of 0.1321%, 0.3665%, and 0.4248%. For OPW, outputs were 0.01888 Wh (50 g), 0.08504 Wh (150 g), and 0.14195 Wh (300 g), with 10% carbohydrate content yielding inputs of 5 cal, 15 cal, and 30 cal. Corresponding efficiencies were 0.3776%, 0.5669%, and 0.4732%, demonstrating a strong improvement up to 150 g and a slight decrease at 300 g. In the combined YMPW–OPW system (1:1 ratio), energy outputs recorded were 0.02599 Wh for 50 g, 0.10281 Wh for 150 g, and 0.18582 Wh for 300 g. Corresponding energy inputs were approximately 4.975 cal, 14.925 cal, and 29.85 cal, yielding efficiencies of 0.5224%, 0.6888%, and 0.6225%.

The initial increase in efficiency from 50 g to 150 g can be attributed to greater substrate availability, which enhances microbial activity and electron production. However, the slight decline at 300 g likely results from substrate oversaturation, leading to diffusion limitations, microbial stress, or reduced oxygen transfer within the MFC system. In the combined group, additional complexity from multiple substrates may also influence microbial competition or byproduct accumulation, slightly reducing overall conversion efficiency. These findings suggest that both substrate mass and composition influence energy efficiency, highlighting the need for optimization to balance substrate loading with system capacity.

(a) *(b)*

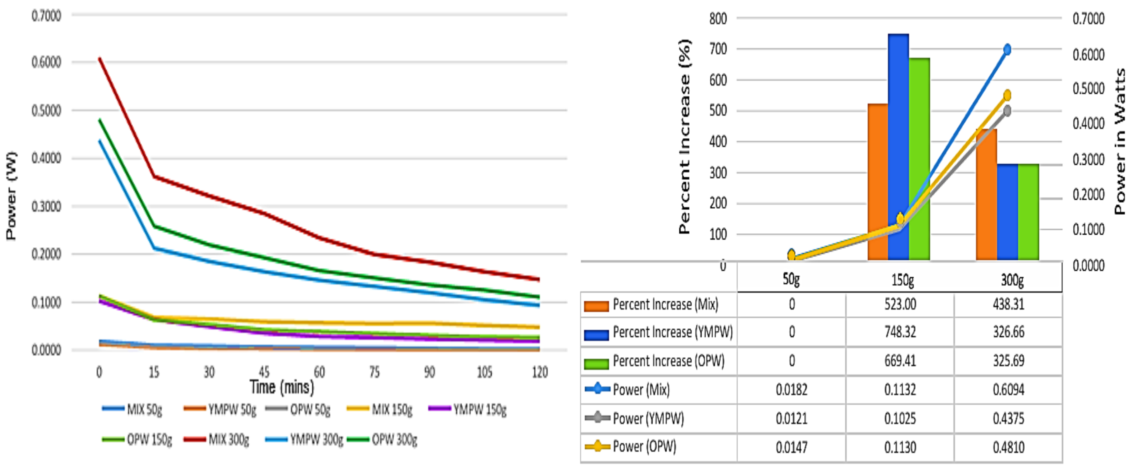

Figure 1: (a) Graph comparison of power versus time (b) Percent Increase Graph

3.5 Power Density

For YMPW, power outputs were 0.0094423 W (50 g), 0.0512 W (150 g), and 0.17501 W (300 g), resulting in power densities of 104.31 W/m³, 189.37 W/m³, and 323.65 W/m³. This indicates that power density increased with substrate mass, reflecting enhanced energy generation efficiency per unit volume.

For OPW, power outputs were 0.02364 W (50 g), 0.0992 W (150 g), and 0.21633 W (300 g), with corresponding power densities of 261.69 W/m³, 366.90 W/m³, and 400.06 W/m³. These results demonstrate a positive correlation between substrate mass and power density, highlighting OPW's ability to enhance MFC performance with increasing input.

Using a combined substrate of YMPW and OPW, power outputs were 0.03075 W (50 g), 0.112728 W (150 g), and 0.28554 W (300 g), yielding power densities of 340.39 W/m³, 416.93 W/m³, and 528.05 W/m³. These findings confirm that combining fruit peel waste leads to significantly higher power densities, indicating enhanced electrochemical activity and energy generation efficiency within the MFC system.

4. Conclusions

This study explored the use of combined YMPW and OPW in MFCs for bioelectricity generation. Using a fixed 1:1 ratio of YMPW to OPW, the system demonstrated the feasibility of converting agricultural waste into electrical energy, addressing both energy and waste management concerns.

Performance evaluation showed that the combined substrate outperformed individual peels in power output, power density, and energy efficiency, likely due to a more balanced nutrient profile supporting microbial activity. A gradual decline in power over time indicated substrate depletion and reduced microbial metabolism.

While the energy conversion efficiency remains below that of conventional technologies, the approach offers a sustainable, low-cost alternative using biodegradable waste. One limitation of the study is the absence of microbial community characterization, which limits understanding of the electrogenic processes involved. Future studies should integrate microbiological analysis to better link microbial behavior with energy performance.

Overall, the findings support the potential of fruit peel-based MFCs as a practical, decentralized renewable energy solution, particularly in agricultural regions like the Philippines

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