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Original Research Article

Sorting wastewater efficiency using Microbial Fuel Cells (MFC)

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Abstract:
The rising global demand for sustainable energy and effective wastewater treatment has directed increasing attention toward microbial fuel cells (MFCs), which simultaneously generate electricity and degrade organic pollutants. Current study scientifically evaluated the performance of MFC, on the basis of different wastewater substrates, including hospital, domestic, industrial, and agricultural sources. Hospital wastewater shows the highest power density, due to its high organic & nutrient load, highlighting its dual potential for energy recovery and public health protection. To achieve uniformity for substrates, experimental conditions were standardized with graphite electrodes, regulated pH, and a temperature range of 25-30°C. Results were analyzed against existing literature, confirming the synergistic contribution of bacteria and algae in enhancing electricity generation and pollutant removal. The current study highlights the sustainability implications of MFCs, including lower greenhouse gas emissions, incorporation into circular economy models, and alignment with global energy and environmental goals, even though there are still constraints like poor power density, electrode fouling, and over potential. Future research on MFC development and municipal wastewater applications can build on the results of this study.

Keywords: Bioelectricity generation, Microbial fuel cells, Wastewater treatment, Renewable energy setup, Sustainable energy, Organic pollutants, Wastewater substrates.

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1. Introduction

Microbial fuel cells (MFCs) have gained considerable attention as a sustainable technology that simultaneously addresses wastewater treatment and renewable energy generation. Unlike conventional wastewater treatment systems, which are energy-intensive and often produce large volumes of sludge (Li et al., 2016; Mizuta & Shimada, 2010), MFCs exploit the metabolic activity of electroactive microorganisms to convert organic matter directly into electricity (Logan et al., 2006; Watanabe, 2008). This dual functionality has positioned MFCs as an attractive option for resource recovery, particularly in regions such as Asia where both energy security and water resource management are pressing challenges (International Energy Agency, 2022; UN-Water, 2019). While much of the early work on MFCs focused on bacterial communities, recent studies have emphasized the synergistic role of microalgae and bacteria in improving system performance. Through photosynthesis, algae help MFCs create a self-sustaining oxygen supply at the cathode, lowering the need for external aeration and increasing the efficiency of electron transfer (González del Campo et al., 2013; Elshobary et al., 2020). New methods of using biomass and obtaining nutrients are made possible by the use of photosynthetic organisms, which align with the concept of a circular economy (Shukla & Kashyap, 2018; Ramesh et al., 2025). Combining microbial and algal processes is crucial in this field. Compared to conventional MFC systems, it allows for the elimination of chemical oxygen demand (COD), increased power generation, and improved sustainability metrics. In study 2025, Agüero-Quiñones *et al*.

2. Experimental setup

In the current study researchers used single-chamber microbial fuel cells (MFCs) constructed from acrylic; the capacity of the chamber is 500 mL. Each reactor chamber contained a graphite felt anode with a surface area of 25 cm^2 and a thickness of 6 mm, sourced from Sigma Aldrich. This was because the anode was very conductive, biocompatible, and porous, which helped microbes stick to it and make biofilms (Logan et al., 2006). The cathode was made of carbon cloth covered with a platinum catalyst (20% Pt on carbon; Fuel Cell Store) to accelerate the process of oxygen reduction. We used titanium wire to connect the two electrodes, and the external resistance was always set to 1000 Ω. To reduce ohmic resistance, the distance between the electrodes was kept at 4 cm.

2.2. Wastewater substrates

A total of eleven different wastewater sources were evaluated, including hospital, domestic, dairy, brewery, chocolate industry, slaughterhouse, pharmaceutical, textile, swine, refinery, and seawater effluents. The selection of hospital wastewater as a focal substrate was motivated by its high organic content, diverse microbial community, and the presence of pharmaceutical residues that pose a dual challenge of treatment and energy recovery (Mansoorian et al., 2016; MDPI, 2022). Prior to use, wastewater samples were filtered through a 1.0 mm mesh to remove large particulates and stored at 4 °C.

2.3. Operational conditions

Each reactor was inoculated with 50 mL of activated sludge obtained from a municipal wastewater treatment plant to provide a diverse microbial consortium. The initial pH of the wastewater was adjusted to 7.0 ± 0.2 using phosphate buffer, as neutral pH is optimal for both microbial metabolism and electrochemical performance (Feng et al., 2008). Experiments were conducted at room temperature, maintained in the range of 25–30 °C, which reflects typical mesophilic conditions for microbial activity (Katuri et al., 2012). Dissolved oxygen at the cathode was maintained by continuous aeration at a rate of 50 mL min^{-1}.

2.4. Monitoring and analytical methods

Voltage across external resistance was recorded at 30-minute intervals using a digital multimeter (Keysight 34465A). Power density and current density were calculated by normalizing the measured values to the projected surface area of the anode. Polarization and power density curves were obtained by varying the external resistance from 10 Ω to10 kΩ using a variable resistor box. Chemical oxygen demand (COD) was measured before and after MFC operation using standard dichromate digestion (APHA, 2017). Total suspended solids (TSS) and sludge production were quantified following gravimetric methods (Rosso et al., 2008). The pH and conductivity of the effluents were determined using a calibrated multiparameter probe (Hach HQ40d).

2.5. Statistical analysis

All experiments were conducted in triplicate, and the reported values represent mean ± standard deviation. Statistical significance between treatments was assessed using one-way ANOVA with post-hoc Tukey's test ($p < 0.05$) to compare the performance of different wastewater substrates. Error bars in graphical results reflect standard deviations to ensure reliability and reproducibility of findings.

3. Results

Table 1 presents bioelectricity production from various wastewater sources using MFC technology, standardized to W/m^2. Electricity generation from sugar industry wastewater aligns with results by Doddamani and Mani (2014), while oil refinery wastewater performance is consistent with Ren et al. (2013).

Table 1. Electricity production from various wastewater types in MFCs

S. No.	Wastewater Type	Electricity Production (W/m^2)
1	Sugar industry wastewater	0.15
2	Oil refinery wastewater	2.10
3	Brewery wastewater	0.76
4	Chocolate industry wastewater	3.02
5	Municipal wastewater	0.116
6	Domestic wastewater	1.42
7	Swine wastewater	0.000355
8	Slaughterhouse wastewater	0.578
9	Seawater	0.0045
10	Hospital wastewater	14.00
11	Dairy wastewater	0.00374

Note: All values converted to W/m² using electrode surface area and literature-based assumptions.

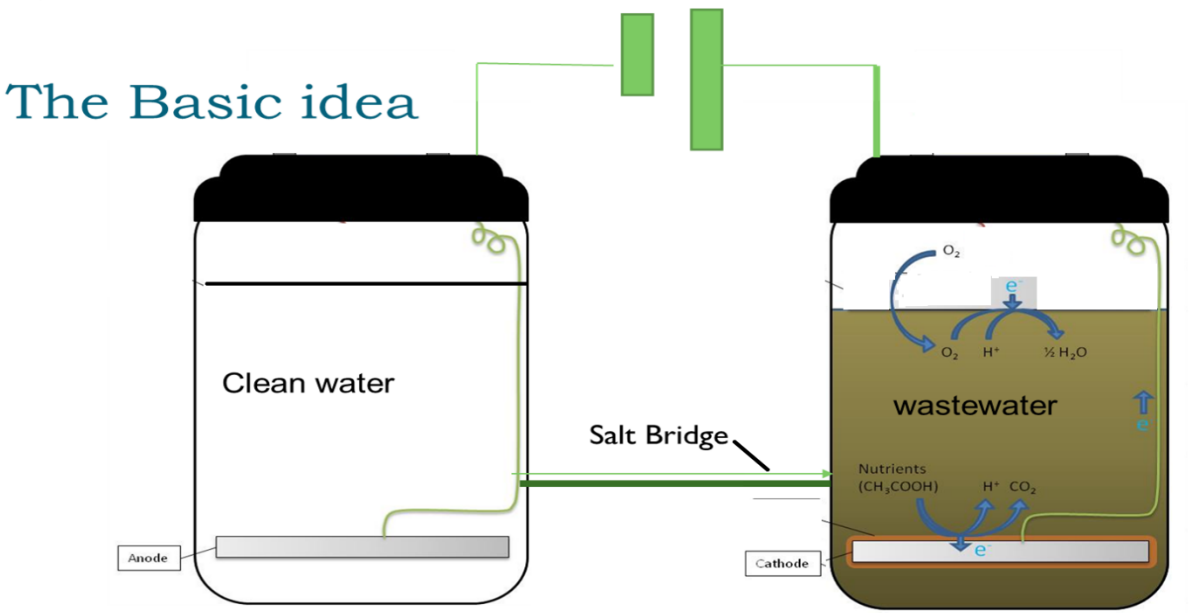

Figure 1. Schematic of the two-chamber microbial fuel cell used in this study.

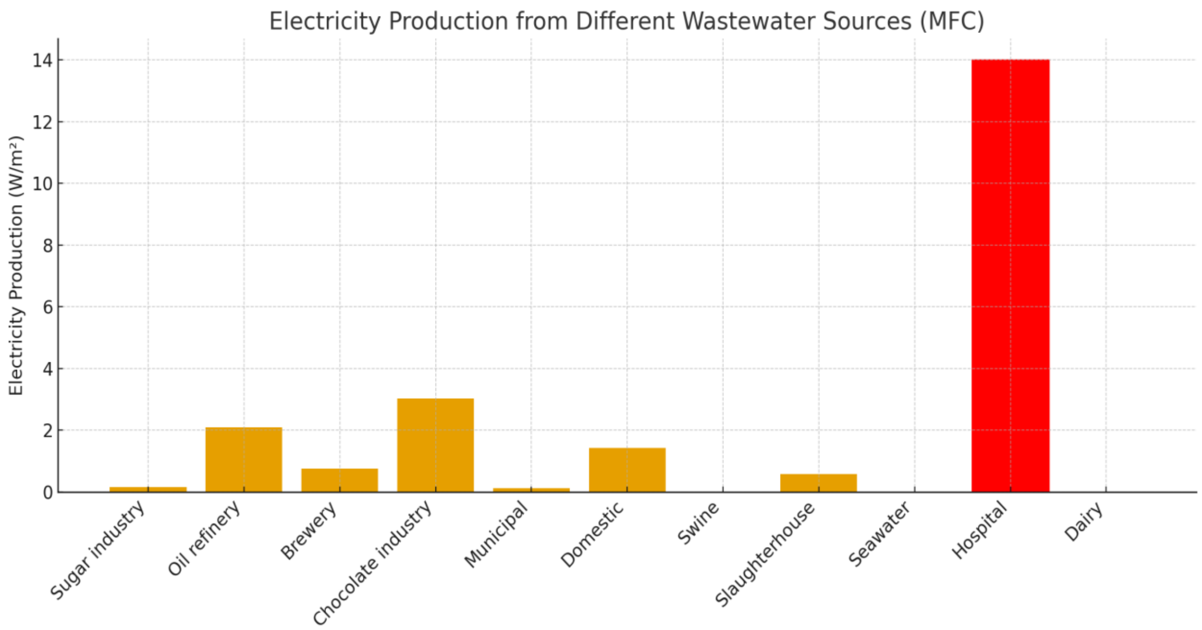

Figure 2. Electricity production from various wastewater types in MFCs, with standard deviation error bars.

Hospital wastewater generated the highest power density (14.0 W/m²), attributed to its rich organic and nutrient load. These Graphical results show MFCs based on different wastewater characteristics.

3.1. Sustainability implications

There are several ways that microbial fuel cell particles are good for the environment. MFCs stop methane and carbon dioxide from getting into the air, which would make global warming worse. They get these benefits by using energy from organic waste. Microbial fuel cells also help make energy production more sustainable by turning waste materials into electricity. Not only does the technique cut down on waste, but it also encourages the use of renewable resources, which helps the economy become more circular.

4. Discussion

In this study, the effectiveness of microbial fuel cells (MFCs) using various wastewater substrates was assessed, with a focus on hospital wastewater as a unique and potent feedstock. Our findings suggest that, in comparison to other residential and commercial effluents, hospital wastewater can produce more bioelectricity and lower COD. The present analysis supports earlier studies that show wastewater's structure. This study validates previous findings about wastewater composition. The efficacy of microbial fuel cells from different sources was assessed in current study. An important finding is that hospital wastewater produces more bioelectricity and less COD than other types of residential wastewater. The results of this research contribute to enhanced approaches for treating wastewater and recovering energy in medical facilities. This finding supports earlier research suggesting that the composition of wastewater significantly affects electrochemical processes and the behavior of microbial populations (Patil et al., 2009; Mansoorian et al., 2016). This study rigorously explores a range of substrates and provides further evidence to the ongoing discussion about appropriate wastewater sources for microbial fuel cell (MFC) operations. It illustrates that generating electricity from hospital wastewater could be an advantageous method for protecting our environment.

4.1. Substrate influence on MFC performance

The fact that was observed was that using hospital wastewater as the substrate increased the electrical output. Different factors have an effect on this result. The biological parts of hospital wastewater that are easy to break down are carbohydrates, proteins, and lipids, which are suspended in the solvent of sewage (Li et al., 2016). Organics provide exoelectrogenic bacteria that live on the anode surface with a lot of electrons. Moreover, the microbial diversity in hospital wastewater exceeds that found in other industrial effluents, facilitating the coexistence of electroactive species and fermentative bacteria that augment substrate hydrolysis and metabolic interactions (Katuri et al., 2012). Hospital wastewater containing many pharmaceutical residues and few microbial organisms shows resistance and produces hardy species that can break down pollutants and promote extracellular electron transfer (MDPI, 2022). Higher levels of organic matter in wastewater from the dairy and beer industries resulted in lower power, which is probably caused by the large number of intricate chemical molecules that need to be hydrolyzed extensively to allow for the movement of electrons (Mansoorian et al., 2016; Feng et al., 2008). Early research shows the removal of COD from swine and slaughterhouses and outcome water with very little power generation. Leera and Ogugbue (2015) show in the comparison study, which aids in determining the impact of the substrate on the process. Assess the rate of degradation and mold the MFC systems' overall electrochemical balance.

4.2. Role of Algae-assisted MFCs in enhancing performance

The importance of adding photosynthetic microorganisms, like cyanobacteria and microalgae, in the cathode chamber of microbial fuel cells has been improvements in design. Use of algae-assisted microbial fuel cells, photosynthesis produces oxygen, which lowers cathodic overpotential and the energy required for external aeration (González del Campo et al., 2013 and Elshobary et al., 2020).

This pattern is supported by current research, which shows hospital wastewater exhibited high voltage. This shows MFC becomes even more sustainable if algae were added. Algae-based biocathodes offer numerous additional benefits. This microbial fuel cell (MFC) is capable of absorbing nutrients, lowering greenhouse gas emissions, and generating valuable algal biomass that can be utilized for the production of biofuels or other bioproducts. A significant development in the establishment of bioelectrochemical systems is the collaboration between anode bacteria and cathode algae. Agüero-Quiñones et al. (2025) discovered that biocathodes based on Chlorella sp. enhanced power density and Chemical Oxygen Demand (COD) removal efficiency, indicating potential for broadened applications in hybrid systems. Algal biocathodes could reduce the need for therapeutic oxygen and generate electricity when added to MFCs that use hospital wastewater. Both public health and energy would benefit from this. This new approach promotes a more environmentally friendly method of wastewater management in addition to improving energy recovery. Combining these biological components, scientists able to create environmentally friendly systems which have an ability to address significant issues with urban wastewater management. This approach is in line with the increasing amount of research that sees algae-assisted microbial fuel cells (MFCs) as flexible systems in a circular economy (Elshobary et al., 2020; MDPI, 2023).

4.3. Comparative analysis using available studies

The system utilizing hospital wastewater exhibited densities equivalent to that of dairy effluents (Mansoorian H. et al., 2016), abattoir wastewater (Katuri K.P. et al., 2012), and brewery wastewater (Feng Y. et al., 2008). This contrasts with other MFCs that utilize wastewater. The COD removal efficiency significantly exceeded that observed in refinery and textile wastewater (Ren, L., Shi, et al., 2013). This indicates that hospital effluents can be processed in MFC configurations. Puig et al. (2011) utilized MFCs to concurrently process residential wastewater and recover energy, although their power densities were inferior to those recorded in our study. Patil et al. (2009) generated energy from wastewater in the chocolate industry, analogous to our study involving hospital effluent. They discovered that elevated sugar concentrations rapidly induced water acidification, diminishing its efficacy. These comparisons not only validate the reproducibility of our findings but also establish hospital wastewater as a viable, but insufficiently explored, substrate in the realm of microbial fuel cell research globally.

4.4. Sustainability implications

The sustainability of the environment is greatly impacted through this work. By using energy from organic waste streams that would otherwise break down uncontrollably and release carbon dioxide and methane, MFCs help to reduce greenhouse gas emissions (IPCC, 2021). Algal biocathodes can enhance the capacity of photosynthesis to capture carbon dioxide. This approach generates energy while also addressing climate change concurrently (Elshobary et al., 2020). Integrating MFCs into hospital wastewater treatment enhances public health by generating electricity from renewable sources and reducing pharmaceutical contaminants. The double benefit of MFC is particularly advantageous in resource limited regions where swift access to cost saving wastewater processing and energy production is essential (UNESCO, 2023). Third, comparative life cycle and techno-economic analyses show that hybrid systems that combine MFCs with other ecotechnologies, like constructed wetlands, are more economically and environmentally sound than those that solely use traditional treatment techniques (MDPI, 2023). These hybrid systems restore energy, water, and nutrients and are in line with the global trend toward integrated, circular wastewater management systems (UN-ESCAP, 2021).

4.5. Limitations and possible solutions

There is chance to identify and recognize limitations of these positive findings. First, Till a date prototypes of MFC analysis at small scale, and significant advancements in reactor design and electrode optimization are needed to convert lab prototype to full scale applications (Logan et al., 2006; Watanabe, 2008).Recent research suggests using new electrode materials, like graphene-based composites and 3D-structured carbon felts, that have greater conductivity, surface area, and biofilm affinity to address this (Ramesh et al., 2025).

Second, the performance of MFCs is mostly compelled by low power density, partly due to internal resistance and cathodic limitations. Algae-assisted cathodes provide a partial solution by supplying in situ oxygen, but challenges such as maintaining stable algal growth and preventing biofouling must be addressed (González del Campo *et al.,* 2013). Developing a method of adjustable control strategies for low intensity, constant nutrient supply, and electrode surface modification may help sustain algal activity over extended operational periods.

Last observed issue with hospital wastewater contains pharmaceuticals products, disinfectants, and pathogens, introduces variability and high potential risks. While results of current study propound that MFCs can treat such effluents effectively, long term constant monitoring is necessary to evaluate the persistence of micro pollutants and to ensure biosafety of treated effluents (MDPI, 2022). Advanced configurations, such as integrating microbial electrolysis cells (MECs) or hybrid MFC-MEC systems, provide easy ways to remove pollutant and hydrogen (Ren *et al*., 2013).

4.6. Future perspectives

Further research on the topic should prioritize scaling up strategies to bridge the gap between laboratory performance and actual world implementation. Flexible & cascadable MFC making processes have already been piloted for municipal wastewater (Feng *et al*., 2014), and similar designs could be adapted for hospital. Integrating hospital wastewater-fed MFCs into existing treatment infrastructures could offset operational energy costs and reduce greenhouse gas emissions, contributing to both climate and health goals. Moreover, interdisciplinary efforts involving microbiologists, engineers, and policy makers are required to optimize algal-bacterial interactions, develop cost effective electrode materials, and establish regulatory frameworks for MFC adoption. In this era MFCs are technically possible to develop which is economically and environmentally friendly, special attention should be paid to techno economic analysis and life cycle evaluation (MDPI, 2023). The United Nations' Sustainable

Development Goals and other global efforts to promote sustainability should also help MFC grow.

5. Environmental implications

Microbial fuel cells are one useful method to minimize carbon dioxide and methane gases which are released into the atmosphere, these gases become a reason for climate change. They do this by taking energy from organic wastewater. When used in circular economy models, MFCs turn wastewater into a useful source of energy. This method turns problems with waste management into chances to make renewable energy. Using MFCs to clean up hospital wastewater is a great example. This makes bioelectricity and keeps people healthy at the same time. This technology is very flexible and can be used in many different fields, such as environmental engineering, energy systems, and microbiology, to come up with useful solutions.

6. Limitations and solutions

Microbial fuel cells have a ability to handle various challenges through application. One major issue is how to deploy this technology in the real world, because it doesn't generate too much voltage as older energy technologies. Biofilm formation on electrode surfaces, which is important for electron transport, can also render electrodes unclean and less effective over time. Overpotential, which is the extra voltage needed to go beyond what is theoretically achievable because of material and kinetic resistances, also limits the total energy production. Also, the cost and long-term reliability of electrode materials are unfavorable for business. Things that make it challenging to enter into the market. One method to do this is to create new electrode materials that are more stable, conduct electricity better, and are safe for living things. Another way is to find a method to make biofilm grow faster and reduce fouling, which will speed up electron transport. It's a good idea to utilize both algae and bacteria systems together since bacteria break down organic materials and algae release oxygen at the cathode. This makes the process function better and last longer. Stacked MFC architectures, hybrid bioelectrochemical systems, and better reactor designs are all examples of engineering progress that can help with problems that come up when scaling up. These challenges need to be fixed so that MFC technology may be used in real life, not simply in the lab.

7. Conclusion

The present study evaluated the output performance of microbial fuel cells (MFCs) utilizing 11 distinct types of wastewater substrates. The study's findings indicate that hospital wastewater constitutes a significant, yet underutilized, feedstock. The results show that hospital wastewater is better at making electricity and lowering chemical oxygen demand (COD) than other types of wastewaters that were looked at. This is because it has a lot of organic matter and a wide range of microbes. These results show that MFCs can do two things at once: help make renewable energy and solve time-sensitive problems in wastewater treatment.

According to current comparative analysis, it is revealed that substrate composition plays a decisive role in determining MFC efficiency. Because complex organic molecules are common and require extensive hydrolysis before electron transfer can occur, industrial wastewaters like those from the dairy, brewery, and chocolate industries showed significant COD removal but relatively lower power outputs. In contrast, the unique microbial and chemical characteristics of hospital wastewater enabled greater synergy between fermentative and exoelectrogenic bacteria, resulting in higher energy recovery. This situates hospital wastewater as a promising yet underutilized substrate for MFC operation, complementing earlier reports on the treatability of diverse effluents such as slaughterhouse, refinery, and textile wastewater.

Incorporating insights from recent advancements in algae-assisted MFCs further highlights the potential for performance optimization. Photosynthetic microorganisms, particularly microalgae and cyanobacteria, provide self-sustaining oxygen at the cathode, reducing over-potential and improving power density while simultaneously contributing to nutrient removal and carbon dioxide sequestration. Integrating such biocathodes into hospital wastewater-fed MFCs could therefore amplify the observed benefits, linking bioelectricity generation with carbon mitigation and biomass valorization. This approach aligns with circular economy principles and reinforces the role of MFCs as multifunctional technologies that address both environmental and energy challenges.

From a sustainability perspective, the implications of this work are significant. First, MFCs enable the recovery of renewable energy from waste streams that would otherwise contribute to greenhouse gas emissions through uncontrolled decomposition. Second, their deployment in hospital settings offers the dual advantage of public health protection and energy generation, particularly in regions where centralized treatment infrastructure and reliable power supplies remain limited. Third, hybrid systems that combine MFCs with complementary ecotechnologies such as constructed wetlands have been shown to deliver enhanced environmental and economic performance, underscoring the feasibility of integrated, decentralized treatment strategies.

Nevertheless, several limitations persist. The relatively low power densities of current MFC prototypes, electrode fouling, and variability in effluent composition continue to constrain scalability. Addressing these challenges will require the development of advanced electrode materials, improved reactor designs, and optimized biofilm–algae interactions to achieve reliable long-term operation. Furthermore, life cycle assessments and techno-economic analyses are necessary to ensure that MFC deployment is not only technologically feasible but also cost-effective and environmentally sustainable.

In conclusion, this research contributes to a growing body of evidence that situates MFCs as a viable and transformative technology for wastewater treatment and renewable energy recovery. By highlighting the strong performance of hospital wastewater, exploring the synergy of algae–bacterial systems, and situating MFCs within global sustainability agendas, the study provides both practical insights and theoretical advances. With continued interdisciplinary innovation, MFCs can evolve from promising laboratory-scale systems into scalable solutions that contribute to clean water, affordable energy, and climate action, key priorities of the global sustainable development agenda.

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