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Fuzzy modelling for power generation in constructed wetland-microbial fuel cell during sewage water treatment

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ABSTRACT

In developing countries, such as India, hybrid constructed wetlands have proven to be an efficient technology due to their cost-effectiveness in installation, practicality, operation, and maintenance over the past decades. This study explores the integration of fuzzy modeling with hybrid constructed wetlands and Microbial Fuel Cells (MFC) for efficient power generation during sewage water treatment. There exists a significant gap between treated and untreated wastewater in India. MFCs, a cutting-edge technology, are gaining considerable attention worldwide due to their potential benefits in producing bioelectricity from wastewater treatment. Referred to as 'Green technology', microbial fuel cells offer an environmentally beneficial method of generating electricity while simultaneously purifying wastewater. MFCs directly convert the inorganic and organic substances present in wastewater into electricity using microorganisms as catalysts. In a standard MFC, a proton exchange membrane separates the anaerobic anode chamber from the aerobic cathode chamber. Electrons, traveling through an external circuit to the cathode chamber, produce electric current and power. Bioelectricity generation depends on the type of MFC, electrode materials, performance, substrates, design, and technological configuration. The choice of electrode material influences current production and power density; materials with high electrical conductivity, such as copper used for the anode and zinc for the cathode, lead to significant current production. In the study, this configuration achieved a power density of 352.125 mW/m² corresponding to a current of 2 mA, with removal efficiencies for COD, BOD, phosphates, and TSS at 64.64%, 77.87%, 70%, and 76.82%, respectively.

1. Introduction

Water is vital for human existence, rendering it the most indispensable resource on Earth. Potable water constitutes the foundation for vital socio-economic activities. Nevertheless, two centuries of industrial and agricultural expansion have resulted in considerable deterioration of water resources, compounded by insufficient regulatory structures. Urbanization and daily population growth are making this picture even more complicated [1-4]. Water degradation has intensified over the past fifty years due to various factors, including the extensive use of fertilizers to

enhance agricultural productivity and the natural drainage of certain wetland regions. Water degradation has intensified over the past fifty years due to various factors, including the extensive use of fertilizers to enhance agricultural productivity and the natural drainage of certain wetland regions. As a result of this drainage tendency, the amount of time that these natural water purification systems are exposed to water-borne contaminants that originate from a variety of anthropogenic sources has substantially decreased. Consequently, there have been large losses of nutrients and waterborne particles from land to essential water supplies [2-5]. These losses have

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happened as a consequence of agricultural practices. Traditional wastewater treatment and management methods are costly in terms of energy, operation, and maintenance, and they generate a substantial amount of sludge throughout the process [2-4, 6]. Therefore, efficient wastewater treatment will be beneficial in resolving both existing challenges and those that will arise in the future. It is of the utmost importance to have wastewater treatment systems that are eco-friendly and self-sufficient. SDG 6 is one of the seventeen Sustainable Development Goals (SDGs) that aim to "ensure the availability and sustainable management of water and sanitation for all." This goal also includes the treatment of wastewater.

Several nations worldwide are experiencing difficulties with their freshwater resources, and India is not an exception. According to a report published by the Central Pollution Control Board (CPCB) in March 2021 [3, 4], the current scenario of sewage wastewater treatment is approximately 27.96%, which is a major cause of water pollution and impacts human health. The increasing population and elevated water demand necessitate the sustainable management of water resources. This results from a significant discrepancy between treated and untreated water. Consequently, the generated wastewater must be managed efficiently and effectively, rather than relying on costly conventional treatment procedures. Water treatment, termed "Green treatment," will be executed utilizing created wetland areas [3, 4, 7-9]. This will be executed to enhance the cost-effectiveness of the procedure. Over the course of the last few decades, manmade wetlands have been shown to be effective in less developed nations due to the low costs associated with their installation, maintenance, and operation. These systems are known as low-cost systems that apply natural wastewater treatment techniques.

In recent decades, constructed wetlands have proven quite satisfactory; in addition, electricity will be generated by the coupling of microbial fuel cells with constructed wetlands [10-16]. In developing countries, hybrid constructed wetlands have been proving efficient due to their cost-effectiveness in terms of installation, operation, functioning, and maintenance over the past decades [1-3, 16-18]. According to Ren, B. et al. [16], Paucar. N.E. et al. [18], and Singh, K.K. et al. [3], the water-energy nexus is essential in order to meet the growing demand for water and energy at affordable prices. Constructed wetlands, often known as CWs, are artificial systems that are designed to utilize natural processes for the purpose of effectively treating wastewater while incurring relatively minimal operational costs. MFCs are able to convert the organic stuff that is present in wastewater into power. By breaking down the organic matter that is present in the sediment, bacteria in the CW are able to produce electrons as a by-product of the wastewater circulating through the CW. Electrons are gathered by an electrode in the process of producing

electricity. There has been a significant increase in the construction of CWs all over the world over the past few decades as an alternative to the conventional methods of treating wastewater. At the time that CWs were initially created, their primary application was to treat traditional secondary and tertiary domestic and municipal wastewater [3, 16, 17, 19-21].

Consequently, there has been a widespread use of CWs for the purpose of eliminating pollutants in a number of contexts. These settings include industrial effluents, agricultural drainage waters, landfill leachates, aquaculture waters, acid mine drainage, and runoff from towns and highways. On the other hand, these processes have an effect on the marshy bed in a direct or indirect manner by affecting the loading rates, temperatures, soil types, operation procedures, and redox reactions that occur there differently. Free water surface (FWS) systems involve the movement of wastewater above ground, whereas subsurface flow systems involve the movement of wastewater below ground through gravel or aggregates [3, 16, 22]. It is simple to create, the horizontal subsurface flow constructed wetland (HSSF-CW) is the form of constructed wetland that is used most frequently. Despite the fact that there are some modest spatial redox changes, the HSSF-CWs are mostly anaerobic (in the deeper or inner portion of the bed). It has been found that the upper layers of these CWs, which are located in close contact with the environment, maintain both aerobic conditions and redox gradients [3, 4, 16, 23]. As part of this investigation, a fuzzy model for assessing water quality was developed, and the water quality parameters of effluent, which were used as output parameters in the fuzzy model, were computed [24, 25]. These parameters included chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), and phosphates. According to the parameter index of the created/output water quality, there are four divisions of one output parameter that correspond to three input parameters. These divisions are very good, good, moderate, and awful. Higher values indicate that the treated water is of worse quality [24, 25]. Using this method, the classification system is able to identify the quality of the water and represent that determination. The robustness of the system is governed by the number of rules as well as the quality of rules. Also, this study determined the power generation during the treatment process using a microbial fuel cell.

2. Materials and methods

2.1. Experimental setup

An experimental setup featuring a single-stage microbial fuel cell-constructed wetland was utilized at the Environmental Engineering Laboratory within the Department of Civil Engineering at Motilal Nehru National Institute of Technology Allahabad, located in Prayagraj,

India. The study involved examining the characteristics of both municipal and synthetic wastewater while simultaneously generating electricity using a Microbial Fuel Cell. The influent was initially collected and transferred using a bucket into 50-litre garbage cans. These containers were then transported every two weeks to the study area, referred to as the plant setup, where the MFC system was installed for treatment and power generation. Synthetic wastewater was prepared in the departmental laboratory, comprising NaNO_3 , KH_2PO_4 , anhydrous dextrose (D-glucose), CaCl_2 , and MgSO_4 . Throughout the experiment, the tank functioned to supply nourishment to the constructed wetland units of a single stage microbial fuel cell that were interconnected. This MFC used as biofuel was a mixture of compost (cow dung), potato pulp, and tomato pulp, while a novel combination was used to investigate the power generation pattern connected with electrodes: specifically, a copper plate serving as the anode and a zinc plate as the cathode. Silicon tubing featuring an inner diameter of 2 millimetres was connected to a Watson Marlow peristaltic pump, which operated within a flow rate range of 0.5–430 millilitres per minute, facilitating the link between the feeding tank and the treatment unit. The bucket utilized for the plant setup had a height of 29 cm and a diameter of 32 cm, while the CW setup was maintained at a height of 25 cm. The setup of a constructed wetland is organized into various layers, arranged from bottom to top, as follows: Coarse gravel is utilized in the bottom-most layer to a height of 7 cm, succeeded by an anode layer composed of copper material positioned just above the coarse gravel [26]. A layer of fine gravel is applied to a height of 3 cm. Next, a coarse sand is applied to a height of 1.5 cm, with glass wool layered on top for an additional height of 1 cm. Fine sand is subsequently applied to a height of 4.5 cm. A zinc material is positioned above as the anode. The separation between the anode and cathode measures 10 cm. The top layer is enriched with soil to a height of 8 cm. *Canna Indica* plants serve as the wetland vegetation in the setup [3, 27, 28]. The schematic diagram is illustrated in Figure 1.

2.2. Influent Wastewater characteristics

The assessment of baseline system performance is facilitated by the use of synthetic effluent, which enables the establishment of controlled conditions and consistent pollutant loading. Conversely, the CW-MFC's real-world applicability and resilience are illuminated by municipal wastewater, which has a complex organic burden and variable composition. This comparative approach is instrumental in determining the impact of wastewater type on the efficacy of pollutant removal, the output of bioelectricity, and the overall stability of the system. Consequently, it provides a thorough comprehension of the operational effectiveness of the CW-MFC in both ideal and practical scenarios. The parameters of testing are pH, Total

dissolved solids (TDS), TSS, BOD, COD, and total phosphorous. Table 1 shows the characterization of the minimum, maximum, and mean value of the influent municipal wastewater.

2.3. Fuzzy model optimization

Fuzzy logic has demonstrated significant efficacy in tackling situations where laboratory data might be imprecise or uncertain, a common occurrence in environmental studies, including those related to constructed wetlands. This methodology facilitates the validation of data gathered from experimental studies by evaluating the appropriateness of the information collected [29-32]. This study utilized a fuzzy model to evaluate the quality of wastewater in a constructed wetland. The standard analytical approach was utilized to assess the water quality data of the wetland in order to establish the membership functions.

Three input parameters (pH, Temperature, and (one of the influents of BOD, COD, TSS, and TP); each point in the input space was categorized into one of three membership functions, namely low, medium, or high, based on a curve referred to as the membership function. The input space was subsequently classified into four categories: bad, moderate, good, and very good. Only one output parameter was used for each analysis of the effluent of BOD, COD, TSS, and TP.

Typically, the three fundamental operations in fuzzy set theory are OR, AND, and NOT. A simulation and classification of low, medium, and high pollution removal levels (low, medium, and high) was performed using the FIS and MATLAB. In addition, the FIS was employed to do classification. In this validation study, the assessment of the data was conducted solely using the AND operation. The evaluation of the fuzzy model was conducted utilizing the Mamdani fuzzy inference technique, as referenced in the works of Czogala et al. [24], Ferson et al. [33], Hassan et al. [34], Tsai et al. [35], and Bai et al. [29].

3. Results and discussion

3.1. Removal Performance of MFC-CW

Table 2 shows the average pH values for effluents from municipal and synthetic wastewater, which were 7.28 and 7.38, respectively. The observation that pH had decreased somewhat in municipal wastewater effluent could be related to the creation of volatile fatty acids, which are byproducts of the anaerobic degradation of complex organic compounds by bacterial action.

Furthermore, the pH decline could be induced by proton accumulation as a result of organic material oxidation. It is worth mentioning that the degradation of municipal wastewater might cause an increase in alkalinity over time. The removal of TSS is an important result of municipal wastewater treatment, with a significant difference when

compared to the comparatively minor decreases in BOD and COD. Tables 1 and 2 present the influent and effluent TSS concentrations, indicating an average removal rate of 77.85% for municipal wastewater and 75.8% for synthetic

wastewater. The treated effluent suspended solids concentrations were 68.92 mg/L for municipal wastewater and 91.92 mg/L for synthetic wastewater.

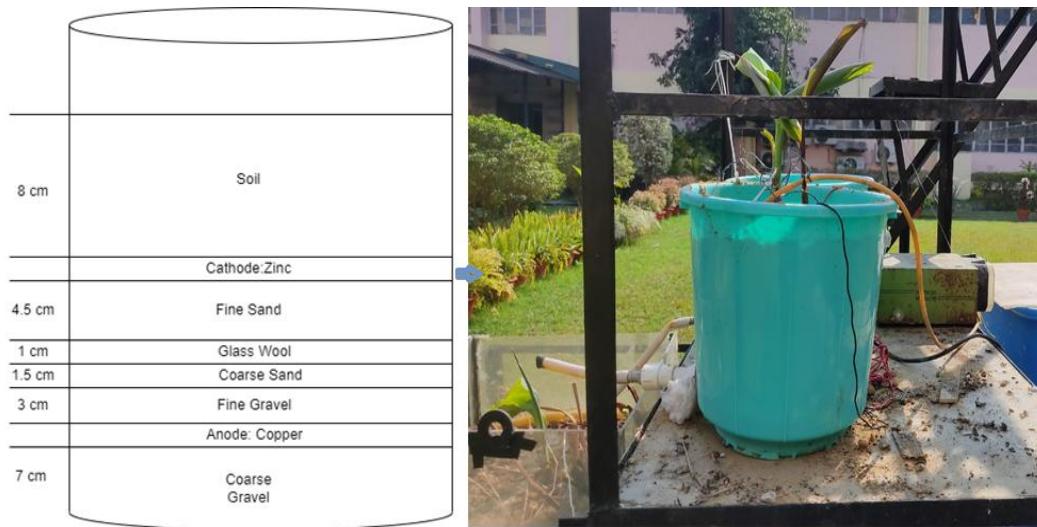


Fig. 1. Cross section of the setup in left side and complete lab scale setup picture of CW coupled MFC in right side.

Table 1. Characteristics of influent municipal wastewater.

Influent flow characteristics					
Parameters	Unit	Max	Min	Avg.	Std.
Municipal wastewater					
pH	-	8.10	7.60	7.84	0.17
TDS	mg/l	920	490	756.67	120.25
TSS	mg/l	375	290	313.13	21
BOD	mg/l	125.80	116.70	121.05	2.70
COD	mg/l	421	375	390.71	12.22
Total Phosphorous	mg/l	22.15	13.28	18.02	2.24
Synthetic wastewater					
pH	-	7.70	7.16	7.35	0.24
TDS	mg/l	1200	860	946.92	101.48
TSS	mg/l	375	290	313.13	21
BOD	mg/l	141	122	133.54	8.96
COD	mg/l	415	340	380.31	29.54
Total Phosphorous	mg/l	23.87	21.57	22.86	0.67

It has been proposed that vegetated submerged wetlands can effectively eliminate BOD and COD via aerobic microbial decomposition and sedimentation. This process initiates with microbes removing soluble organic substances from media surfaces prior to their adherence to plant roots and rhizomes [9, 16, 28].

Table 2 and Figure 2 show the BOD and COD concentrations in MFC-constructed wetland effluents. Municipal wastewater BOD and COD removal efficiency was 77.33% and 71.85%. In contrast, synthetic wastewater exhibited removal efficiencies of 78.42% for BOD and 57.44% for COD. The average concentrations of treated effluent were 27.5 mg/L for BOD and 110.42 mg/L for COD in municipal wastewater, while in synthetic wastewater, the values were 28.46 mg/L for BOD and 159.82 mg/L for COD. Additionally, the investigation recorded average surface organic loading

rates of 17.35 g BOD/m²/day and 55.99 g COD/m²/day for the treatment of municipal wastewater, whereas the treatment of synthetic wastewater yielded 19.14 g BOD/m²/day and 54.50 g COD/m²/day.

The noteworthy removal efficiencies are the consequence of a combination of physical and microbiological processes. The physical mechanisms in hybrid constructed wetlands facilitate water filtration via the wetland's restricted porosity, which is the reason for the effectiveness of the removal processes. Significant efficacy has been demonstrated by devices designed for subsurface filtration and interception in the removal of particulate-bound phosphorus. On the other hand, soluble phosphorus continues to be carried along with the water [4, 5, 18].

Both Table 2 and Figure 2 demonstrate that the average phosphorus removal rate in municipal wastewater was

43.88%, which resulted in 6.12 mg/L of treated effluent. It was determined that the elimination of synthetic wastewater was 57.16%, which led to 9.81 mg/L of treated effluent phosphorus. Therefore, from both municipal and

synthetic wastewater, similar removal efficiency was found, with only TDS and TP from synthetic wastewater achieving slightly better removal. This may be because the synthetic wastewater had less TDS and TP content.

Table 2. Characteristics of effluent municipal wastewater.

Effluent flow characteristics						
Parameters	Unit	Max	Min	Avg.	Std.	Avg. removal efficiency
Municipal wastewater						
pH	-	8.10	6.41	7.28	0.42	
TDS	mg/l	680.00	320.00	475.46	95.40	36.25
TSS	mg/l	110.00	30.00	68.92	20.42	77.85
BOD	mg/l	43.00	4.00	27.50	7.85	77.33
COD	mg/l	208.00	75.00	110.42	44.78	71.85
Total Phosphorous	mg/l	15.45	2.70	6.12	3.80	43.88
Synthetic wastewater						
pH	-	7.80	6.75	7.38	0.35	
TDS	mg/l	535.00	426.00	490.54	29.81	47.69
TSS	mg/l	140.00	70.00	91.92	23.50	75.80
BOD	mg/l	45.00	23.00	28.46	6.41	78.42
COD	mg/l	224.00	51.20	159.82	55.42	57.45
Total Phosphorous	mg/l	21.75	3.00	9.81	5.57	57.16

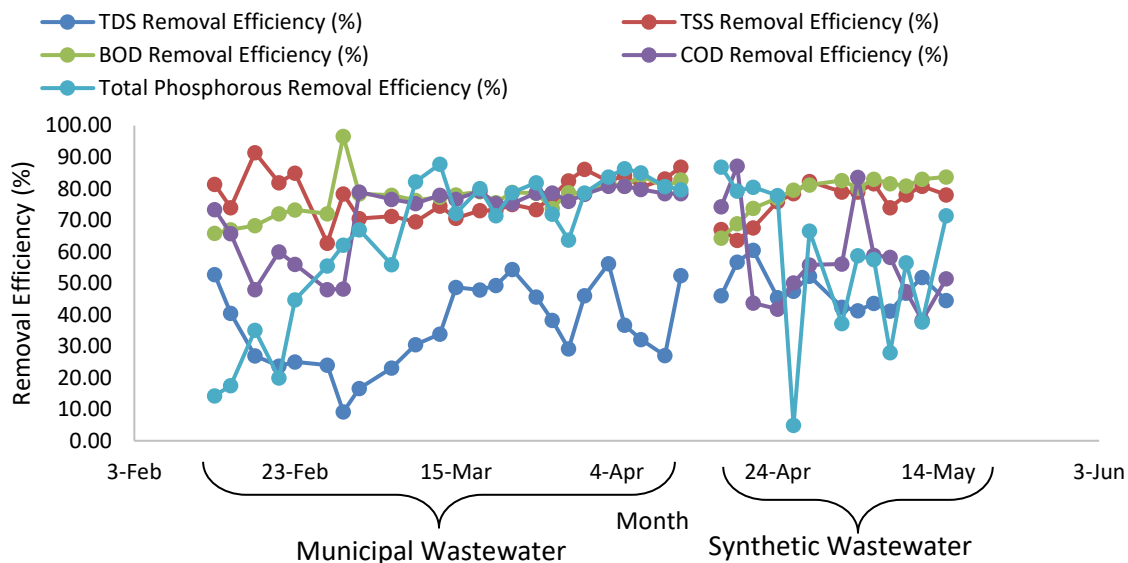


Fig. 2. Removal efficiency of wastewater from municipal and synthetic wastewater.

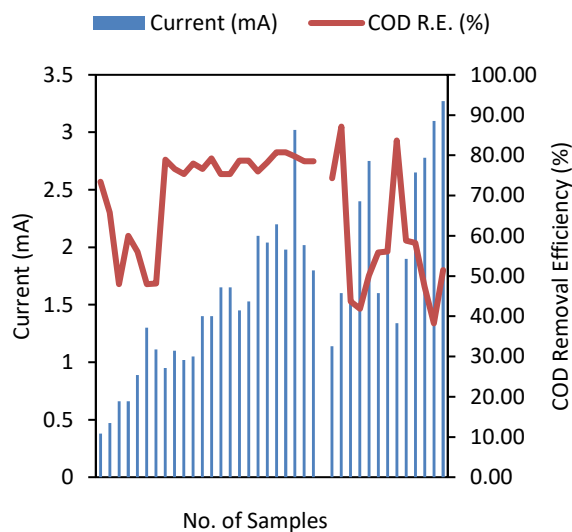
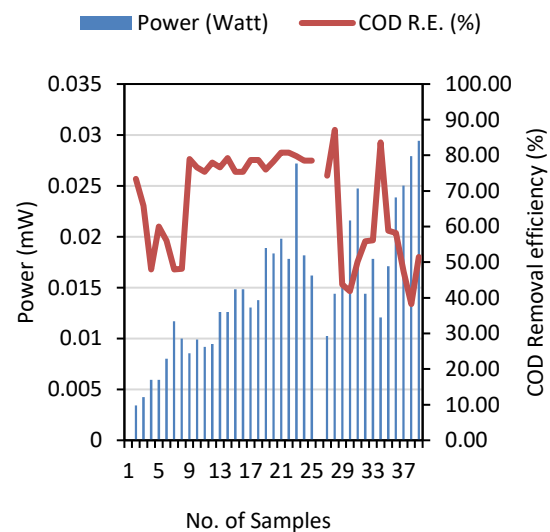
3.2. Power generation from MFC-CW

The process by which bacteria decompose organic or inorganic substrates in an anaerobic environment can be harnessed in MFC, which can then be utilized to generate electricity. This method has further applications, including producing hydrogen and oxygen. Microorganisms in the anodic chamber help to oxidize the substrate, which eventually leads to the release of electrons that are transferred to the anode electrode. Electron transfer can be assisted by soluble electron shuttles or components attached to the membrane.

Both of these mechanisms are possible. As soon as the electrons have passed through the resistor, they will continue on their journey in the direction of the cathode [36-41]. As a consequence of this, the anode functions as the source of current, which stands in contrast to the process that electrons go through. In most cases, the greatest power density is used to evaluate MFC energy, which is both environmentally benign and sustainable electricity. As shown in Table 3 and Figures 3 and 4, the electrode potential worked exceptionally well in this investigation, with current and power production corresponding to the configuration of the plant.

Table 3. Power generation data of the wetland setup coupled MFC.

Parameters	Unit	Max	Min	Avg.	Std.
Municipal wastewater					
Current	mA	3.02	0.38	1.41	0.63
Current Density	mA/m ³	375.69	47.27	175.35	78.25
Power	mWatt	27.18	3.42	12.68	5.67
Power density	mW/m ²	338.13	42.55	157.82	70.43
C.E.	%	0.20	0.03	0.01	0.01
NER	Watt-hr/kg-COD	5.99 E-5	0.76 E-5	3.12 E-5	1.21 E-5
Synthetic wastewater					
Current	mA	3.27	1.14	2.17	0.70
Current Density	mA/m ³	406.79	141.89	269.5	86.53
Power	mWatt	29.43	10.26	19.52	6.26
Power density	mW/m ²	366.12	127.64	242.87	77.88
C.E.	%	0.50	0.08	0.24	0.13
NER	Watt-hr/kg-COD	1.5 E-4	0.24 E-4	0.71 E-4	0.38 E-4

**Fig. 3.** Representation of current and COD removal efficiency wrt. No. of samples.**Fig. 4.** Representation of Power and COD removal efficiency wrt. No. of samples.

Considering that the cost of the electrode plates is relatively inexpensive, the electrodes performed exceptionally well in the examination of MFC linked to fulfil the requirements for power generation. The highest current and power generation were measured to be 3.2 milliamperes and 0.032 milliwatts, respectively, as shown in Table 3 and Figures 3 and 4. Also, similar findings have been published by the various researchers [10, 12, 36, 37].

Other researchers have used different electrodes. In this study, biofuel is generated using a mixture of compost (cow dung), potato pulp, and tomato pulp, while a novel combination is used to investigate the power generating pattern connected with electrodes: specifically, a copper plate serving as the anode and a zinc plate as the cathode. As an anode, copper performed rather well and helped biofilm grow. Table 4 shows that this mix produces a considerably higher power density of 0.352 watt/m² [7, 8, 14, 39, 41].

3.3. Simulation of resulting fuzzy logic system

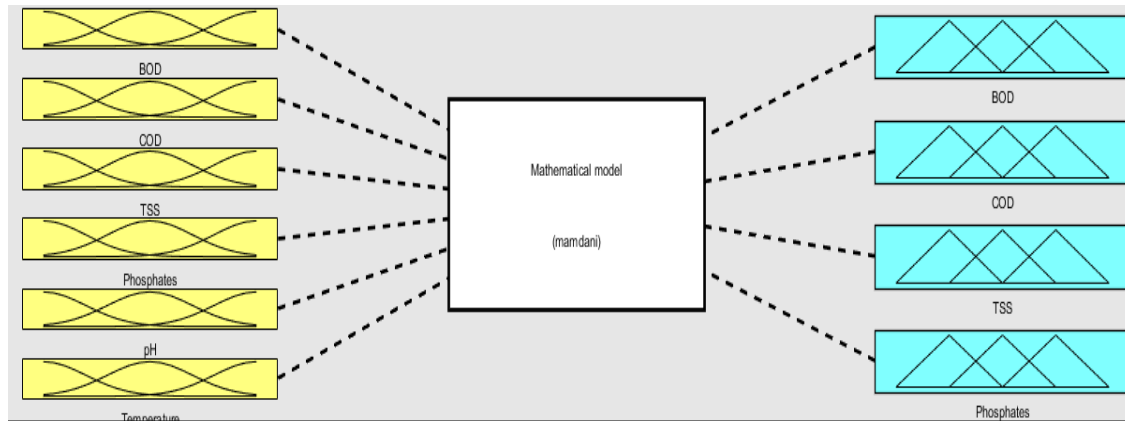
The Mamdani model utilizing Maximum-Minimum operation was applied to de-fuzzify the fuzzy output for each Fuzzy Inference System (FIS) to assess effluent from BOD, COD, TSS, and TP (Figure 5). Figure 6 presents the fuzzy rules for these models.

The categorization of every effluent condition of BOD, COD, TSS, and TP by the FIS should correspond with the classification obtained from the measured effluent data to validate the precise formulation of each FIS. Moreover, when the effluent condition is classified as high, the discrepancies between the FIS-predicted high effluent quality and the measured high effluent quality ought to be minimal. This is essential to guarantee that the FIS functions as a valuable instrument for delivering insights into scenarios of high effluent quality [24, 29, 30, 34].

- i. Membership function
- ii. Rules of fuzzy model

Table 4. Representation of Max. Power density generation corresponding to biofuel and electrodes.

Biofuel (Energy) Source	Anode electrode	Cathode electrode	Max. power density (mW/m ²)	References
Wastewater	Graphite	Graphite	0.0128	[39]
Plant + Compost	Carbon fiber	Carbon fiber	39.2	[41]
Composted soil	Zinc	Graphite	5335.5	[14]
Organic matters	Carbon felt	Carbon felt	7.07	[7]
Compost	Carbon felt	Mno ₂	5.29	[30]
Moss	Zinc	Cu	17.6	[37]
Moss	Zinc	Cu	18.24	[36]
Potato + Sludge	Carbon felt	Carbon felt	6.8	[37]
Compost + Potato pulp + tomato pulp	Copper	Zinc	352.125	This study

**Fig. 5.** Block diagram of mathematical model of input/output parameters in fuzzy inference system.

3.3.1 BOD Study using fuzzy model

The classification of BOD removal in effluents is illustrated by calculated findings and surface representations of effluent BOD characteristics. These classifications are based on the state's conditions, and they are made possible by combining the FIS produced with the data seen. We considered three aspects when examining these parameters: BOD_{in}, pH, and temperature. The average absolute BOD_{eff} expected to be present in high-quality effluent was measured at 22.3 mg/l, based on pH, BOD_{in}, and temperature values of 7.39, 115 mg/l, and 33.5°C, respectively. This was predicated on the temperature of 3.35 degrees Celsius.

In order to illustrate this, the values of each were compared individually. The predicted and actual levels of BOD in the effluent showed a significant difference of 5.67 mg/l when the mean simulated BOD_{eff}, which was evaluated at 27.97 mg/l, was compared. This was the case since the true BOD levels were measured at 27.97 mg/l. Furthermore, as compared to an experimental value of 222.5 mA/m³, the current density under the given conditions (pH 7.39, BOD_{in} 115 mg/l, temperature 33.5°C) showed an average absolute value of 175 mA/m³, therefore producing an average disparity of 47.5 mA/m³.

The capacities of the FIS to accurately infer high effluent BOD quality are brought to light by the results that are displayed in Figure 7. [3, 4, 10, 11, 30-34] illustrate the

inference performance of the FIS by a comparison of the inferred high effluent BOD with the observed values.

3.3.2 COD Study using fuzzy model

In a similar manner, the output parameters include a) COD_{effluent} (mg/l) and b) Current density; MATLAB was used to determine the categorization of pollutant removal as low, medium, or high within a fuzzy inference system. The surface view illustrates the relationship between effluent COD and current density parameters in relation to the input parameters of COD_{input}, pH, and temperature, as derived from the generated FIS and observed data. Predictions from the fuzzy model for high-quality effluent at a pH of 7.24, an input COD of 375 mg/l, and a temperature of 33.6 °C indicated an average absolute value of 142 mg/l for effluent COD. The absolute difference between the actual and simulated COD values for the effluent was 6.88 mg/l. The current density in relation to pH 7.24, COD input of 375 mg/l, and a temperature of 33.6 °C exhibited an average absolute value of 194 mA/m³. The experimental value recorded was 222.5 mA/m³, resulting in an average difference of 28.5 mA/m³, as illustrated in Figure 8. Figure 8 illustrates a top-down view of COD output and current density for COD input, pH, and temperature, respectively. The inferential efficacy of the FIS established in this study is evidenced by a comparison of the increased effluent BOD to the documented increased effluent COD [3, 4, 11, 30, 34, 36, 40].

1. If (pH is low) and (COD_input is low) and (Temperature is low) then (COD_Output is moderate)(Current_Density is moderate) (1)
2. If (pH is low) and (COD_input is medium) and (Temperature is high) then (COD_Output is Very_Good)(Current_Density is good) (1)
3. If (pH is low) and (COD_input is High) and (Temperature is medium) then (COD_Output is Good)(Current_Density is moderate) (1)
4. If (pH is low) and (COD_input is medium) and (Temperature is medium) then (COD_Output is Good)(Current_Density is good) (1)
5. If (pH is low) and (COD_input is High) and (Temperature is high) then (COD_Output is Good)(Current_Density is good) (1)
6. If (pH is low) and (COD_input is low) and (Temperature is high) then (COD_Output is Very_Good)(Current_Density is very_good) (1)
7. If (pH is low) and (COD_input is High) and (Temperature is low) then (COD_Output is Bad)(Current_Density is bad) (1)
8. If (pH is low) and (COD_input is medium) and (Temperature is low) then (COD_Output is moderate)(Current_Density is moderate) (1)
9. If (pH is low) and (COD_input is low) and (Temperature is medium) then (COD_Output is Very_Good)(Current_Density is very_good) (1)
10. If (pH is medium) and (COD_input is low) and (Temperature is low) then (COD_Output is Good)(Current_Density is good) (1)
11. If (pH is medium) and (COD_input is medium) and (Temperature is high) then (COD_Output is Good)(Current_Density is moderate) (1)
12. If (pH is medium) and (COD_input is High) and (Temperature is medium) then (COD_Output is moderate)(Current_Density is moderate) (1)
13. If (pH is medium) and (COD_input is medium) and (Temperature is medium) then (COD_Output is Good)(Current_Density is good) (1)
14. If (pH is medium) and (COD_input is High) and (Temperature is high) then (COD_Output is Good)(Current_Density is good) (1)
15. If (pH is medium) and (COD_input is low) and (Temperature is high) then (COD_Output is Very_Good)(Current_Density is very_good) (1)
16. If (pH is medium) and (COD_input is High) and (Temperature is low) then (COD_Output is Bad)(Current_Density is bad) (1)
17. If (pH is medium) and (COD_input is medium) and (Temperature is low) then (COD_Output is Bad)(Current_Density is bad) (1)
18. If (pH is medium) and (COD_input is low) and (Temperature is medium) then (COD_Output is Good)(Current_Density is good) (1)
19. If (pH is high) and (COD_input is low) and (Temperature is low) then (COD_Output is moderate)(Current_Density is moderate) (1)
20. If (pH is high) and (COD_input is medium) and (Temperature is high) then (COD_Output is Good)(Current_Density is good) (1)
21. If (pH is high) and (COD_input is High) and (Temperature is medium) then (COD_Output is Bad)(Current_Density is bad) (1)
22. If (pH is high) and (COD_input is medium) and (Temperature is medium) then (COD_Output is moderate)(Current_Density is moderate) (1)
23. If (pH is high) and (COD_input is High) and (Temperature is high) then (COD_Output is Bad)(Current_Density is bad) (1)
24. If (pH is high) and (COD_input is low) and (Temperature is high) then (COD_Output is Very_Good)(Current_Density is very_good) (1)
25. If (pH is high) and (COD_input is High) and (Temperature is low) then (COD_Output is Bad)(Current_Density is bad) (1)
26. If (pH is high) and (COD_input is medium) and (Temperature is low) then (COD_Output is moderate)(Current_Density is moderate) (1)
27. If (pH is high) and (COD_input is low) and (Temperature is medium) then (COD_Output is Good)(Current_Density is good) (1)

Fig. 6. Rules of fuzzy model example for COD.

3.3.3. TSS Study using fuzzy model

Consequently, the analysis of TSS utilizing a fuzzy model presents the effluent TSS parameters in relation to TSS input, pH, and TSS parameters concerning pH and temperature, as derived from the generated FIS and observed data, which are illustrated in the surface view.

Predictions from the fuzzy model for high-quality effluent at pH 7.71, with an input TSS of 325 mg/l and a temperature of 31.5 °C, indicated an average absolute value of 51 mg/l for effluent TSS. The absolute difference between the actual and simulated TSS values for the effluent was 20 mg/l. The average absolute value of the current density was 210 mA/m³ when pH was 7.71, TSSinput was 325 mg/l, and the temperature was 31.5°C. Figure 9 shows that the experimental number was 222.5 mA/m³, which means that there was an average difference of 12.5 mA/m³. Figure 9 illustrates the surface view in the FIS model concerning current density in relation to TSS input, pH, and TSS input temperature. An overview of the FIS Framework of the inference performance of the FIS developed in this study is demonstrated through a comparison of the high effluent TSS with the observed high effluent TSS [3, 4, 17, 19-21, 30, 34].

3.3.4 Total Phosphorous (TP) Study using fuzzy model

The study of TP removal using a fuzzy model involved examining the effluent TP parameters in connection to TP input, pH, and temperature, using the created FIS alongside the observed data presented in the surface view.

Forecasts derived from the fuzzy model suggested that for high-quality effluent, characterized by a pH of 7.26, a TP input of 21.3 mg/L, and a temperature of 34°C, the mean absolute value of effluent TP was 3.92 mg/L. The difference between the actual and simulated TP values was 3 mg/L, indicating the model's effectiveness in predicting effluent TP levels. In addition, the current density was investigated under conditions that were equivalent, and the fuzzy model produced an average value of 196 mA/m³.

This was in contrast to the experimental setup, which produced a value of 222.5 mA/m³, resulting in an average disparity of 26.5 mA/m³. The findings are illustrated in Figure 10, which portrays the surface view of the FIS model with regard to the current density in relation to the TP input, pH, and temperature. The inference performance of the newly constructed FIS was validated by comparing the high effluent TP values that were anticipated with those that were actually observed. The study findings indicated that the FIS successfully forecasted effluent quality across various conditions [2-5, 13-17, 30, 34].

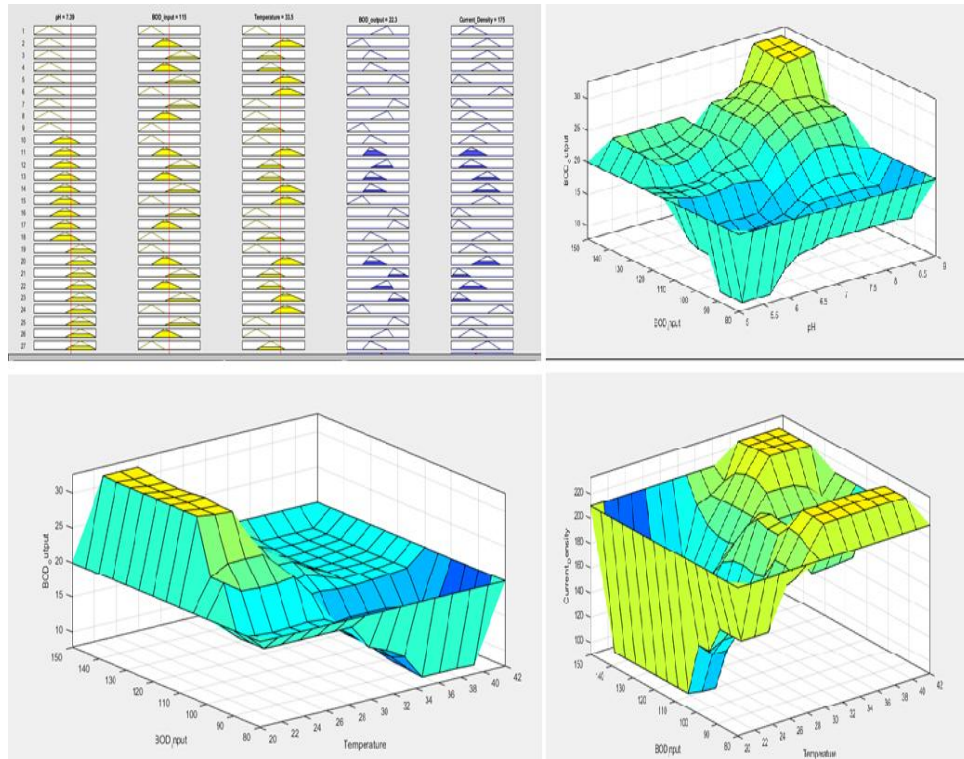


Fig. 7. (a) BOD in effluent Fuzzy inference, (b) Surface view of effluent BOD with influent BOD and pH of raw water, (c) Surface view of effluent BOD with influent BOD and temperature of raw water, (d) Surface view of current density with influent BOD and Temperature of raw water.

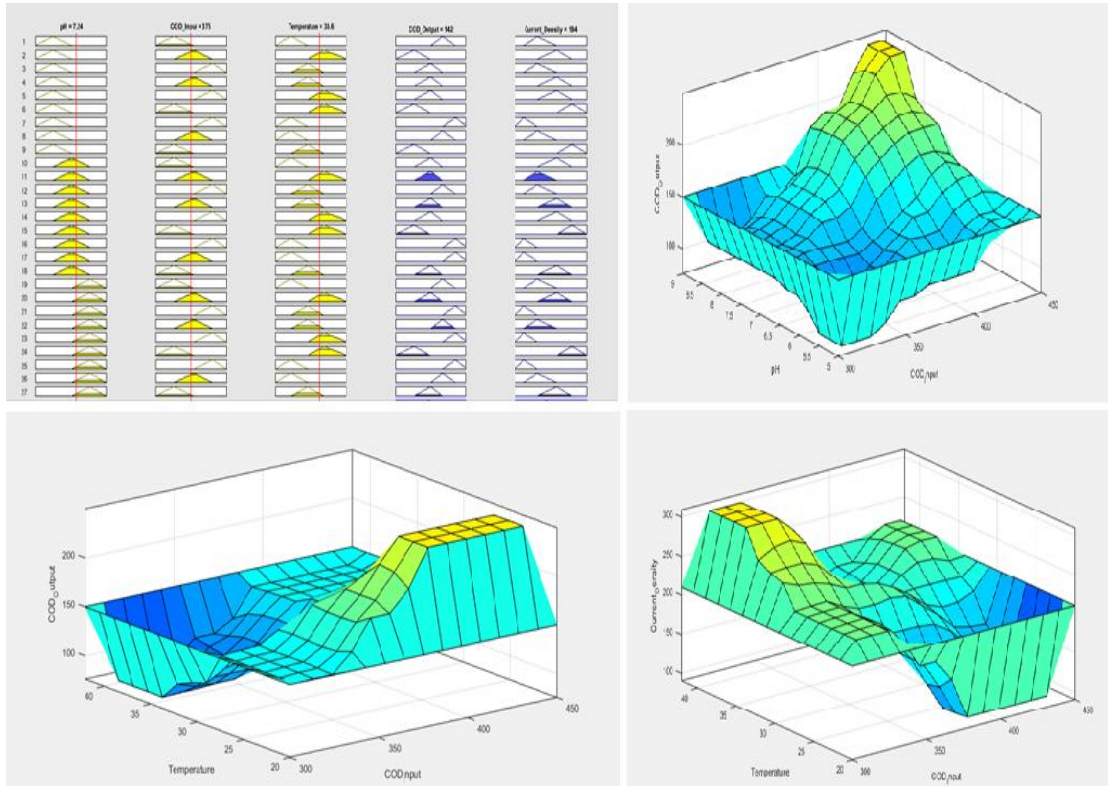


Fig. 8. (a) COD in effluent Fuzzy inference, (b) Surface view of effluent COD with influent COD and pH of raw water, (c) Surface view of effluent COD with influent COD and temperature of raw water, and (d) Surface view of Current density with influent COD and Temperature of raw water.

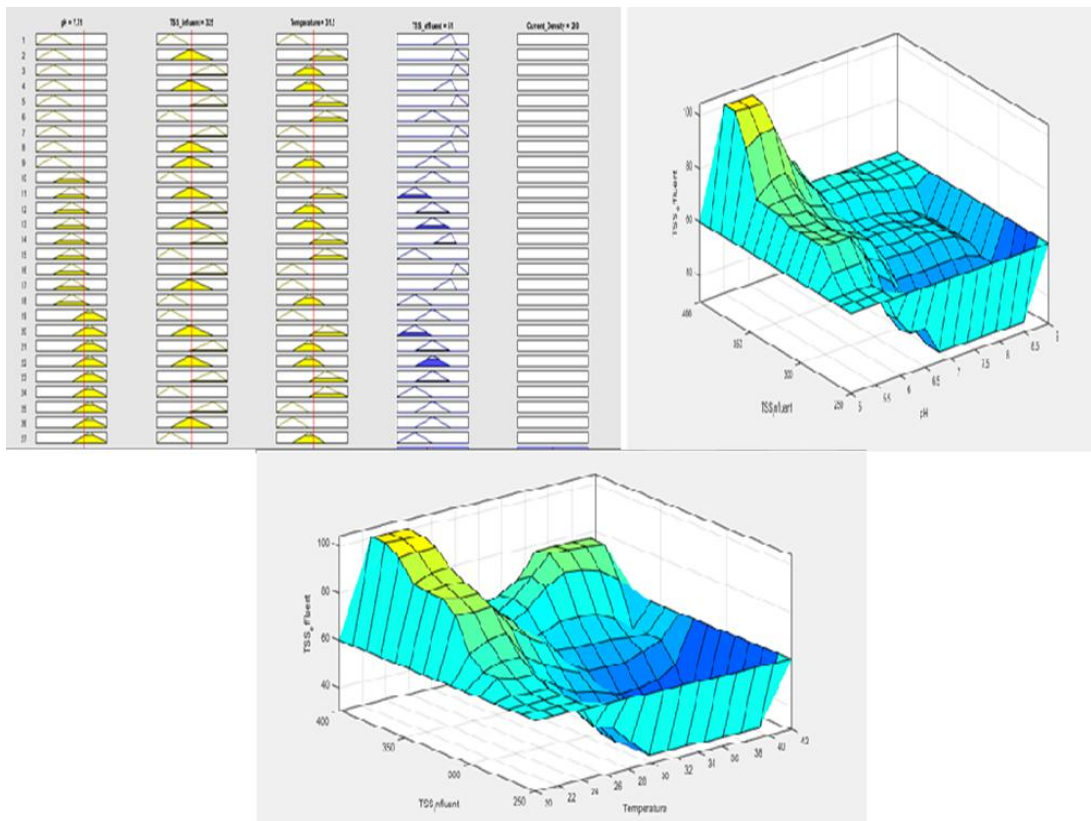


Fig. 9. (a) TSS in effluent Fuzzy inference, (b) Surface view of effluent TSS with influent TSS and pH of raw water, and (c) Surface view of effluent TSS with influent TSS and temperature of raw water.

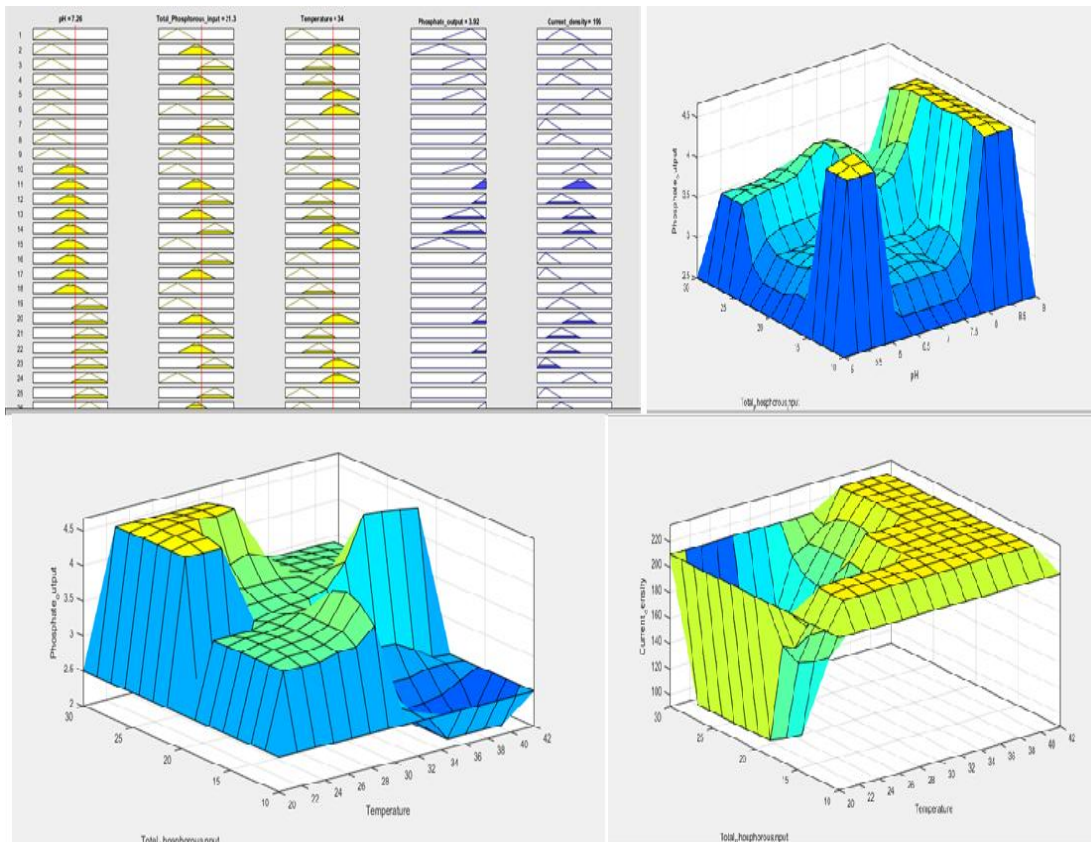


Fig. 10. (a) TP in effluent Fuzzy inference, (b) Surface view of effluent TP with influent TP and pH of raw water, (c) Surface view of effluent TP with influent TP and temperature of raw water, and (d) Surface view of Current density with influent TP and Temperature of raw water.

4. Conclusion

Cities are looking at sustainable water management methods, like water reclamation and reuse, to meet the growing demand for clean water caused by climate change and population increase. The integration of hybrid constructed wetlands with MFC technology presents a promising solution for sustainable wastewater management and renewable energy generation in urban areas facing increasing clean water demands. This study highlights the effectiveness of using a fuzzy model to evaluate water quality, enabling real-time monitoring and classification of effluent quality based on critical parameters. The primary findings of this research indicate significant improvements in treatment efficiency with regard to essential parameters, such as the elimination of TP, the stabilization of pH, the BOD₅ at 27 °C, the COD, and the total soluble solids. The removal efficiencies are as follows: 64.64 percent for COD, 77.87 percent for BOD, 70 percent for phosphates, and 76.82 percent for total soluble solids. Further notable power output was noted at 352.125 mW/m² using a copper plate as the anode and a zinc plate as the cathode. Importance in both treatment and power generation, the MFC component was shaped by numerous variables, including the type of plants, substrate material, gravel, sand, electrode material, and their varying electrical conductivities. To underline their great wastewater treatment properties, they were effectively produced in a laboratory-scale wetland model using locally grown plants, including *Canna indica*. The hybrid wetland has promise for usage in small-scale or low-population areas since it consistently shows high pollutant removal efficiency while also producing electricity. The study emphasizes the need of further investigation on the simplification of geographic design and the categorization of vegetation to improve the next built wetland systems. Based on the findings, hybrid-constructed wetlands with MFC technology are a viable choice for controlling municipal wastewater since they are both ecologically friendly and less costly than alternative tertiary treatment choices. Since this system is simple to run, takes minimal maintenance, and effectively removes pollutants, poor countries with limited resources to handle wastewater management issues will find it to be a great choice. Apart from simplifying wastewater treatment, this all-encompassing strategy offers a long-term answer for the generation of renewable energy, therefore supporting more general worldwide environmental protection and resource management.

Author's contribution

Sakshi Gupta contributed to the study setup installation, data collection. Krishna Kumar Singh contribute to the methodology, data analysis, and preparation of the original manuscript. Rakesh Chandra Vaishya contributed to

supervision setup installation and manuscript preparation, Resource provided.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

All data generated and analyzed during this study are included in this published article.

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