The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Treatment of Textile Wastewater Through Constructed Wetland Coupled Microbial Fuel Cell by *Canna indica*

Deepika Sheoran✉ | Simranjeet Singh

Department of Environmental Science, Faculty of Science SGT University, Gurugram, Haryana, India

Article Info

Article type:
Research Article

Article history:
Received: 20 December 2023
Revised: 13 March 2024
Accepted: 27 April 2024

Keywords:
Constructed wetland
Microbial fuel cell
Canna indica
Wastewater
Pollutant

ABSTRACT

Constructed wetland coupled microbial fuel cell (CW-MFC) encompasses both aerobic and anaerobic zones to produce electrical energy while facilitating the oxidative breakdown of pollutants. In this study, we ascertained the effective setup of CW-MFC in order to assess the pollutant removal efficiency and electricity generation. The CW-MFC system was initially filled with textile wastewater. Stainless steel mesh with granular activated carbon as the anode and graphite rods as the cathode were used. Soil and gravel were used as substrates and *Canna indica* as macrophyte. Over the course of 4 weeks, regular assessments were conducted every 3rd day to monitor the alternations in the wastewater properties. Throughout the treatment phase, the planted CW-MFC system achieved a significant reduction in phosphate, nitrate, BOD, COD, and chloride as compared to the unplanted CW-MFC system. From this study, the results also show that planted CW-MFC produce maximum peak voltage (0.112V) and current (1.12 mA) in comparison to CW-MFC without plants. Consequently, the finding suggests that *Canna indica* possesses the capacity to treat textile wastewater.

Cite this article: Sheoran, D., & Singh, S. (2024). Treatment of Textile Wastewater Through Constructed Wetland Coupled Microbial Fuel Cell by Canna indica. *Pollution*, 10 (2), 766-778.
https://doi.org/10.22059/poll.2024.369922.2187

DOI: https://doi.org/10.22059/poll.2024.369922.2187

INTRODUCTION

The Earth's most essential natural resource is water, a fundamental necessity for all living organisms. However, less than 3% of the planet's total water supply is comprised of fresh water. The existing freshwater reservoirs face significant pressure stemming from both pollution and limited availability. Consequently, ensuring a sustainable water supply in the 21st century presents a formidable challenge (Albert et al., 2021). Urbanization, industrial expansion, and the constant growth of the population are contributing to a rapid depletion of non-renewable energy and water resources (Shahid et al., 2015). As a result, there is a pressing requirement for eco-friendly and economically viable technologies to address the demand for a sustainable and accessible supply of both water and energy.

Constructed Wetland is an engineered wastewater treatment approach that relies on the force of gravity. It involves the synergy between macrophytes, substrates, and microbes to effectively treat a wide range of wastewater types, including industrial, residential, agricultural, and stormwater runoff. This treatment process combines physical, chemical, and biological mechanisms (Vymazal 2014a, b and Wu et al., 2015). Constructed wetlands are known for their cost-effective and environmentally friendly attributes in comparison to traditional methods (Li et al., 2014).

*Corresponding Author Email: *deepikasheoran11985@gmail.com*

At the outset of this century, Microbial Fuel Cell technology piqued the curiosity of researchers. In 1911, M.C. Potter delved into this field, laying the groundwork for microbial fuel cell by showcasing electricity generation through *E. coli* (Potter 1911). MFCs are primarily composed of two electrodes, known as the anode and the cathode, in addition to a salt bridge, microbes, and an external circuit. The anode operates in an anaerobic environment, while the cathode functions aerobically. These electroactive microorganisms facilitate the conversion of organic energy from wastewater into electrical energy (Logan 2008). Over recent years, MFC technology has gained global recognition as a means to generate electricity and has emerged as a sustainable solution (Singh et al., 2019).

Yadav (2010) was the first to demonstrate the novel integration technology known as CW-MFC (Yadav 2010). The initial comprehensive investigation of CW-MFCs occurred in Yadav et al.'s study in 2012, which utilized a laboratory-scale vertical constructed wetland for dye removal (Yadav et al., 2012). The motivation for this research stemmed from the compatibility and similarities between the two technologies in terms of substrate utilization, design configuration, and microbial activities. Subsequently, Zhao et al. (2013) examined CW-MFC performance in both continuous and batch modes, revealing that the continuous mode system exhibits superior COD removal compared to the batch mode systems.

Yadav et al., in 2022 compared CW-MFC with the conventional CW. They used graphite plates and carbon felt as electrode materials. They found that the CW-MFC achieved remarkable reductions in organic matter, phosphate, and total nitrogen by 92%,93%, and 70%, respectively, surpassing the performance of the conventional CW. The maximum power density was 16.33 mWm^{-2} (Yadav et al., 2022).

Kumar et al., in 2023 assessed a distinctive setup involving a pilot-scale CW-MFC system, focusing on its ability to remove COD from synthetic wastewater and generate electricity. *Typha angustifolia,* a type of wetland plant, was employed in the system. In the fed-batch mode, the CW-MFC unit within the system achieved a maximum COD removal efficiency of 97.56% ± 1.6% from the wastewater. The auxiliary MFCs reached their highest power density of 58.55 mW/m^2 and current density of 229.6 mA/m^2 (Kumar et al., 2023).

Chaijak and Sola in 2023 garnered attention for CW-MFC's dual capabilities in wastewater treatment and electricity generation, showcasing remarkable efficiency in power generation and the removal of xenobiotic compounds. A large range of macrophytes including *Crinum asiaticum, Canna indica, Hanguana malayana, Philodendron erubescens,* and *Dieffenbachia seguine* were employed as cathodic biocatalysts. The results of the electrochemical analysis revealed that the highest half-cell potential was attained using the macrophyte *Dieffenbachia seguine*. The CW-MFC with *D. seguine* as the cathode achieved the highest power output, generating 5.42±0.17 mW/m^2. Notably, that particular CW-MFC exhibited impressive wastewater treatment capabilities, with COD removal efficiency reaching 94.00±0.005%. the study advances the understanding of the potential of CW-MFCs, particularly when planted with the macrophyte *Dieffenbachia seguine*, for domestic wastewater treatment and the concurrent generation of electrical power as a valuable by-product (Chaijak and Sola 2023).

The main objectives of the study were to determine the amount of current and potential generated at different resistors and the pollutant removal efficiency of CW-MFCs with and without the *Canna indica* plant.

MATERIAL AND METHODS

Construction of CW-MFC

In this study, two vertical flow, laboratory-scale CW-MFC systems with identical specifications were constructed. *Canna indica* plants were obtained from the university nursery and were introduced into the Planted CW-MFC setup. CW-MFC without plants, named as

Unplanted CW-MFC, were utilized, but all design parameters were kept consistent with those of planted CW-MFC. The system had an outlet at 3cm from the bottom with screwed clips, while the upper portion was open. A layer of washed gravel was placed at the bottom of CW-MFC systems followed by a layer of soil. A mesh of stainless steel was placed and granular activated carbon was spread over it which acts as an anode for the systems. After that, a thin layer of soil was placed which provided support for the plants to grow. Four identical graphite rods were placed on the top to act as an air cathode. Both anode and cathode were connected via copper wire to an external resistor and connected to a multimeter for monitoring of voltage and current generation. The plants before experimental use were cleaned with tap water and then acclimatized in the planted CW-MFC setup containing fresh tap water for 7-10 days under natural environmental conditions. Good growth of new, robust leaves and the emergence of inflorescence were signs that the plants were ready for additional testing.

SSM- Stainless Steel Mesh, GAC- Granular Activated Carbon

The surface of both CW-MFC systems was loaded with each 500 mL textile wastewater in down-flow mode, and the water that had been treated was collected at predetermined time intervals through the outlets. Sampling was done every 3rd day and the treated water was analyzed using APHA, 1995 standards methods. The current and voltage were also measured at two different resistors (100Ω and 330Ω) every third day using a multimeter.

Instruments/Methods used for characterization

The following major physiochemical parameters of the effluent were studied:

Parameters	Units	Instrument /Method used	Methods number followed
pH	--	pH-EC-TDS meter	4500-H^+
EC	µS/cm	pH-EC-TDS meter	2510
TDS	mg/L	pH-EC-TDS meter	2540 C
TSS	mg/L	Filtration and weighing	2540 D
TDS	mg/L	Filtration and weighing	2540
Chloride	mg/L	Argentometric titration	4500-Cl^-
BOD	mg/L	BOD Incubator	5210
COD	mg/L	COD Digestor	5220
Phosphate	mg/L	Spectrophotometer	4500-P
Nitrate	mg/L	Spectrophotometer	4500- NO3 -

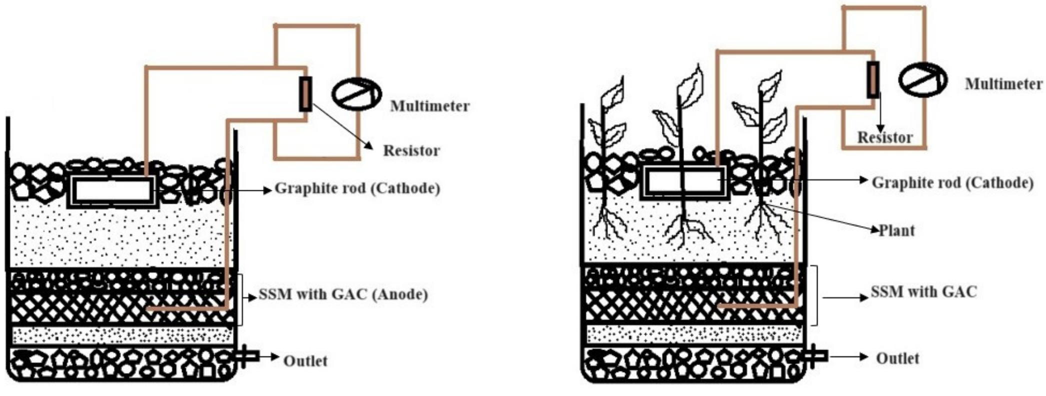

Fig. 1. Schematic diagram of CW-MFC, A. Unplanted CW-MFC B. Planted CW-MFC

RESULTS AND DISCUSSION

Wastewater treatment

The initial characteristics of textile wastewater are shown in Table 1.

Changes in pH and electrical conductivity (EC)

The textile wastewater had an initial pH of 7.8, indicating a slightly alkaline nature. As demonstrated in Figure 2, after 24 days of treatment in the CW-MFC system, the pH at the outlet decreased slightly, ranging from 7.11 to 6.94. This suggests that the treatment process within the CW-MFC tends to neutralize ions present in the wastewater.

Following a 24-day treatment period, the electrical conductivity (EC) of textile wastewater exhibited notable reductions from an initial value of 20.38 mS/cm. Specifically, the EC values for Unplanted CW-MFC and Planted CW-MFC systems decreased to 5.21 mS/cm, and 2.33 mS/cm respectively, as illustrated in Figure 3.

The most significant decline in EC was observed in planted CW-MFC. This decrease in conductivity can be attributed to the active roles of bacteria and plants within the CW-MFC system, as they effectively consumed micro and macro elements and ions from wastewater. Additionally, these elements and ions were removed through processes such as adsorption to plant roots, and settling of suspended particles, as described by DeBusk and DeBusk 2001.

Table 1. Characteristics of Textile Wastewater

Parameters	Parameter value
pH	7.8
EC (µS/cm)	20.38
Total Dissolved Salts (mg/L)	16.02
Total Suspended Solids (mg/L)	1380
Total Dissolved Solids (mg/L)	3720
Chloride (mg/L)	3372
BOD (mg/L)	1020
COD (mg/L)	4240
Phosphate (mg/L)	338.06
Nitrate (mg/L)	50.12

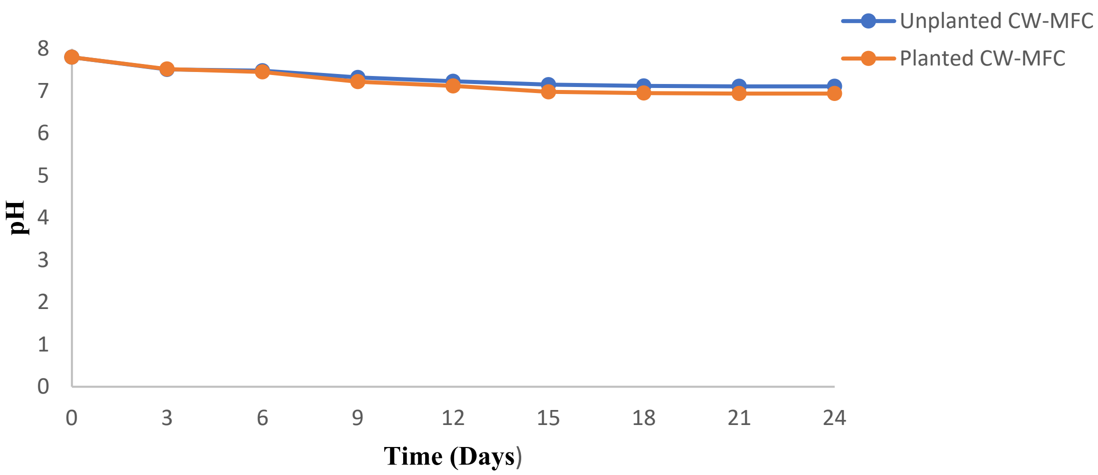

Fig. 2. Variation of pH in the water sample with time

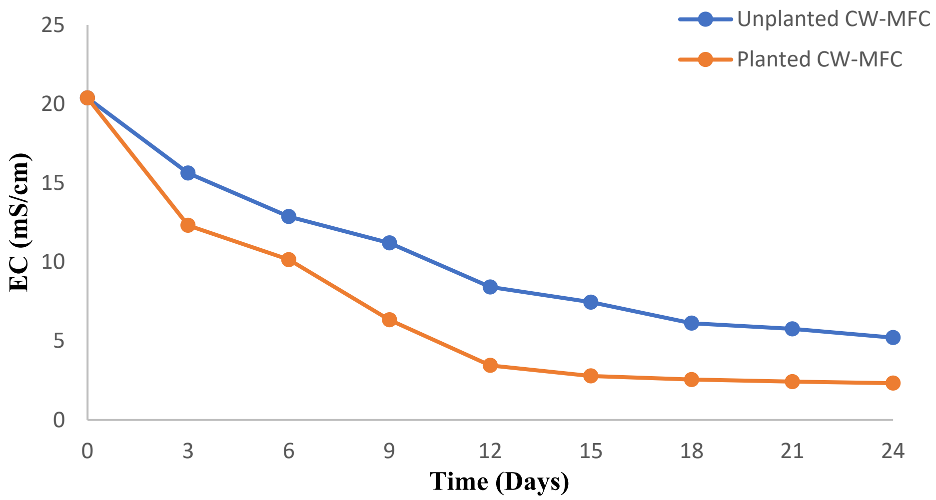

Fig. 3. Variation of EC in the water sample with time

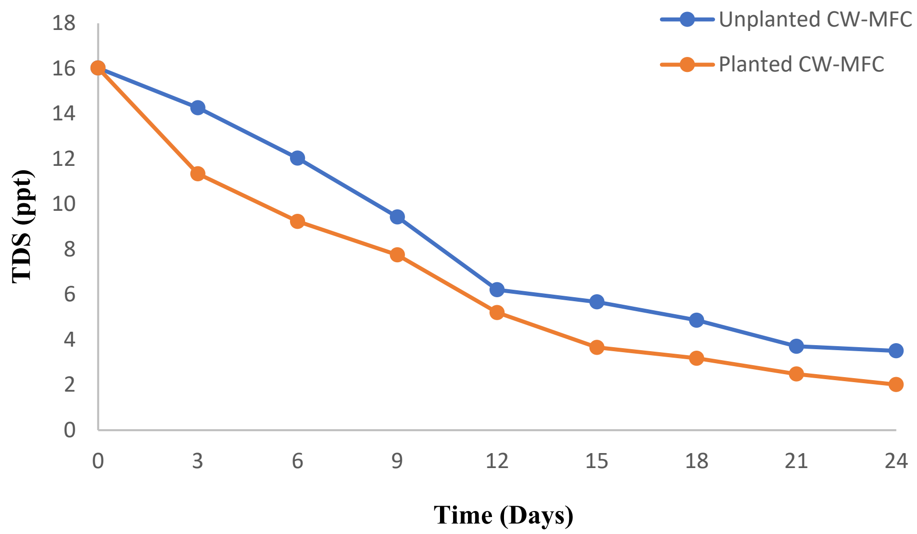

Fig. 4. Variation of TDS in the water sample with time

Removal of TDS, TSS, and TDS

The textile wastewater had an initial total dissolved salts (TDS) of 16.02 ppt. As demonstrated in Figure 4, there was a decline in TDS, ranging from 3.51 to 2.02. The most significant decline in TDS was observed in planted CW-MFC as compared to unplanted. The removal of TDS in the CW-MFC system is primarily achieved through a combination of biological (microbial activity and ions uptake), physical (sedimentation), and electrochemical processes. Sometimes, a reduction in TDS has also been associated with microbial conversion of nitrate into diatomic nitrogen as noted by Sehar et al. in 2013 (Sehar et al., 2013).

The total solids content is a crucial factor in assessing water quality, and it is noteworthy that there was a gradual decrease in total solids within the wastewater. Over the 24-day treatment period, the CW-MFC systems effectively reduced the total suspended solids (TSS) from the initial 1380 mg/L to 165 mg/L, and 131.67 mg/L in unplanted CW-MFC and planted CW-MFC respectively as shown in Figure 5. The systems also reduced the total dissolved solids (TDS) from the initial 3720 mg/L to 550 mg/L in unplanted CW-MFC and 301.67 mg/L in planted CW-

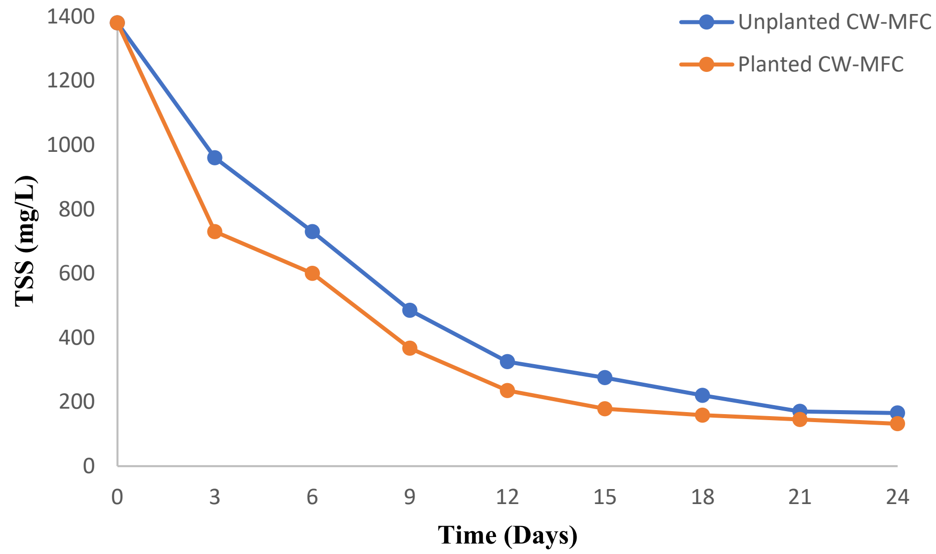

Fig. 5. Variation of TSS in the water sample with time

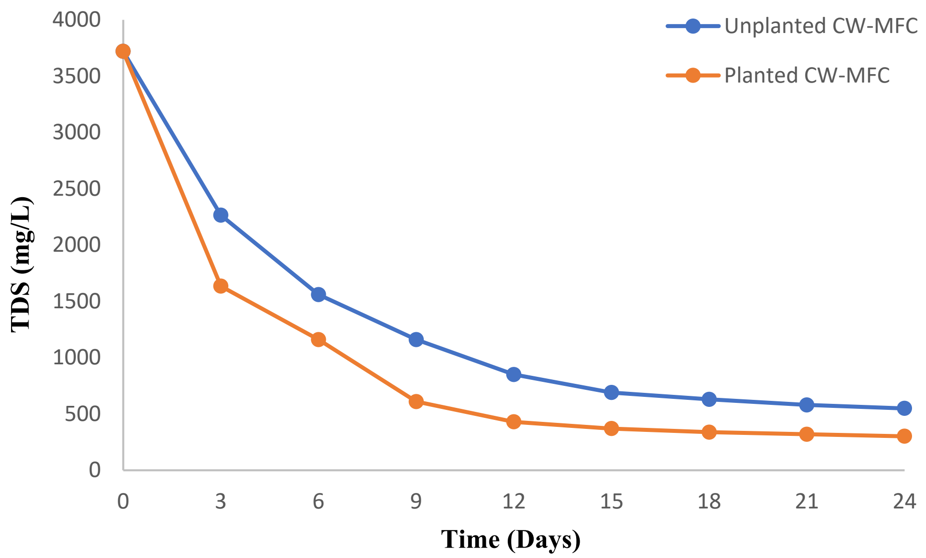

Fig. 6. Variation of TDS in the water sample with time

MFC as demonstrated in Figure 6. The total solids removal in the CW-MFC system involves physical settling, biological degradation, plant uptake, adsorption, and filtration.

Removal of Chlorides

Reducing the chloride content is a crucial aspect of water treatment to ensure its safety. The CW-MFC had successfully lowered content as demonstrated in Figure 7. During the investigation of the CW-MFC system, the chloride content decreased significantly, from an initial value of 3372 mg/L to a final value of 1378 mg/L, and 1179.33 mg/L in Unplanted CWMFC, and planted CW-MFC respectively.

Removal of BOD and COD

BOD represents a significant parameter that has undergone substantial reduction within the CW-MFC systems. Starting at 1020 mg/L, BOD steadily declined, reaching 220- 143.33 mg/L

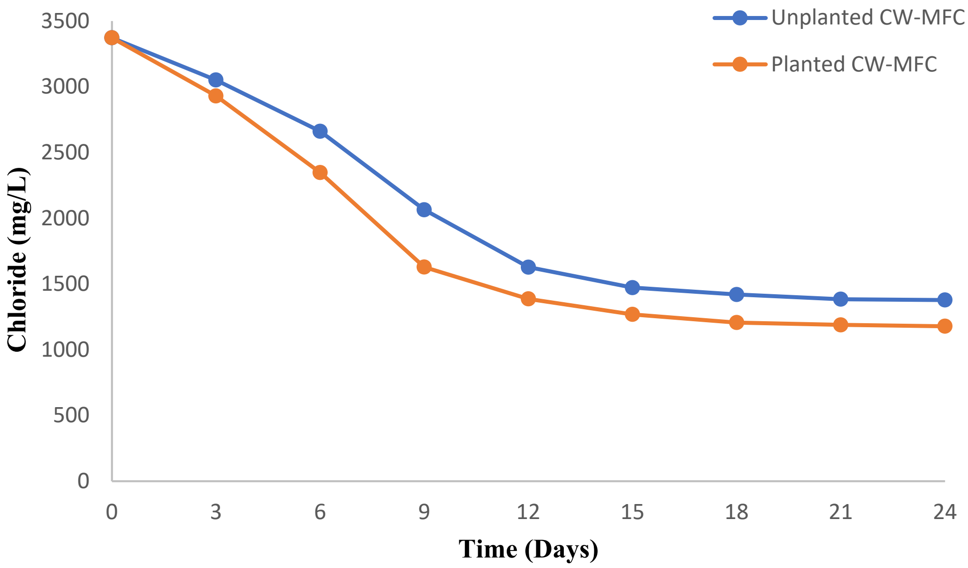

Fig. 7. Variation of Chloride content in the water sample with time

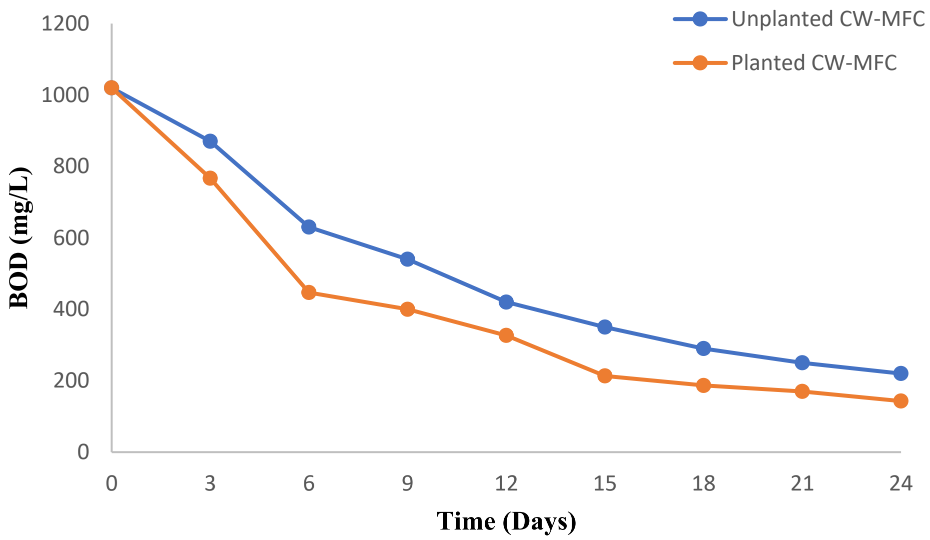

Fig. 8. Variation of BOD content in the water sample with time

by the end of 24 days as demonstrated in Figure 8. This decline in BOD levels underscores the effectiveness of *Canna indica* in wastewater treatment, as BOD reduction is a pivotal objective in the overall water treatment process.

The textile wastewater had an initial chemical oxygen demand (COD) of 4240 mg/L. As demonstrated in Figure 9, there was a sharp decline in COD ranging from 1140 to 846.67 mg/L. The highest COD removal efficiency was observed in planted CW-MFC. This superior performance can likely be attributed to the enhanced adsorption capacity and microbial growth within the substrate matrix layer.

In CW-MFC systems, COD removal occurs primarily through the rapid removal of settleable organic matter via deposition and filtration. Additionally, the organic compounds are subject to both aerobic and anaerobic degradation by microbes, depending on the oxygen concentration within the bed. The provision of oxygen for aerobic and anaerobic degradation can occur through various mechanisms such as diffusion, convection, and oxygen release from macrophyte roots

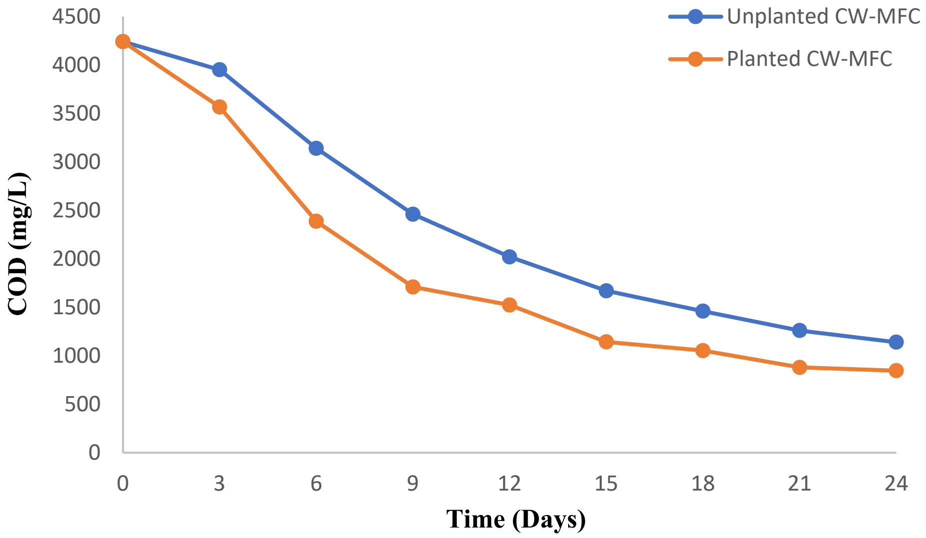

Fig. 9. Variation of COD content in the water sample with time

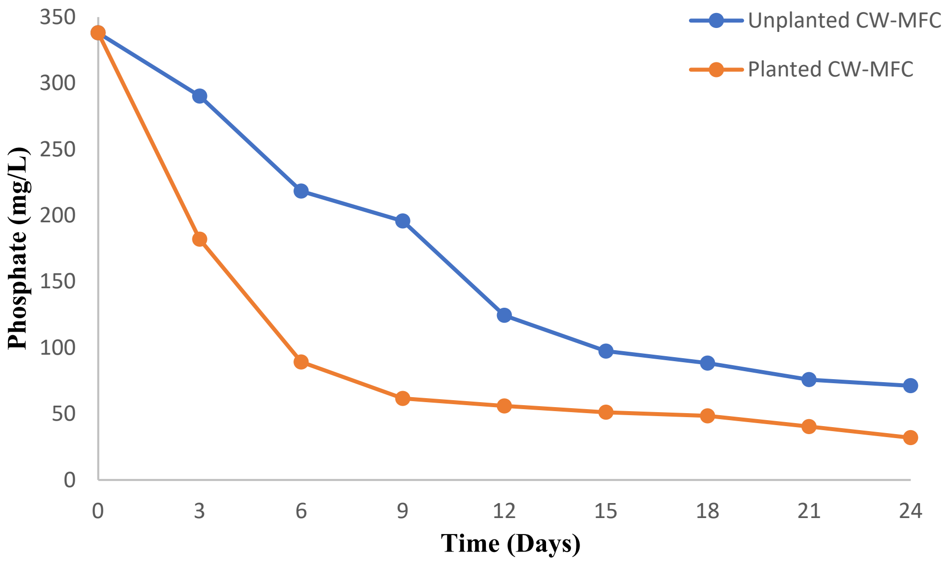

Fig. 10. Variation of phosphate content in the water sample with time

into the rhizosphere, as demonstrated by Abou-Elela and Hellal in 2012.

Furthermore, the presence of aerenchymatous tissue in the roots of *Canna* plants plays a vital role in facilitating oxygen diffusion, as highlighted by Bhardwaj et al. in 2015. Microbial activity within the anodic chamber played a significant role in reducing COD, as the microbes utilized organic substrates as a source of carbon to support their metabolic processes as noted by Virdis et al., 2008 and Mook et al., 2013.

Removal of Phosphates

The wastewater had an initial concentration of phosphate was 338.06 mg/L. There was a sharp decline in the phosphate ranging from 71.24 to 31.91 mg/L as shown in Figure 10. The removal of phosphate is a physicochemical process that usually occurs by adsorption over the substrates and precipitation. The results depicted an increase in phosphate removal rate over periods. Biological P removal might also contribute to the efficient phosphate removal in

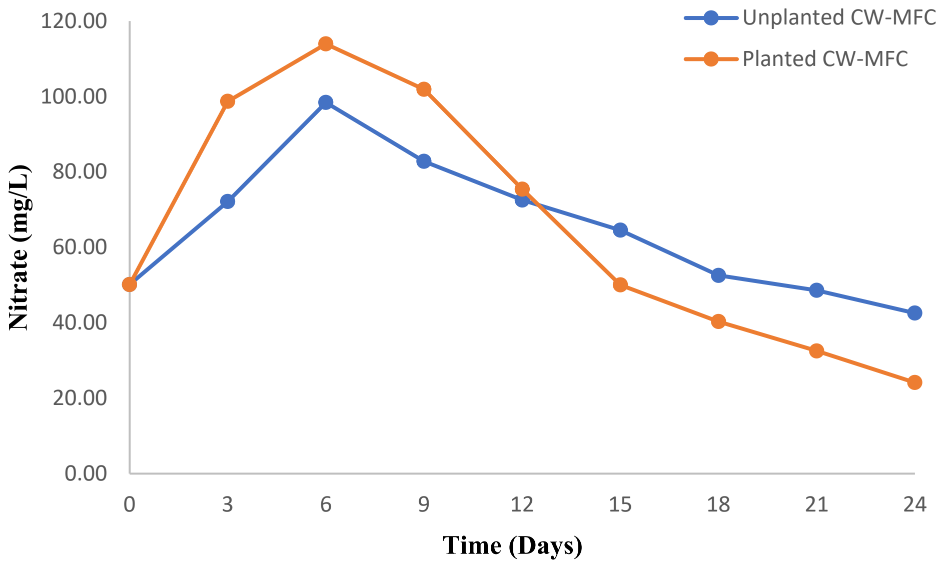

Fig. 11. Variation of nitrate content in the water sample with time

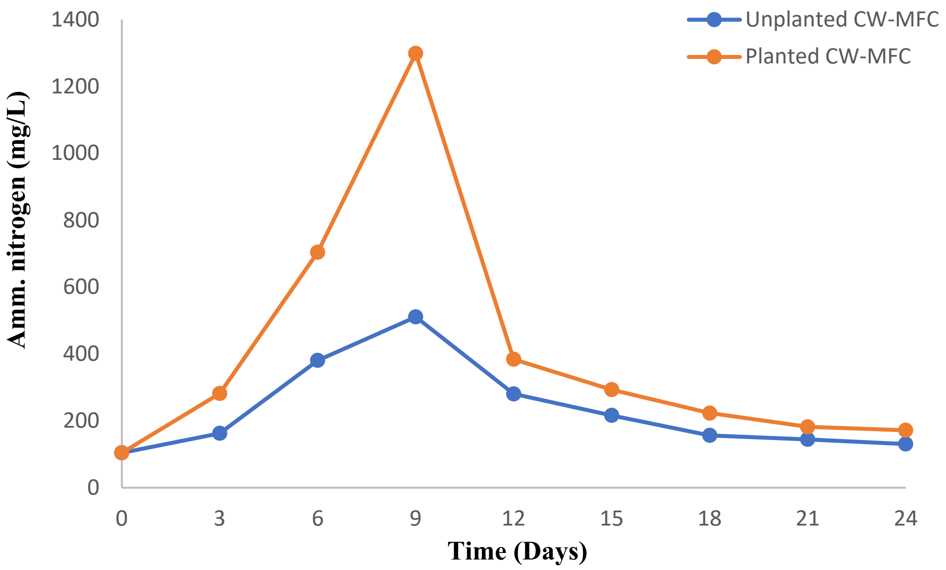

Fig. 12. Variation in Ammonical Nitrogen content in the water sample with time

planted CW-MFC.

Removal of Total Nitrogen, Ammonia nitrogen and Nitrate

In the case of both planted and unplanted CW-MFCs, there was an increase in nitrate concentration as shown in Figure 11, which can likely be attributed to an elevated rate of nitrification within the treatment process. This phenomenon may also be linked to a significant decrease in ammonia nitrogen as shown in Figure 12. As treatment progressed, the nitrate level decreased, possibly indicating concurrent nitrification and denitrification processes or the assimilation of nitrates by plants.

Notably, due to the presence of plants, planted CW-MFC exhibited the most effective nitrate removal as compared to unplanted CW-MFC. This superior performance may be attributed to the creation of an optimal environment that supports microbes engaged in the simultaneous

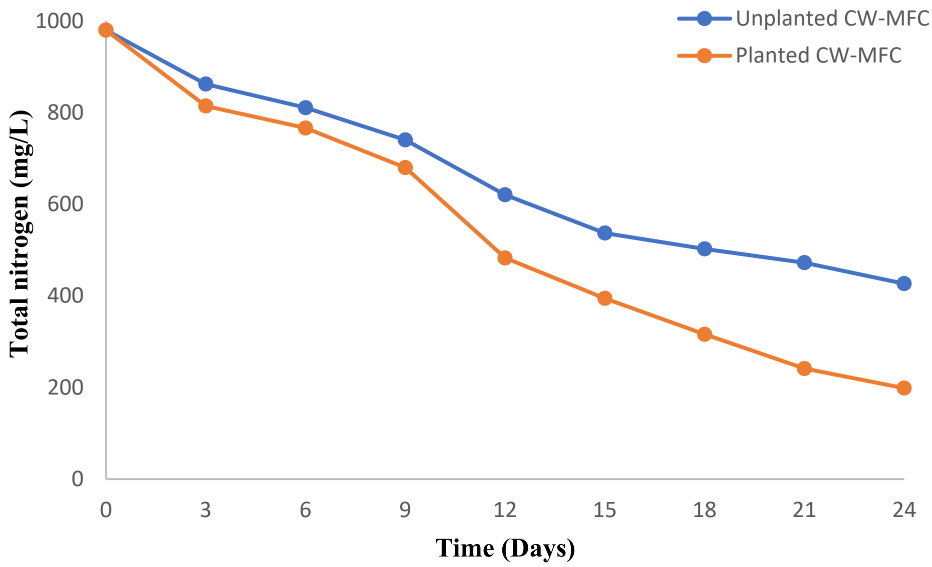

Fig. 13. Variation in Total Nitrogen content in the water sample with time

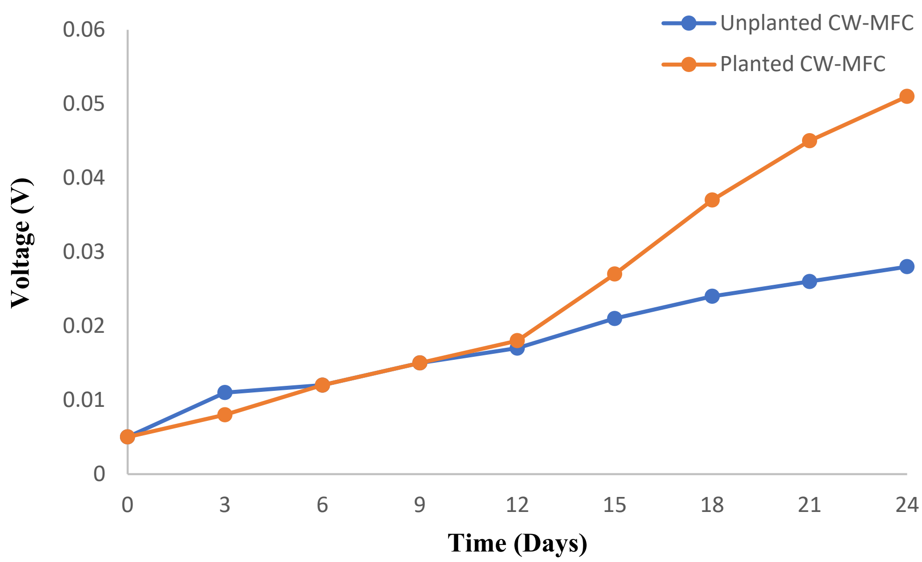

Fig. 14. Potential (V) produced at 100Ω resistor

nitrification and denitrification processes, which are pivotal mechanisms in the nitrogen treatment within constructed wetlands as stated by Khatiwada and Polprasert, 1999.

The final concentration of Total Nitrogen was also reduced from an initial conc. of 980 mg/L to 426.4, and 198.47 mg/L in unplanted CW-MFC and planted CW-MFC 2 respectively, as shown in Figure 13.

Electricity generation

A series of comparative studies was conducted to examine the impact of *Canna indica* on the generation of electricity from CW-MFCs. Potential and current were measured at two different external resistors i.e., 100Ω and 330Ω for a specific period of time. The study revealed a significant influence of plants on the current and voltage of CW-MFCs. The findings indicated maximum current was produced in planted CW-MFC. The maximum current produced was

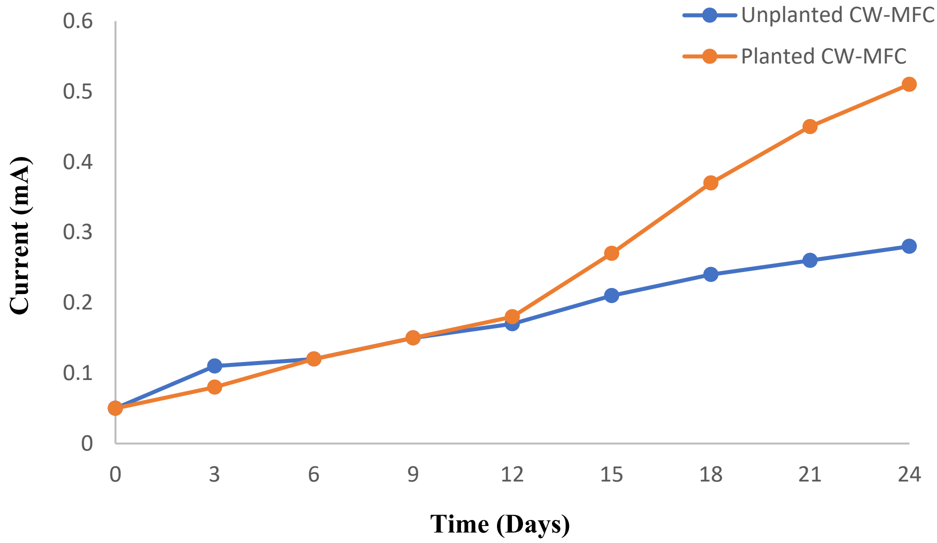

Fig. 15. Current produced (mA) at 100Ω resistor

Table 2. The percentage removal efficiency of different parameters CW-MFC system with or without plants after 24 days of the treatment period

Parameters	Parameter value
pH	7.8
EC (µS/cm)	20.38
Total Dissolved Salts (mg/L)	16.02
Total Suspended Solids (mg/L)	1380
Total Dissolved Solids (mg/L)	3720
Chloride (mg/L)	3372
BOD (mg/L)	1020
COD (mg/L)	4240
Phosphate (mg/L)	338.06
Nitrate (mg/L)	50.12

0.51 mA when external resistance was 100Ω. While the maximum voltage produced 0.168 V, when the external resistance was 330Ω. As shown in Figures 14 and 15 there was an increase in voltage and current with time.

An elevated concentration of oxygen in the cathode can facilitate and bolster this reaction, thereby reinforcing the cell's overall performance. Conversely, a greater oxygen concentration can elevate the cathode potential, consequently leading to an enhancement in the electricity generation of the planted CW-MFCs (Narayana et al., 2018).

CONCLUSION

The plant species *Canna indica* was cultivated within the CW-MFC system for a span of 4 weeks, during which the qualities of the textile wastewater and the amount of voltage and current produced were examined regularly. The analysis of the textile water revealed that as the duration of cultivation increased, the plant's effectiveness in treating the water also improved.

Canna indica proved to be exceptionally proficient in the removal of chloride content, BOD, COD, phosphate, and nitrate from wastewater. It reduced the chloride content by 65.12%, BOD by 86.27%, COD by 80.18%, phosphate by 91.01%, and nitrate by 78.80% within a week timeframe in the CW-MFC. The electricity generation was assessed in terms of variation in voltage and current. The maximum amount of voltage and current produced was 0.112V and 1.12 mA respectively.

This approach using the CW-MFC system demonstrated its potential as an efficient solution for wastewater treatment and electricity generation, with the benefit of not discharging any effluent during the treatment process. Furthermore, this environmentally friendly method of wastewater treatment, involving the growth of plants, contributes positively to reducing carbon dioxide emissions in the atmosphere.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the Department of Environmental Science and Soil Testing Lab, Faculty of Agricultural Sciences of SGT University for all their technical support with the experiments.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

REFERENCES

Abou-Elela, S. I., & Hellal, M. S. (2012). Municipal wastewater treatment using vertical flow constructed wetlands planted with Canna, Phragmites and Cyprus. *Ecological engineering*, *47*, 209-213.

Albert, J. S., Destouni, G., Duke-Sylvester, S. M., Magurran, A. E., Oberdorff, T., Reis, R. E., ... & Ripple, W. J. (2021). Scientists' warning to humanity on the freshwater biodiversity crisis. *Ambio*, *50*(1), 85-94.

Aparna Bhardwaj, C.P Kaushik, Anubha Kaushik. Rhizosphere properties of three wetland macrophytes under conditions of varying organic load in the microcosm. Int. J. Multi. Res. & Dev. 2015; 10, vol.2, 75-79.

APHA Standard Methods fir Examination of Water and Wastewater, 19th edn., 1995. American Public Health Association, (American Water Association) Water Environment Federation, Washington, DC, USA.

Chaijak, P., & Sola, P. (2023). The new report of domestic wastewater treatment and bioelectricity generation using Dieffenbachia seguine constructed wetland coupling microbial fuel cell (CW-MFC). *Archives of Environmental Protection*, 57-62.

DeBusk, T. A, and DeBusk, W. F., (2001), Wetlands for water treatment', in D.M. Kent (ed.),Wetlands science and technology, 2nd edn, CRC Press, Boca Raton, USA.

Khatiwada, N. R., and Polprasert, C. (1999). Assessment of effective specific surface area for frees water surface constructed wetlands Water Sci. Technol. 1999, 40(3), 83– 89.

Kumar, V. K., Manangath, S. P., & Gajalakshmi, S. (2023). Innovative pilot-scale constructed wetland-microbial fuel cell system for enhanced wastewater treatment and bioelectricity production. *Chemical Engineering Journal*, *460*, 141686.

Li, F., Lu, L., Zheng, X., Ngo, H. H., Liang, S., Guo, W., & Zhang, X. (2014). Enhanced nitrogen removal in constructed wetlands: effects of dissolved oxygen and step-feeding. *Bioresource technology*, *169*, 395-402.

Logan, B. E. (2008). *Microbial fuel cells*. John Wiley & Sons.

Mook, W. T., Aroua, M. K. T., Chakrabarti, M. H., Noor, I. M., Irfan, M. F., & Low, C. T. J. (2013). A review on the effect of bio-electrodes on denitrification and organic matter removal processes in bio-electrochemical systems. *Journal of Industrial and Engineering Chemistry*, *19*(1), 1-13.

Narayan, M., Solanki, P., Rabha, A. K., & Srivastava, R. K. (2018). Treatment of pulp and paper industry effluent and electricity generation by constructed wetland coupled with microbial fuel cell (CW-MFC). *Journal of Pharmacognosy and Phytochemistry*, *7*(6), 493-498.

Potter, M. C. (1911). Electrical effects accompanying the decomposition of organic compounds. *Proceedings of the royal society of London. Series b, containing papers of a biological character*, *84*(571), 260-276.

Sehar, S., Aamir, R., Naz, I., Ali, N., & Ahmed, S. (2013). Reduction of contaminants (physical, chemical, and microbial) in domestic wastewater through hybrid constructed wetland. *International Scholarly Research Notices*, *2013*.

Shahid, N., Zia, Z., Shahid, M., Faiq Bakhat, H., Anwar, S., Mustafa Shah, G., & Rizwan Ashraf, M. (2015). Assessing Drinking Water Quality in Punjab, Pakistan. *Polish Journal of Environmental Studies*, *24*(6).

Singh, H. M., Pathak, A. K., Chopra, K., Tyagi, V. V., Anand, S., & Kothari, R. (2019). Microbial fuel cells: a sustainable solution for bioelectricity generation and wastewater treatment. *Biofuels*, *10*(1), 11-31.

Virdis, B., Rabaey, K., Yuan, Z., & Keller, J. (2008). Microbial fuel cells for simultaneous carbon and nitrogen removal. *Water research*, *42*(12), 3013-3024.

Vymazal, J. (2014a). Constructed wetlands for treatment of industrial wastewaters: A review. *Ecological engineering*, *73*, 724-751.

Vymazal, J. (2014b). Long-term treatment efficiency of a horizontal subsurface flow constructed wetland at Jimlíkov, Czech Republic. *Environmental Engineering & Management Journal (EEMJ)*, *13*(1).

Wu, H., Zhang, J., Ngo, H. H., Guo, W., Hu, Z., Liang, S., ... & Liu, H. (2015). A review on the sustainability of constructed wetlands for wastewater treatment: design and operation. *Bioresource technology*, *175*, 594-601.

Yadav, A. K. (2010). Design and development of novel constructed wetland cum microbial fuel cell for electricity production and wastewater treatment. In *Proceedings of 12th international conference on wetland systems for water pollution control (IWA)* (pp. 4-10).

Yadav, A. K., Dash, P., Mohanty, A., Abbassi, R., & Mishra, B. K. (2012). Performance assessment of innovative constructed wetland-microbial fuel cell for electricity production and dye removal. *Ecological Engineering*, *47*, 126-131.

Yadav, A., Jadhav, D. A., Ghangrekar, M. M., & Mitra, A. (2022). Effectiveness of constructed wetland integrated with microbial fuel cell for domestic wastewater treatment and to facilitate power generation. *Environmental Science and Pollution Research*, 1-13.

Zhao, Y., Collum, S., Phelan, M., Goodbody, T., Doherty, L., & Hu, Y. (2013). Preliminary investigation of constructed wetland incorporating microbial fuel cell: batch and continuous flow trials. *Chemical Engineering Journal*, *229*, 364-370.