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A Review of Selected Energy-Efficient Technologies for Wastewater Treatment

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Abstract

The need for energy-efficient wastewater treatment technologies has grown due to increasing water scarcity and the high energy demands of conventional treatment methods. This review examines emerging approaches that reduce energy consumption while maintaining treatment efficacy. The study categorizes them into biological, membrane-based, electrochemical, advanced oxidation processes (AOPs), and hybrid/integrated systems. Biological methods which include anaerobic digestion (AD) and microbial fuel cells (MFCs) provide dual benefits of treatment and energy generation, while membrane technologies, such as membrane bioreactors (MBRs), enhance water recovery and reduce chemical usage. Electrochemical methods and AOPs, including electrocoagulation and photocatalysis, offer energy-efficient alternatives with promising contaminant removal capabilities. The integration of these technologies in hybrid systems further optimizes energy efficiency and treatment performance and demonstrates significant potential for sustainable wastewater management. This review compiles recent advances to guide future research and application of energy-efficient solutions in wastewater treatment

1. Introduction

The global demand for clean water and the challenges posed by wastewater management continue to grow as populations expand and industrial activities increase [1][2]. Wastewater treatment plants (WWTPs) are critical for maintaining public health and environmental protection, yet they are also some of the largest energy consumers within municipalities [3][4][5][6][7][8]. Hence this technology is still a pipe dream in many developing countries. Traditional treatment methods, such as activated sludge, can make up to 50% of a WWTP's operational expenses thereby driving the need for energy-efficient technologies to mitigate both economic and environmental impacts [9][10][11]. Energy-efficient wastewater treatment technologies aim to reduce energy consumption while maintaining high treatment performance. This can be achieved through biological, chemical, and electrochemical methods, among others [2][12]. Biological processes such as anaerobic digestion not only treat wastewater but also generate energy in the form of biogas [13][14].

Similarly, emerging techniques like microbial fuel cells (MFCs) directly convert the organic content of wastewater into electricity and offer a dual advantage of treatment and energy recovery [15][16][17][18][19]. Membrane-based technologies such as membrane bioreactors (MBRs) are also gaining popularity for their ability to reduce energy usage through the integration of advanced filtration systems[20][21].

Electrochemical methods are also becoming important in the quest for energy efficiency. These methods show promise in reducing both energy consumption and chemical use, particularly when powered by renewable energy source. Additionally, advanced oxidation processes (AOPs) and ozonation, are being explored for their ability to reduce energy consumption while effectively removing contaminants, particularly in decentralized or remote applications. This review aims to provide a comprehensive overview of energy-efficient technologies in wastewater treatment, analyzing their mechanisms, advantages, and potential for future adoption. By compiling findings from recent studies, this paper highlights the importance of integrating energy-efficient methods to ensure the sustainability of wastewater treatment processes.

2. Energy-Efficient Wastewater Technologies

A flow chart of energy-efficient technologies in wastewater treatment are presented in Figure 1.While Table 1 presents a summary of selected studies on energy efficient waste water treatment technologies. The figure illustrates a range of energy-efficient wastewater treatment technologies categorized by biological, membrane-based, electrochemical, advanced oxidation processes (AOPs), and hybrid/integrated systems. Biological methods, such as anaerobic digestion (AD) and microbial fuel cells (MFC), are well-established for both waste stabilization and energy recovery, with MFCs demonstrating dual benefits of COD reduction and electricity generation [19]. Membrane technologies, including membrane bioreactors (MBRs) and forward osmosis (FO), are known for their high filtration efficiency and potential in nutrient recovery, though challenges related to fouling persist [22]. Electrochemical methods like electrocoagulation (EC) and capacitive deionization (CDI) offer promising alternatives by leveraging electric fields to treat contaminants and enhance deionization, respectively, with minimal chemical addition [23]. Advanced oxidation processes, particularly photocatalysis and ozonation, provide effective solutions for degrading recalcitrant pollutants through radical generation, though they often require high energy inputs. Finally, hybrid and integrated systems combining these technologies have gained attention for optimizing treatment efficiency and enhancing sustainability by addressing limitations of standalone approaches [24]. Collectively, these technologies represent a diverse toolkit aimed at achieving high efficiency in wastewater treatment while minimizing environmental impact.

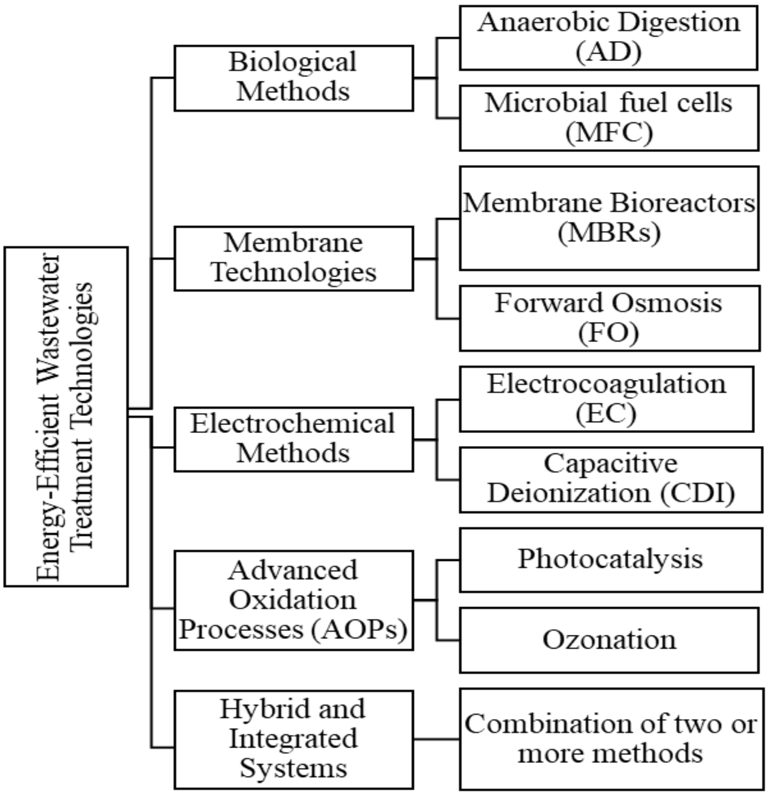

Figure 1: Energy Efficient Wastewater Treatment Technologies

2.1 Biological Methods

2.1.1 Anaerobic Digestion (AD)

Anaerobic Digestion (AD) is widely recognized as one of the most energy-efficient methods for wastewater treatment, this is because it offers the dual benefits of waste stabilization and energy recovery. AD is a biological process where microorganisms break down organic matter in the absence of oxygen, thereby producing biogas, which can be harnessed as energy. [25] reported that AD holds substantial promise for sustainable biogas production, effective waste management, and contributing to climate change mitigation. [26] found that the anaerobic co-digestion of water hyacinth and poultry manure significantly enhances biogas production, demonstrating the potential of these substrates for renewable energy generation in sustainable waste management. This makes AD a highly energy-efficient process, with the added benefit of energy generation. [24] reported that using a two-stage serial AD process for sewage sludge improves biogas production by 9.5–40.1% and enhances volatile suspended solids reduction compared to a single-step digestion process. This combination of waste treatment and energy recovery highlights the dual benefits of AD as both a treatment technology and a renewable energy source. In AD, microorganisms break down organic matter in the absence of oxygen, producing biogas—a mixture of methane and carbon dioxide—that can be used as a renewable energy source. This process not only treats wastewater but also helps offset energy costs by producing biogas, which can be converted into electricity or heat. Moreover, AD is highly versatile and can be applied to various types of wastewater, including municipal, industrial, and agricultural waste. The energy efficiency of AD systems can be further enhanced by co-digestion, where multiple waste streams (e.g., wastewater sludge and food waste) are treated together to increase biogas yields. [27] investigated the interplay between various AD parameters in a pig-dung aided water hyacinth digestion process and demonstrated the impact of these parameters on biogas production and process efficiency.

Advanced AD technologies, such as high-rate anaerobic reactors and two-phase digestion, improve process stability and methane production, making the method even more attractive for energy-efficient wastewater treatment [23][28]. Despite these benefits, AD does have some limitations, including the need for careful monitoring of operational parameters like pH and temperature to ensure optimal performance. [29] examined how temperature and pH levels influence biogas production from the co-digestion of food waste and cow dung and revealed that optimal conditions significantly enhance biogas yield.

2.1.2. Microbial Fuel Cells (MFCs)

Microbial Fuel Cells (MFCs) are an innovative and energy-efficient technology for wastewater treatment that harnesses the metabolic activity of microorganisms to generate electricity while simultaneously treating organic waste [30]. Fuel cells are promising candidates for energy conversion systems [31], of which MFCs represent an advanced technology that converts the chemical energy of organic matter in wastewater directly into electricity through electroactive bacteria [19]. In an MFC, organic substrates in wastewater serve as fuel for electroactive bacteria, which catalyze the oxidation of these substrates at the anode, releasing electrons that travel through an external circuit to the cathode, where they reduce oxygen or other electron acceptors. [32] found that MFC technology effectively treats wastewater for irrigation purposes while generating electricity, providing a dual benefit in sustainable water reuse and energy generation. Through a case study on fruit-processing wastewater in a semi-arid region, the authors demonstrated that MFC technology leaves low nutrient concentrations in the effluent and offers economic potential by creating value from both treated water and electricity production, positioning MFCs as economically viable and environmentally beneficial for addressing water and energy shortages in agricultural settings.

The efficiency of MFCs can be enhanced by optimizing factors such as electrode materials, microbial consortia, and reactor configurations, paving the way for their application in decentralized wastewater treatment systems and resource recovery frameworks. According to [33], MFCs can reach a peak voltage of 0.8 V, achieve a Chemical Oxygen Demand (COD) reduction of 81.81% and a Biochemical Oxygen Demand (BOD) reduction of 64%, with optimized MFC parameters thereby demonstrating significant potential for both wastewater treatment and energy production. [22] affirmed that MFC technology provides an innovative solution for sustainable wastewater treatment by simultaneously optimizing electricity generation and phosphorus removal, demonstrating potential for self-powered wastewater treatment plants that support both clean water access and renewable energy production. Although still in early stages, the energy generation potential of MFCs makes them a promising addition to the future of wastewater treatment.

2.2. Membrane Technologies

2.2.1. Membrane Bioreactors (MBRs)

MBRs combine biological treatment with membrane filtration, offering high-quality effluent and reducing the energy demand compared to conventional methods. MBR technology offers an efficient and sustainable solution for industrial wastewater treatment in developing countries, with key advantages in treatment efficiency, reduced chemical usage, and water reuse potential [21]. [34] conducted a study that found out that osmotic MBR hybrid system has the capability to achieve contaminant removal efficiencies exceeding 80% in wastewater treatment.

2.2.2. Forward Osmosis (FO)

Forward osmosis is another emerging membrane technology that uses a natural osmotic pressure gradient to separate water from contaminants. FO has shown significant potential in reducing energy consumption [43]. [35] underscored that FO technology holds promise for desalination and water treatment due to its low energy requirements and fouling resistance. The low-energy demand and high water recovery rates make FO a strong candidate for large-scale operations, particularly in water-scarce regions. The integration of FO with other treatment technologies in hybrid systems further enhances energy efficiency, underscoring FO's potential as a sustainable solution for reducing energy consumption in water treatment processes [36].

2.3. Electrochemical Methods

2.3.1. Electrocoagulation (EC)

Electrocoagulation (EC) is an electrochemical process that uses electrical currents to destabilize and remove pollutants from wastewater. This method has gained attention for its energy efficiency, especially when powered by renewable energy sources like solar power. [37] demonstrated that EC optimized via response surface methodology, effectively removed up to 92.3% of color, 95.28% of COD, and 83.33% of turbidity from hospital wastewater under specific conditions, highlighting EC's potential for treating various wastewaters with minimal energy consumption. Electrocoagulation (EC) is gaining recognition for its effectiveness in purifying water, particularly in removing emerging contaminants such as microplastics [38].

2.3.2. Capacitive Deionization (CDI)

Capacitive deionization (CDI) is a novel electrochemical process used to remove dissolved ions from water. CDI systems use electrically charged electrodes to adsorb ions, making them a lower-energy alternative to reverse osmosis (RO) for desalination and water purification. [39] found that capacitive deionization (CDI) technology, especially when enhanced with activated carbon electrodes, offers an energy-efficient and low-maintenance approach for removing heavy metal ions and other contaminants from brackish water. This makes it a promising alternative for water desalination and treatment in industrial applications.

2.4. Advanced Oxidation Processes (AOPs)

2.4.1. Photocatalysis

Photocatalysis uses light-activated catalysts to degrade pollutants in wastewater, thereby offering energy-efficient solutions especially when driven by solar energy. [40] highlighted the key factors that influence the performance of solar photocatalysis in removing emerging micro-pollutants and inactivating pathogens to include catalyst type, water matrix composition, and microbial load. The use of sunlight as a free energy source significantly enhances the energy efficiency of this treatment method. [41] highlighted the dual nature of nano-photocatalysts in wastewater treatment by emphasizing their efficiency in removing pollutants while also noting their potential to introduce emerging secondary contaminants that pose health and environmental risks. [42] discussed the promising role of photocatalysis in wastewater treatment and focused on the use of nanomaterials for enhanced filtration, the advantages of green synthesis methods over chemical approaches, and the integration of artificial intelligence and machine learning in designing photocatalysts. However, despite its potential for wastewater decontamination, photocatalytic technology faces challenges in real-world application due to low photo efficiency under visible light [43].

2.4.2. Ozonation

Ozonation, a method for wastewater disinfection, offers the dual benefits of effective contaminant removal and reduced chemical use. Ozonation can be particularly energy-efficient when coupled with ultraviolet (UV) light. [44] found that while UV photolysis was effective in reducing concentrations of anticancer drugs while ozonation proved significantly more energy-efficient by achieving nearly complete degradation of doxorubicin, daunorubicin, epirubicin, and irinotecan across pH levels in a shorter time. [45] affirmed the effectiveness of advanced oxidation processes

(AOPs) like photolysis, ozone-based systems, and Fenton reactions in degrading organic pollutants, with a focus on the role of hydroxyl and sulfate radicals in enhancing wastewater treatment.

2.5. Hybrid and Integrated Systems

The integration of multiple treatment technologies in hybrid systems has shown great promise in enhancing energy efficiency while maintaining high performance. [46] reviewed hybrid anaerobic osmotic membrane bioreactors (AnOsMBRs) and emphasised their potential for energy-efficient municipal wastewater treatment by producing reusable high-quality effluent and recovering resources. However challenges like salt accumulation, membrane fouling, and optimal draw solute selection must be addressed to maintain performance and reduce energy consumption. [47] highlighted membrane bioreactor (MBR) technology's advantages over conventional activated sludge (CAS) processes, its improved permeate quality, reduced space requirements, and operational simplicity were applauded, despite challenges like fouling and energy demands. Despite the challenges, these integrated approaches are increasingly being recognized as the future of energy-efficient wastewater treatment.

Table 1: Summary of Previous Studies on Energy-Efficient Wastewater Treatment Technologies

Technology	Study	Key Findings
Anaerobic Digestion (AD)	[25]	AD has significant potential in biogas production as sustainable renewable energy, waste management and climate change mitigation
Microbial Fuel Cells (MFC)	[32]	MFCs can achieve a maximum voltage of 0.8 V, 81.81% COD reduction, and 64% BOD reduction, with optimized MFC parameters showing promising results for wastewater treatment and energy generation
Membrane Bioreactors	[33]	Osmotic membrane bioreactor hybrid system has the potential of achieving over 80% contaminant removal efficiency in wastewater treatment
Forward Osmosis (FO)	[35]	FO technology is a promising solution for desalination and water treatment that offers benefits such as low energy consumption and resistance to fouling.
Electrocoagulation (EC)	[38]	EC is increasingly recognized for its effectiveness in water purification in the removal of emerging contaminants like microplastics.
Capacitive Deionization (CDI)	[39]	CDI provides a low-energy and easy-to-maintain method for extracting heavy metal ions and other impurities from brackish water.
Photocatalysis	[42]	The promising role of photocatalysis in wastewater treatment focuses on the use of nanomaterials for enhanced filtration and the advantages of green synthesis methods over chemical approaches
Ozonation	[44]	Ozonation proved significantly more energy-efficient by achieving nearly complete degradation of contaminants across pH levels in a shorter time.
Hybrid Systems	[46]	emphasised the potential of hybrid anaerobic osmotic membrane bioreactors (AnOsMBRs) for energy-efficient municipal wastewater treatment by producing reusable high-quality effluent and recovering resources.

Wastewater treatment technologies each have unique strengths and limitations. Anaerobic digestion (AD) excels in biogas production and climate change mitigation but struggles with contaminant removal [2][25][49]. Microbial fuel cells (MFCs) combine energy recovery with moderate pollutant reduction but face scalability and high material costs [30][32][50]. Membrane bioreactors (MBRs) achieve >80% contaminant removal but are hindered by fouling and energy demands [21][33][51]. Forward osmosis (FO) offers low-energy, fouling-resistant treatment, though scalability remains a challenge [35][52][53].

Electrocoagulation (EC) is effective for emerging contaminants like microplastics but generates sludge and consumes significant energy [38][54][55]. Capacitive deionization (CDI) provides efficient heavy metal removal from brackish water but is unsuitable for high-salinity applications [39][56][57]. Photocatalysis, driven by nanomaterials, is eco-friendly but depends on light availability [42][43][58], while ozonation ensures rapid degradation across pH levels at high operational costs [44][59][60].

Hybrid systems, such as anaerobic osmotic membrane bioreactors, combine resource recovery with energy efficiency but require substantial initial investment and expertise [46][61][62]. Thus, integrating these technologies based on specific needs can optimize performance and sustainability [63][64].

3. Conclusion

The continuous development of energy-efficient technologies for wastewater treatment presents promising opportunities for reducing operational costs and minimizing environmental impacts. Innovations such as anaerobic digestion, membrane bioreactors, and electrochemical methods have shown significant potential to lower energy consumption. The integration of hybrid systems further enhances treatment efficiency and energy savings. As research progresses, these technologies will play an important role in ensuring sustainable and cost-effective wastewater treatment on a global scale.

References

[1] Silva, J. A. (2023a). Water supply and wastewater treatment and reuse in future cities: A systematic literature review. *Water*, *15*(17), 3064. https://doi.org/10.3390/w15173064

[2] Singh, B. J., Chakraborty, A., & Sehgal, R. (2023). A systematic review of industrial wastewater management: Evaluating challenges and enablers. *Journal of Environmental Management, 348*, 119230. https://doi.org/10.1016/j.jenvman.2023.119230

[3] Gandiglio, M., Lanzini, A., Soto, A., Leone, P., & Santarelli, M. (2017). Enhancing the energy efficiency of wastewater treatment plants through co-digestion and fuel cell systems. *Frontiers in Environmental Science, 5*, 70. https://doi.org/10.3389/fenvs.2017.00070

[4] Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Robinson, Z. P., Wang, X., Wu, J., & Li, F. (2017). The feasibility and challenges of energy self-sufficient wastewater treatment plants. *Applied Energy, 204*, 1463-1475. https://doi.org/10.1016/j.apenergy.2017.02.069

[5] Wang, X., Dong, Y., Yu, S., Mu, G., Qu, H., Li, Z., & Bian, D. (2022). Analysis of the electricity consumption in municipal wastewater treatment plants in Northeast China in terms of wastewater characteristics. *International Journal of Environmental Research and Public Health, 19*(21), 14398. https://doi.org/10.3390/ijerph192114398

[6] Gupta, U., Chauhan, A., Tuli, H. S., Ramniwas, S., Shahwan, M., & Jindal, T. (2024). Energy requirement of wastewater treatment plants: Unleashing the potential of microalgae, biogas, and solar power for sustainable development. *Nature Environment and Pollution Technology, 23*(1), 559-568. https://doi.org/10.46488/NEPT.2024.v23i01.053

[7] Tsalas, N., Golfinopoulos, S. K., Samios, S., Katsouras, G., & Peroulis, K. (2024). Optimization of energy consumption in a wastewater treatment plant: An overview. *Energies, 17*(12), 2808. https://doi.org/10.3390/en17122808

[8] Twi-Yeboah, N., Osei, D., Dontoh, W. H., Asamoah, G. A., Baffoe, J., & Danquah, M. K. (2024). Enhancing energy efficiency and resource recovery in wastewater treatment plants. *Energies*, *17*(13), 3060. https://doi.org/10.3390/en17133060

[9] Guo, Z., Sun, Y., Pan, S. Y., & Chiang, P. C. (2019). Integration of green energy and advanced energy-efficient technologies for municipal wastewater treatment plants. *International Journal of Environmental Research and Public Health, 16*(7), 1282. https://doi.org/10.3390/ijerph16071282

[10] Cairone, S., Hasan, S. W., Choo, K. H., Lekkas, D. F., Fortunato, L., Zorpas, A. A., Korshin, G., Zarra, T., Belgiorno, V., & Naddeo, V. (2024). Revolutionizing wastewater treatment toward circular economy and carbon neutrality goals: Pioneering sustainable and efficient solutions for automation and advanced process control with smart and cutting-edge technologies. *Journal of Water Process Engineering, 63*, 105486. https://doi.org/10.1016/j.jwpe.2024.105486

[11] Silva, J. A. (2023b). Wastewater treatment and reuse for sustainable water resources management: A systematic literature review. *Sustainability, 15*(14), 10940. https://doi.org/10.3390/su151410940

[12] Cardoso, B. J., Rodrigues, E., Gaspar, A. R., & Gomes, Á. (2021). Energy performance factors in wastewater treatment plants: A review. *Journal of Cleaner Production, 322*, 129107. https://doi.org/10.1016/j.jclepro.2021.129107

[13] Vutai, V., Ma, X. C., & Lu, M. (2016). The role of anaerobic digestion in wastewater management. *EM (Pittsburgh, Pa), 0*(September 2016), 12-16. PMCID: PMC5884444.

[14] Tshemese, Z., Deenadayalu, N., Linganiso, L. Z., & Chetty, M. (2023). An overview of biogas production from anaerobic digestion and the possibility of using sugarcane wastewater and municipal solid waste in a South African context. *Applied Systems Innovation, 6*(1), 13. https://doi.org/10.3390/asi6010013

[15] Verma, P., Daverey, A., Kumar, A., & Arunachalam, K. (2021). Microbial fuel cell – A sustainable approach for simultaneous wastewater treatment and energy recovery. *Journal of Water Process Engineering, 40*, 101768. https://doi.org/10.1016/j.jwpe.2020.101768

[16] Malik, S., Kishore, S., Dhasmana, A., Kumari, P., Mitra, T., Chaudhary, V., Kumari, R., Bora, J., Ranjan, A., Minkina, T., & Rajput, V. D. (2023). A perspective review on microbial fuel cells in treatment and product recovery from wastewater. *Water, 15*(2), 316. https://doi.org/10.3390/w15020316

[17] Nawaz, A., Haq, I. u., Qaisar, K., Gunes, B., Raja, S. I., Mohyuddin, K., & Amin, H. (2022). Microbial fuel cells: Insight into simultaneous wastewater treatment and bioelectricity generation. *Process Safety and Environmental Protection, 161*, 357-373. https://doi.org/10.1016/j.psep.2022.03.039

[18] Naha, A., Debroy, R., Sharma, D., Shah, M. P., & Nath, S. (2023). Microbial fuel cell: A state-of-the-art and revolutionizing technology for efficient energy recovery. *Cleaner and Circular Bioeconomy, 5*, 100050. https://doi.org/10.1016/j.clcb.2023.100050

[19] Roy, H., Rahman, T. U., Tasnim, N., Arju, J., Rafid, M. M., Islam, M. R., Pervez, M. N., Cai, Y., Naddeo, V., & Islam, M. S. (2023). Microbial fuel cell construction features and application for sustainable wastewater treatment. *Membranes, 13*(5), 490. https://doi.org/10.3390/membranes13050490

[20] Qin, L., Zhang, Y., Xu, Z., & Zhang, G. (2018). Advanced membrane bioreactors systems: New materials and hybrid process design. *Bioresource Technology*, *269*, 476-488. https://doi.org/10.1016/j.biortech.2018.08.062

[21] Jijingi, H. E., Yazdi, S. K., Abakar, Y. A., & Etim, E. (2024). Evaluation of membrane bioreactor (MBR) technology for industrial wastewater treatment and its application in developing countries: A review. *Case Studies in Chemical and Environmental Engineering, 10*, 100886. https://doi.org/10.1016/j.cscee.2024.100886

[22] Kurniawan, T. A., Othman, M. H. D., Liang, X., Ayub, M., Goh, H. H., Kusworo, T. D., Mohyuddin, A., & Chew, K. W. (2022). Microbial Fuel Cells (MFC): A potential game-changer in renewable energy development. *Sustainability, 14*(24), 16847. https://doi.org/10.3390/su142416847

[23] Nayeri, D., Mohammadi, P., Bashardoust, P., & Eshtiaghi, N. (2024). A comprehensive review on the recent development of anaerobic sludge digestions: Performance, mechanism, operational factors, and future challenges. *Results in Engineering, 22*, 102292. https://doi.org/10.1016/j.rineng.2024.102292

[24] Athanasoulia, E., Melidis, P., & Aivasidis, A. (2012). Optimization of biogas production from waste activated sludge through serial digestion. *Renewable Energy,47*, 147–151. https://doi.org/10.1016/j.renene.2012.04.038

[25] Adeleke, A. J., Ajunwa, O. M., Golden, J. A., Antia, U. E., Adesulu-Dahunsi, A. T., Adewara, O. A., Popoola, O. D., Oni, E. O., Thomas, B. T., & Luka, Y. (2023). Anaerobic digestion technology for biogas production: Current situation in Nigeria (A review). *UMYU Journal of Microbiology Research (UJMR)*, *8*(2), 153–164. https://doi.org/10.47430/ujmr.2382.018

[26] Ojo, O. M. (2021a). Biogas production through anaerobic co-digestion of water hyacinth and poultry manure. *Nigerian Research Journal of Engineering and Environmental Sciences*, 6(2), 735–740.

[27] Ojo, O. M., Babatola, J. O., & Olabanji, T. O. (2022). Relationship between different anaerobic digestion parameters in a pig-dung aided water hyacinth digestion process. *European Journal of Engineering and Technology Research*, *7*(4), 10-13

[28] Sevillano, C.A., Pesantes, A.A., Peña Carpio, E., Martínez, E.J., & Gómez, X. (2021). Anaerobic Digestion for Producing Renewable Energy—The Evolution of This Technology in a New Uncertain Scenario. *Entropy, 23*(2), 145. https://doi.org/10.3390/e23020145

[29] Ojo, O. M. (2021b). Temperature and pH effects on biogas yield from co-digestion of food waste and cow-dung. *ABUAD Journal of Engineering Research and Development (AJERD), 4*(2), 10-17.

[30] Jalili, P., Ala, A., Nazari, P., Jalili, B., & Ganji, D. D. (2024). A comprehensive review of microbial fuel cells considering materials, methods, structures, and microorganisms. *Heliyon, 10*(3), e25439. https://doi.org/10.1016/j.heliyon.2024.e25439

[31] Ighodaro, O. O., Scott, K., & Xing, L. (2017). An isothermal study of the electrochemical performance of intermediate temperature solid oxide fuel cells. *Journal of Power and Engineering*, *5*(2), 97–122. https://doi.org/10.4236/jpee.2017.52006

[32] Abourached, C., English, M. J., & Liu, H. (2016). Wastewater treatment by Microbial Fuel Cell (MFC) prior to irrigation water reuse. *Journal of Cleaner Production, 137*, 144–149. https://doi.org/10.1016/j.jclepro.2016.07.048

[33] Mukherjee, A., Zaveri, P., Patel, R., Shah, M. T., & Munshi, N. S. (2021). Optimization of microbial fuel cell process using a novel consortium for aromatic hydrocarbon bioremediation and bioelectricity generation. *Journal of Environmental Management, 298*, 113546. https://doi.org/10.1016/j.jenvman.2021.113546

[34] Chang, H.-M., He, C.-C., Zhan, M., Kim, H., & Pan, S.-Y. (2024). Perspective trends of osmotic membrane bioreactor hybrid system for a circular economy. *Chemical Engineering Journal*, 500, 157374. https://doi.org/10.1016/j.cej.2024.157374

[35] Wang, J., & Liu, X. (2021). Forward osmosis technology for water treatment: Recent advances and future perspectives. *Journal of Cleaner Production, 280*, 124354. https://doi.org/10.1016/j.jclepro.2020.124354

[36] Abounahia, N., Ibrar, I., Kazwini, T., Altaee, A., Samal, A. K., Zaidi, S. J., & Hawari, A. H. (2023). Desalination by forward osmosis: Advancement and challenges. *Science of the Total Environment, 886*, 163901. https://doi.org/10.1016/j.scitotenv.2023.163901

[37] Xu, Y., Zhu, Y., Chen, Z., Zhu, J., & Chen, G. (2022). A comprehensive review on forward osmosis water treatment: Recent advances and prospects of membranes and draw solutes. *International Journal of Environmental Research and Public Health, 19*(13), 8215. https://doi.org/10.3390/ijerph19138215

[38] Ebba, M., Asaithambi, P., & Alemayehu, E. (2022). Development of electrocoagulation process for wastewater treatment: Optimization by response surface methodology. *Heliyon, 8*(5), e09383. https://doi.org/10.1016/j.heliyon.2022.e09383

[39] Mao, Y., Zhao, Y., & Cotterill, S. (2023). Examining current and future applications of electrocoagulation in wastewater treatment. *Water, 15*(8), 1455. https://doi.org/10.3390/w15081455

[40] Wang, X., Shan, S., Zhang, Y., Shi, S. Q., & Xia, C. (2024). Enhancing capacitive deionization for water desalination: the role of activated carbon in contaminant removal. *Environmental Science: Water Research & Technology, 10*(5), 1034-1060. https://doi.org/10.1039/D4EW00026A

[41] Venieri, D., Mantzavinos, D., & Binas, V. (2020). Solar photocatalysis for emerging micro-pollutants abatement and water disinfection: A mini-review. *Sustainability, 12*(23), 10047. https://doi.org/10.3390/su122310047 [41] Thakur, S., Ojha, A., Kansal, S. K., Gupta, N. K., Swart, H. C., Cho, J., Kuznetsov, A., Sun, S., & Prakash, J. (2024). Advances in powder nano-photocatalysts as pollutant removal and as emerging contaminants in water: Analysis of pros and cons on health and environment. *Advanced Powder Materials, 3*(6), 100233. https://doi.org/10.1016/j.apmate.2024.100233

[42] Thakur, S., Ojha, A., Kansal, S. K., Gupta, N. K., Swart, H. C., Cho, J., Kuznetsov, A., Sun, S., & Prakash, J. (2024). Advances in powder nano-photocatalysts as pollutant removal and as emerging contaminants in water: Analysis of pros and cons on health and environment. *Advanced Powder Materials, 3*(6), 100233. https://doi.org/10.1016/j.apmate.2024.100233

[43] Hassaan, M. A., El-Nemr, M. A., Elkatory, M. R., Ragab, S., Niculescu, V.-C., & El Nemr, A. (2023). Principles of photocatalysts and their different applications: A review. *Topics in Current Chemistry, 381*(6), 31. https://doi.org/10.1007/s41061-023-00444-7

[44] Muscetta, M., Ganguly, P., & Clarizia, L. (2024). Solar-powered photocatalysis in water purification: Applications and commercialization challenges. *Journal of Environmental Chemical Engineering, 12*(3), 113073. https://doi.org/10.1016/j.jece.2024.113073

[45] Mello Souza, D., Reichert, J. F., Ramos do Nascimento, V., & Figueiredo Martins, A. (2022). Ozonation and UV photolysis for removing anticancer drug residues from hospital wastewater. *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering, 57*(8), 635-644. https://doi.org/10.1080/10934529.2022.2099195

[46] Khan, Z. U. H., Gul, N. S., Sabahat, S., Sun, J., Tahir, K., Shah, N. S., Muhammad, N., Rahim, A., Imran, M., Iqbal, J., Khan, T. M., Khasim, S., Farooq, U., & Wu, J. (2023). Removal of organic pollutants through hydroxyl radical-based advanced oxidation processes. *Ecotoxicology and Environmental Safety, 267*, 115564. https://doi.org/10.1016/j.ecoenv.2023.115564.

[47] Nguyen, H. T., Chen, S.-S., Duong, H. C., Nguyen, N. C., Le, H. Q., Duong, C. C., & Bui, X.-T. (2022). Integrated and hybrid anaerobic treatment technology. In X.-T. Bui, D. D. Nguyen, P.-D. Nguyen, H. H. Ngo, & A. Pandey (Eds.), *Current Developments in Biotechnology and Bioengineering* (pp. 451-476). Elsevier. https://doi.org/10.1016/B978-0-323-99874-1.00016-6

[48] Rahman, T. U., Roy, H., Islam, M. R., Tahmid, M., Fariha, A., Mazumder, A., Tasnim, N., Pervez, M. N., Cai, Y., Naddeo, V., & Islam, M. S. (2023). The advancement in membrane bioreactor (MBR) technology toward sustainable industrial wastewater management. *Membranes, 13*(2), 181. https://doi.org/10.3390/membranes13020181

[49] Zieliński, M., Kazimierowicz, J., & Dębowski, M. (2023). Advantages and limitations of anaerobic wastewater treatment—Technological basics, development directions, and technological innovations. Energies, 16(1), 83. https://doi.org/10.3390/en16010083

[50] Fatehbasharzad, P., Aliasghari, S., Shaterzadeh Tabrizi, I., Khan, J. A., & Boczkaj, G. (2022). Microbial fuel cell applications for removal of petroleum hydrocarbon pollutants: A review. Water Resources and Industry, 28, 100178. https://doi.org/10.1016/j.wri.2022.100178

[51] Lazrak, A., Hannoun, G., Elabbas, S., Oumani, A., Mandi, L., & Ouazzani, N. (2023). Advancements and challenges in membrane bioreactor technology for industrial wastewater treatment. *International Journal of Water and Wastewater Treatment*, *9*(2). https://doi.org/10.16966/2381-5299.192

[52] Giwa, A., Okolie, J., Amusa, H. K., Yusuf, A. O., Abid, H. A., Amna, R., & Alsayer, I. (2024). Overcoming the challenges of forward osmosis using electric field: A comprehensive review of recent advances. *Chemical Engineering Journal, 500*, 157169. https://doi.org/10.1016/j.cej.2024.157169

[53] Zhu, L., Ding, C., Zhu, T., & Wang, Y. (2022). A review on the forward osmosis applications and fouling control strategies for wastewater treatment. *Frontiers of Chemical Science and Engineering, 16*(5), 661–680. https://doi.org/10.1007/s11705-021-2084-4

[54] Shen, M., Zhang, Y., Almatrafi, E., Hu, T., Zhou, C., Song, B., Zeng, Z., & Zeng, G. (2022). Efficient removal of microplastics from wastewater by an electrocoagulation process. *Chemical Engineering Journal*, 428, 131161. https://doi.org/10.1016/j.cej.2021.131161

[55] Boinpally, S., Kolla, A., Kainthola, J., Kodali, R., & Vemuri, J. (2023). A state-of-the-art review of the electrocoagulation technology for wastewater treatment. *Water Cycle, 4,* 26–36. https://doi.org/10.1016/j.watcyc.2023.01.001

[56] Chai, S., Xi, J., Chen, L., He, W., Shen, J., & Gong, H. (2022). Selective ion removal by capacitive deionization (CDI)-based technologies. *Processes*, *10*, 1075. https://doi.org/10.3390/pr10061075

[57] Xu, Y., Zhong, Z., Zeng, X., Zhao, Y., Deng, W., & Chen, Y. (2023). Novel materials for heavy metal removal in capacitive deionization. *Applied Sciences, 13*, 5635. https://doi.org/10.3390/app13095635

[58] Li, X., Chen, Y., Tao, Y., Shen, L., Xu, Z., Bian, Z., & Li, H. (2022). Challenges of photocatalysis and their coping strategies. *Chem Catalysis, 2*(6), 1315-1345. https://doi.org/10.1016/j.checat.2022.04.007

[59] Canatto, A. K., da Silva, T. F., Machado, B. dos S., Gozzi, F., de Brito, D. A. S., Nazário, C. E. D., Filho, F. J. C. M., Cavalheri, P. S., de Oliveira, S. C., & Machulek Junior, A. (2024). Ozonation process at neutral pH integrated with anaerobic treatment system to methylparaben removal. *Journal of Water Process Engineering, 64*, 105741. https://doi.org/10.1016/j.jwpe.2024.105741

[60] Das, P. P., Dhara, S., Samanta, N. S., & Purkait, M. K. (2024). Advancements on ozonation process for wastewater treatment: A comprehensive review. *Chemical Engineering and Processing - Process Intensification, 202,* 109852. https://doi.org/10.1016/j.cep.2024.109852

[61] Fernandes, J., Ramísio, P. J., & Puga, H. (2024). A Comprehensive Review on Various Phases of Wastewater Technologies: Trends and Future Perspectives. *Eng*, *5*(4), 2633-2661. https://doi.org/10.3390/eng5040138

[62] Sadeq, A. M., Homod, R. Z., Hussein, A. K., Togun, H., Mahmoodi, A., Isleem, H. F., Patil, A. R., & Moghaddam, A. H. (2024). Hydrogen energy systems: Technologies, trends, and future prospects. *Science of The Total Environment, 939,* 173622. https://doi.org/10.1016/j.scitotenv.2024.173622

[63] Al-Dahidi, S., Alrbai, M., Al-Ghussain, L., & Alahmer, A. (2024). Maximizing energy efficiency in wastewater treatment plants: A data-driven approach for waste heat recovery and an economic analysis using Organic Rankine Cycle and thermal energy storage. *Applied Energy, 362*, 123008. https://doi.org/10.1016/j.apenergy.2024.123008

[64] Alrbai, M., Al-Dahidi, S., Al-Ghussain, L., Alahmer, A., & Hayajneh, H. (2024). Minimizing grid energy consumption in wastewater treatment plants: Towards green energy solutions, water sustainability, and cleaner environment. *Science of The Total Environment, 926,* 172139. https://doi.org/10.1016/j.scitotenv.2024.172139