Innovative Approaches to Wastewater Treatment Using Bioengineering Techniques

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ABSTRACT

In the recent past, effluent disposal has become one of the greatest concerns in the world because of increase industrialization and urbanization resulting to water pollution. This has facilitated the attempt at looking at diseases in a new light and therefore coming up with a new paradigm shift on treating diseases or diversification of the approach by overcoming environmental, economical or social barriers to diseases and treatment through out of the box thinking. Therefore, bioengineering, a branch of biology and engineering sciences, is regarded as one of the most suitable solutions to the problems of wastewater treatment. The function of microorganisms, plants as well as bioengineering activities such as bioreactors, bio augmentation and phytoremediation on wastewater is discussed in this paper. It explores stet opportunities that can be exploited in the removal of pollutants and the potential for getting valuable resources back in the form of microbial technologies, constructed wetlands and NMIs. In addition, there are modern materials like nanomaterials, microbial electrochemical system, and membrane bioreactor for wastewater treatment included in the subject. From this paper, it is concluded that bioengineering is about enhancing the mechanism of wastewater treatment through sustainable approaches and the circular economy.

INTRODUCTION

As a result of the upsurge in industrialization and urbanization, water pollution has become rampant and calls for the inventions on the effective treatment of wastewater (Sahu et al., 2019). Such conventional methods depict social, economic and environmental inconveniences hence necessitating a favorable, technological method to recycle water from wastewater which has been defined well to contain nutrients and other organic matter (Machineni, 2019). While focusing on inventory, the bioengineering, the integration of life and engineering science could possibly produce routes to achieve sufficient removal of Wastewater addresses the problem of eco adequateness and technical efficiency (López et al., 2011). Thus these methods are practiced in conjunction for purposes such as elimination of contaminants, generation of energy and the regeneration of resources alongside minimizing the overall effect of the treatment processes. Bioaugmentation in WWTP include a use of microorganisms, enzymes and plants to remove or degrade pollutants from the wastewater, thus obtaining cleaner effluent for reuse, or recovery of valuable products afterwards (Donkadokula et al., 2020). There is evidence that the application of bioengineering presents a lot of opportunities and technology in the existing, as well as newly developing, wastewater treatment for environmental yet with the aim of circular economy as conducted in Tetteh et al., 2019. Among them I ranked advanced oxidation processes, adsorption, and membrane separation essential as some of the best approaches to depollute industrial and municipal wastewater for environmental, social corporate responsibility, human health, and wealth creation (Martini & Roni, 2021).

Microbial Technologies for Wastewater Treatment

In the opinion of the author, the microbial technologies' application in a water solution can be regarded as one of the most efficient approaches to tackle the bioengineering issues of the dye industry, particularly addressing the presence of pollutants and potential for resource completion (Shindhal et al., 2020). Out of those, bacteria, fungi, algae and yeast forms of microorganisms are used in bioremediation to a greater extent because they increase the uptake and assimilation of pollutants in the ecosystem (Ihsanullah et al., 2020). Among the various methods employed in the elimination of soluble biodegradable organic contaminants the aerobic and the anaerobic methods are very popular (Awaleh, 2014). Crude oil and its byproducts are preferred more employing bioremediation for the removal of various industrial effluents by using terrestrial as well as aquatic plants and microorganisms due to their environment friendly approach (Deeba et al., 2017). Microbial fuel cell is among the bio-electrochemical systems that have the combined aim of wastewater treatment and power production (Jain, Pant, Bhatia, Shrestha, & Das, 2020). The selection and subsequent enhancement of the strains of microbes also have significant contribution to the efficiency and steadiness of the different methods of wastewater treatment. Recrision two also has the implication that microbial facilitates can be further extended to utilize 'superbugs' to degrade these resistant pollutants or even synthesize useful product out of waste streams. Bioelectrochemical systems are technologies are relatively new in wastewater treatment since they take advantage of microbial activity and electrochemical processes for expunging pollutants and generating energy (Taheri et al., 2021). These two processes help in the removal of organic pollutants in the wastewater and at the same time it also produces renewable energy. Constructed wetlands are one of the viable solution to treat wastewater bioengineering systems that imitate wetlands and provide physical, chemical and biological removal of different contaminants.

Phytoremediation and Constructed Wetlands

Bioremediation that mainly involves the use of plant life in the purification of wastewaters can be described as the incorporation of plant life in examination and cleaning of contaminated waters and as a result it is has beenconfirmed as a green technology which is relatively cheaper in the treatment of wastewaters. The constructed wetlands as engineered systems that are well-managed to emulate natural wetlands are effective and in some cases can achieve the recovery of a range of pollutants (Ahmad et al., 2024). Some of the wetlands use only the physical, chemical and biological processes for treatment of water and are eco-friendly and aesthetically more pleasing than any other wastewater treatment option. Phytoremediation comprises tasks of Rhizofiltration, phytodegradation, phytoaccumulation, and phytotransformation, and all these are significant in the removal of pollutants in the wastewater. Water lettuce, water hyacinth, and duckweed confirmed that local plant materials are capable of removing wastewaters effectively (Justin et al., 2022). H, previous studies suggest that phytoextraction could be of significant value in decreasing the levels of mesocosm water quality as postulated by Tshithukhe et al., 2021. Several factors include the type of plant to be used for the phytoremediation due to its ability to tolerate the pollutants, the ability to accumulate the pollutants, and the growth rate and biomass of the chosen type of plant. Constructed wetlands have been established to be efficient in wastewater treatment most especially if the structure infrastructure in the region is limited or will cost a lot of money (Hamilton et al. , 1993). As a result of the natural process, the septic systems are economic and efficient in the promotion of quality water and stream on the influenced ecosystems (Mthembu et al., 2013).

Integrated and Nature-Based Solutions

This is because various approaches of bioengineering are being realized where biological systems are used in combination as they offer numerous fold advantages and the efficiency of the end treatment has been observed to have increased in the current wastewater industry (Qin, 2020). An evaluation of the application of NBS in wastewater management reveals that it uses ideas and methods borrowed from ecosystems to provide realistic and sustainable practices for the mechanisms and processes of established ecosystem functions. Techniques like rain gardens, bioretention systems, and other green infrastructure that can also help with the management of stormwater runoff, reducing pollutants, and enhancing the ability of communities to bounce back naturally (Qin, 2020). These integrated risks point out the need in synergy-focused plans that aim to deal with water shortage and the lack of sewage systems provision (Dharmarathne et al., 2024). The alteration of the land use has placed concrete pavements and convergence inbuilt structures reducing the natural absorption and evapotranspiration of rainfall into run offs (Qin, 2020). Deficiencies in underdeveloped wetlands, which in India have reduced by thirty percent over the past fifty years have made flood an even a bigger calamity as they were designed to manage runoff flood perfectly right from when they did not call for costly infrastructure like dams, dikes, and leves. Explaining how the enhanced wastewater treatment practices policy and the urban runoff management policies have to be integrated to provide sound structural integrity on water pollution control (Bai et al., 2021). As green infrastructure retains the water in the local landscape, it plays a significant role in regulating the volume of the runoff water and the pollutants present in it thus has a significant impacts on the environmental management and stormwater.

Future Directions and Challenges

In the subsequent steps, it will be relevant for more research to focus on the implication of bioengineering in the filtration of new pollutants, which are being revealed in the water system including the use of pharmaceuticals, and micro plastics that are gradually affecting water sources and health of people. Thus, new molecular techniques such as metagenomics and proteomics may be beneficial in identifying the microbial community that participates in the organic matter degradation in wastewater treatment and thus may be informative for designing target niche bioaugmentation. Using such systems as real time monitoring and control bring improvement in the performance and stability of Bio engineering based WWTP and also assist in adapting the plant to the new conditions of influent. These solutions should be affordable and scalable because the recommendation is that this technology should used on a large scale especially in developing nations where resources are scarce and infrastructure is poor (Grimm et al., 2008). Mitigating these risks involves how to establish integrated structures, and/or correct and strategise the patterns of cities, and/or how to provide mechanisms that will assist urban transport systems that have been stricken by climate change (Dharmarathne et al., 2024).

Literature Review

These surfaces also create demand for stormwater that is implicated for causing local floods and worse with climate change, there is enhanced intensity and frequencies of intense rain (Zölch et al., 2017). The previous general stormwater management practices are unable to deal with the challenge as witnessed by population growth and climate change (Wu et al., 2020). Low Impact Development and Water Sensitive Urban Design has been recommended to retain, detain, infiltrate, convey, evaporate, seep or store, release or discharge rainwater in its natural form where it falls. The processes of urbanisation affect geochemical circulation and water circulation, and this, in turn, leads to environmental degradation if the development of infrastructure is not adequate for it (Li et al., 2017). Moreover, with expansion of urban areas, there is full utilization of water hence generation of waste water which put pressure on the rivers or lakes which are components of the environment that should be conserved, a factor that is negative in the environment (Gupta & Nair, 2011). In the case of urban flood, the flow rate has to be lowered significantly while at the same time, the overall duration of the flow also has to be increased (Qin, 2020).

Table 1: Comparison of Conventional vs. Bioengineering Wastewater Treatment Methods

Treatment Method	**Advantages**	**Disadvantages**
Activated Sludge	Well-established, effective for BOD removal	High energy consumption, sludge disposal issues
Microbial Fuel Cells	Generates energy, efficient in low energy usage	Expensive technology, limited scalability
Phytoremediation	Cost-effective, environmentally friendly	Slow process, requires large land area
Membrane Bioreactors	High-quality effluent, space-efficient	Membrane fouling, high maintenance costs

Methodology

Bioreactors are continuous systems, that are used for the cultivation of microorganisms involving bacteria, fungi or algae for purposes of carrying out chemical transformations.

Some of the common types of bioreactors that are used in wastewater treatment plants include the activated sludge facilities, trickling filters and membrane bioreactor systems (Huamán et al., 2022). They have been shown to work effectively in the elimination of organic matters and the suspended solids from the wastewaters and therefore enhance the quality of the various water sources and prevent future pollution. Another more advanced water treatment system in the industries involve trickling filters which are used to treat effluent. For the removal of the non-biodegradable organic pollutants, tertiary treatment measures such as ozonation and uv irradiation are normally used. Bioaugmentation refers to the process of adding a particular microbial culture for improving the performance of water systems in treating wastewaters (Huamán et al., 2022). Bioaugmentation is also beneficial in that it provides the system with additional microorganisms that can further metabolise the non-degraded compounds, improve the overall performance and minimise sludge production (Trikoilidou et al., 2016).

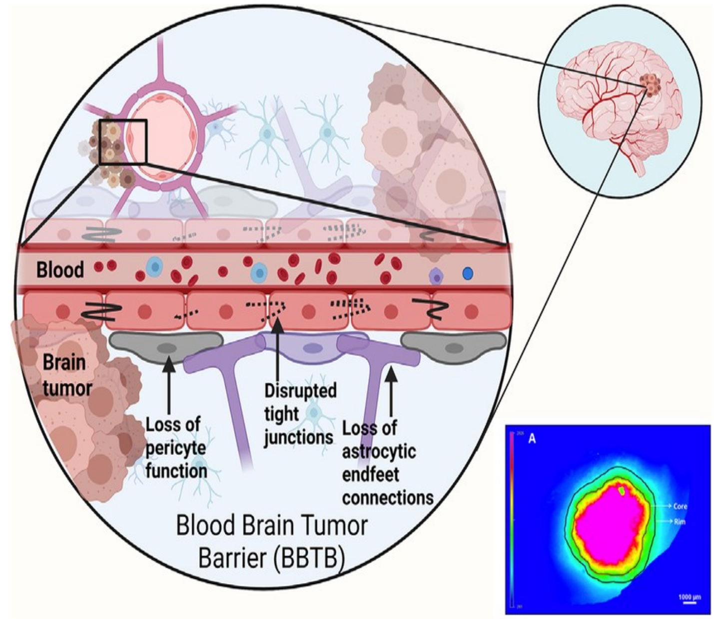


Figure 1: Flowchart of Bioengineering Techniques for Wastewater Treatment

Biofilms, microbial settlers that group themselves in an orderly manner on the surface and form a community are helpful in bioengineering particularly in water treatment (Quan et al., 2018). For instance, the biofilm reactors, the rotating biological contactors and the packed bed reactors have vast surface area that avails microbial attachment and fosters the development of meningitis biomimetic strong and highly active biofilms. These have been helpful in the general removal of organic content, nutrients, and other pollutive materials within the wastewater. Currently, carrier media made of basalt fiber is mostly used actively in treating wastewater with high concentration of organics and nitrogen as it reduces energy cost according to Ni et al., 2020.

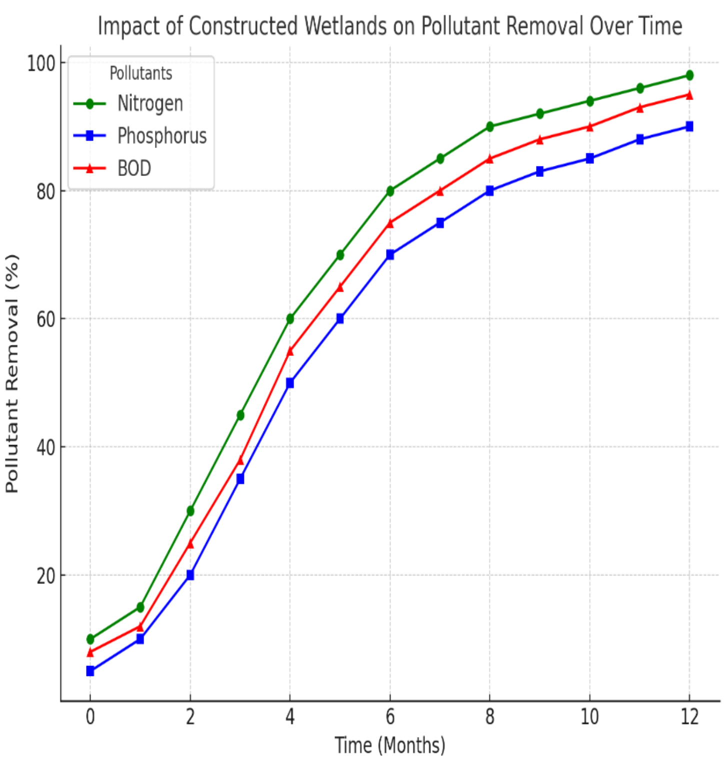
Membrane Bioreactors integrates membrane filtering and biological process, and these are the advantages of MBR compared to the conventional process: These reactors use activated sludge treatment to high quality water low concentration of suspended and pathogenic organisms are removed through membrane separation. Other studies have also proposed that aerobic granulation can be achieved within the SBR with biomass concentrations of 6.0–12.0 g L−1 since the granules have high densities (Zeng et al., 2024). It has the capacity to attain high pollutant removal efficiency: The average COD removal efficiency in this study was 95%, nitrogen removal efficiency was 90% and phosphorus removal efficiency was 95%, therefore suggesting that the phenomenon of aerobic granulation is beneficial for wastewater treatment. Molecularly, thus, mycoremediation of the water, the use of fungi to treat contaminated water can be posited as a novel form of bioengineering in the treatment of wastewater (Samer, 2015). Pollutants formed consisting of organic compounds, heavy metals, and pharmaceutical drugs and these pollutants can be degraded by fungi through enzymatic and biosorption.

Microalgae might be used in integration with the other wastewater treatment systems because the process is efficient, economical and eco-friendly. They also can effectively utilise nitrogen and phosphorus in domestic sewage and turn them into microalgae biomass which is useful for bio-fuel and fish meal and abakar (Alazaiza et al., 2023). Genetic engineering and synthetic biology can therefore be applied to develop microbial life forms capable of featuring abilities to metabolize energy and withstand harsh environments. Such genetically modified microbes can be used for degradation of pollutants; biosynthesis of useful products and enhancement of the efficiency of the wastewater treatment plants (Campos et al., 2009). Microalgae cultivation as a wastewater treatment system is beneficial in two ways, such as elimination of pollutants from wastewater and generation of biomass (Abdelfattah et al., 2022). The integration of wastewater treatment and micro-algae based energy production is possible and the methods of utilizing naturally existing microalgae requires further development to gain industrial applicability (Ranjbar & Malcata, 2022). Real-time monitoring of the quality of wastewater using biosensors is crucial in reversing lingering effects and management of the treatment procedures. Some of the pollutants present can be of organic type, heavy metals, or even pathogens which the biosensors are able to detect in order to check on certain processes and also decision making.

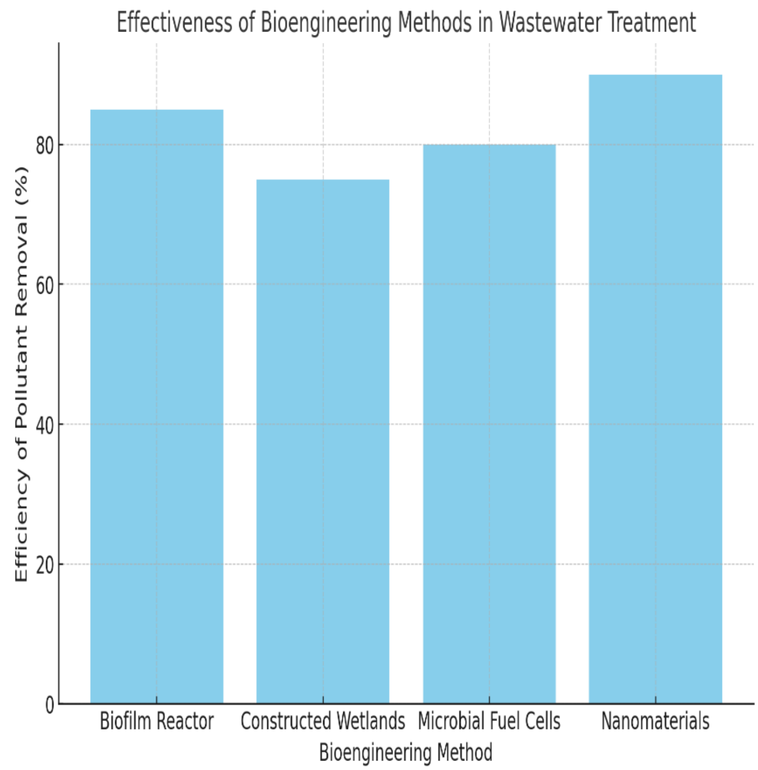
Results and Discussion

Bioengineering Techniques

Sewage disposal has always remained an important factor in the preservation of the environment and prevention of diseases through eradicating contaminants and bioengineering is cheap and efficient. Biochemical solutions include all solutions that employ principles of bioreactors or organized wetlands or microbial decontamination in order to remove or degrade a contaminant in wastewater. They reduce the organic substance and also eliminate nutrients from the water; therefore, this makes their methods environmentally friendly for water purification. Bioengineering is particularly beneficial in wastewater treatments since they can be bioreactors can be developed to treat one kind of pollutant or condition in the wastewater. Biological management of the industrial effluent is gradually being deliberated upon as a possibility due to its conceivable lower cost and sludge generation potentialities as well as higher effectiveness in comparison with the conventional techniques. By combining preliminary physicochemical treatments with biological processes that use ligninolytic enzymes produced by *Phanerochaete chrysosporium*, recalcitrant contaminants can be removed.



Graph 2: Impact of Constructed Wetlands on Pollutant Removal Over Time



Graph 2: Effectiveness of Bioengineering Methods in Wastewater Treatment

Aerobic Treatment Systems

The aerobic treatment systems are those where microorganisms are used in an aerobic condition for the treatment of wastewaters and removal of the organic load present in them (Mullai et al., 2016). The conventional and advance treatment process includes activated sludge systems, trickling filters, and rotating biological contactors that support the growth of aerobic lives that help in reducing the concentration of bacteria and other microorganisms for the utilization of the organic matters, nutrients as well as pathogens. The Activated Sludge Systems is one of the most common treatment systems practiced in WWTPs and involve mixing of aeration of the wastewater in a certain tank so as to enhance the growth of microbes that have the ability to breakdown of the pollutants. This is done to achieve high biomass concentration that is required in the waste water treatment process before the sludge is pumped back to the aeration tank. On the other hand a trickling filter is the treatment of wastewater through a bed of rocks or plastic media with a thin layer of microbes on top of the bed. The organic pollutants are degraded by the microorganisms that live on the surface of the filter when wastewater flows past it. Rotating biological contactors, also another kind of aerobic systems, involves the use of a rotating drum fitted with a biofilm in treatment of the wastewater.

Anaerobic Treatment Systems

Anaerobic systems deal with wastes where oxygen is not present, and the wastes undergo microbial degradation of organic pollutants with the production of biogas which is the cheap source of energy. One of the most widely used processes of the anaerobic treatment is the anaerobic digestion which produces the biogas out of the organic matter, mainly methane and carbon dioxide. The process of anaerobic digestion can be described in the following steps: hydrolysis, acidogenesis, and methanogenesis. Specifically, they include the following several reasons why anaerobic treatment is particularly suitable for high strength industrial wastewaters and sludge: There are several reasons such as high capital investment, high energy consumption, and low percentage of sludge yield.

Integrated Fixed Film Activated Sludge

The integrated fixed-film activated sludge system is a blend between fixed film and suspended types of waste water treatment in order to gain improved efficiency of the treatment process. It has characteristics of both the activated sludge and fixed-film reactors and therefore has high efficiency and reliability. It is an advanced version of activated sludge process and it works by adding an inert support medium such as plastic or ceramics into the aeration chamber in which the biofilm is formed. The attached growth bacteria, the suspended bacteria and the algae in the biofilm envelope are all involved in the decomposition of the organics, nutrient removal and improving quality of final liquid effluent. The integration of both the fixed-film and suspended growth unit aids the wastewater treatment plant in controlling flow variation and variation of pollution concentration while on the other note the IFAS is quite effective in enhancing the performance of the current AS plants. The Mutag BioChip 25™ increases bacterial attachment on the surface area and thereby increases the conversion rate of substrate by 20-30 % in Sequencing Batch Reactor (SeSR) in addition to bringing down the removal efficiency of organic matters by 10-15 %.

Membrane Bioreactors

MBR process is a biological treatment system and then followed by filtration process to remove pollutants from water. Membrane bioreactors involve the separation of the solids and microorganisms from the treated water using a membrane with high quality water as the end product. It can be applied to treat both the municipal and industrial wastewaters because of the following reasons; small space utilization, high capability in removing newly emerged pollutants and above all high efficiency in polluting removal. Membrane bioreactors are further categorized based on the position of the membrane module, submerged or side stream based on the kind of membrane used and the operation conditions. Submerged membrane bioreactors have membranes located in the aeration tank while the side-stream membrane bioreactors filter mixed liquor using a side stream membrane module. It is widely implemented in treatment of wastewaters and to allow its reuse due to its effectiveness in the overall treatment of wastewaters. In the past, MBR used pressurized modules in the recirculation loops and the present submerged membranes operate at low vacuum. Membrane bioreactors particularly the anaerobic ones are widely used by scholars since they are know[n] to operate at a low energy efficiency while at the same time having a high COD removal efficiency. Fouling especially, in the form of biofilm could not be reduced down to lower level by applying air-scouring-aided backwashing according to the study referred to by Díaz et al 2023.

Sequencing Batch Reactors

Sequencing batch reactors are fill-and-draw system fitting all optimal treatment operations in the reactor. They can be flow-through or non-flow through and go through a series of five cycles, such as; fill, react, settle, decant, and idle to clean the wastewater. SBR are more versatile, and depending on the required treatment efficiency and type of wastewater, the cycle time, aeration rate, and other working conditions may be changed. Sequencing batch reactors are thus suitable for the removal of organic matter, nutrients and pathogens in wastewater. Granules of aerobic sludge are easy to settle in sequencing batch reactor where a large biomass is produced owing to the features of granules. The special operation mode of sequencing batch reactor is the batch operation on which the process runs through fill, aeration, sedimentation, and discharge phases. This is because the process of sequencing batch reactant has the capacity of working under so many conditions hence it's suitable for treating wastewater of all natures.

A sequencing batch reactor is relatively easy to design since it only includes a sewage and excess sludge pump, submersible mixers, an aeration system, and a filling and decanting system to remove treated sewage, depending on the company. The treating SBR used was operated at a specific temperature of room temperature and a 6 h cycle of anaerobic, aerobic, sedimentation, and withdrawal phases.

DISCUSSION

Technological Advancements

Dye removal techniques: Thanks to the improved technology in the scientific field there have been developed a number of methods to remove dyes from industrial and domestic effluents. Biological methods, as a method of wastewater treatment, has been found to have significant advantages due to its simplicity, ease of application, versatility, and low costs (Ahmad et al., 2022). These methods involve the use of microorganisms to break down pollutants present in water, adsorb, or accumulate in the biological system Muthukumar et al., 2023. Microbial consortia can be defined as several populations of bacterias, fungi and algae mixed together which can efficiently bring out the various mechanisms of transporting pollutants into the centre of the treatment plants. Microbial electrochemical systems have become attractive technologies for wastewater treatment and the recovery of valuable resources from wastewater, as well as electricity generation (Tetteh et al., 2019).

Table 2: Summary of Emerging Nanotechnology Approaches in Wastewater Treatment

Nanotechnology Approach	Pollutants Targeted	Efficiency (%)	Key Advantages
Nano-filtration	Organic compounds, salts	90%	High efficiency, compact
Carbon Nanotubes	Heavy metals, dyes	95%	Excellent adsorption, reusability
Graphene Membranes	Pharmaceuticals, oils	92%	High permeability, energy-efficient

Bioremediation is an environmentally friendly and sustainable solution to the treatment of dye-containing wastewater, which holds an edge over other conventional techniques (Ihsanullah et al., 2020). In essence, bioremediation is a process that can be applied to treat water and soil contaminated with different types of pollutants including; heavy metals, pesticides, and petroleum hydrocarbons.

Nanomaterials

When nanomaterials are used in the field of wastewater treatment, the benefits encompass a large surface area of the nanomaterial, increased reactivity and selective adsorption of pollutants (Zhang et al., 2021). The rice husk also has been used in this research because of its low cost in the modification for the removal of dyes from the wastewater. Some of these include nanofiltration, electrodialysis, electrocoagulation, bioremediation, ozonation, fenton reaction, adsorption, and ion exchange to remove dyes from water (Sachin et al., 2023). Carbon nanotubes, graphene, and metal oxides are some of the nanomaterials that have been found effective in eliminating pollutants in the wastewater (Qu et al., 2013). Nanotechnology has a significant presence in the purification of water, with new methods and processes used for the synthesis of nanomaterials used in water purification (Singh et al., 2021). Nanomaterials also possess the property to remove pollutants from the water through adsorption, catalytic degradation, as well as membrane filtration (Sadegh, et al., 2017).

Integrated Systems

Integrated systems are whereby two or more treatment processes are linked to work together as the treatment processes are interdependent on the other, this makes the process efficient since the desired treatment goals are met. This paper indicates that an integration of the advanced oxidation processes with the biological treatment would improve the removal of the POPs in the wastewaters. Integrated urban water management requires washing of water at the source; removing or mitigating human modifications (Qin, 2020). The integration of membrane bioreactors and reverse osmosis can thus yield high quality effluent that can be used in industrial and agricultural purposes. The nanomaterials used in the research are obtained with a particular focus on the location, practicality, accessibility, and economical factors to ensure the research is cost-efficient and environmentally sustainable (Jangid & Inbaraj, 2021).

This is due to the ability of bioengineering to continuously enhance its tools and mechanisms in the treatment of wastewater which offer a ray of hope in combating water pollution and proper management of water resource (Guerra et al., 2018). According to the studies done by Patanjali et al., 2019 ; Qiao et al., 2015, Zahmatkesh et al., 2022). When the mechanisms of the pollutant removal and the processes used are fully understood, these techniques become helpful in protecting the health of the people and the environment.

CONCLUSION

In conclusion, this paper has established that bioengineering is an effective way of enhancing the methods of wastewater treatment which in turn enhances water management. , Still, more research and innovation is needed to tackle the question of water availability and its contamination to help future generations have a decent access to fresh water. The global production of wastewaters is increasing hence wastewater treatment is one of the key problems the world will be addressing over the next few decades (Gehrke et al., 2015; Macías-Quiroga et al., 2022). We can suggest that the biological techniques in wastewater treatment are of great promising in the reduction of pollution and in the creation of a better world for people.

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