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Eco-environmental assessment of industrial wastewater treatment for sustainability and potable reuse

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Abstract: Currently, water pollution remains a major global concern, and sustainable wastewater treatment is essential to addressing water scarcity and achieving potable water standards. This article presents an integrated environmental and sustainability assessment of an advanced industrial wastewater treatment system for a textile industry generating 2,000 m^3/day of effluent. A hybrid treatment system, comprising a membrane bioreactor (MBR), activated carbon filtration, and reverse osmosis (RO), achieved significant pollutant removal: 98.6% COD, 99.3% TSS, and 95.1% heavy metals (Pb, Cd, Cr). The treated water met WHO drinking water standards with TDS <300 mg/L, and microbial contaminants are undetectable. Sustainability metrics showed an 87% water recovery rate and a specific energy consumption of 2.8 kWh/m^3. Life Cycle Assessment (LCA) revealed a 32% lower carbon footprint than conventional methods, while economic analysis estimated a treatment cost of \$0.92/m^3 and a 6.5-year payback period when combined with water reuse. Additionally, this research focused on the potential of microalgae-based bioremediation as an eco-friendly alternative. Microalgae offer effective nutrient recovery, greenhouse gas reduction, and biomass valorization for biofuels, fertilizers, food additives, and therapeutic compounds. Thus, microalgae integration presents a cost-effective, sustainable solution for wastewater treatment and bioenergy production.
Keywords: *Bioremediation, chemical fertilizers, Pesticides, Sustainability, wastewater treatment.*

1. Introduction

The world's environmental problems have been worsened by the population's explosive growth. Global warming and ecological imbalance are caused by major forms of environmental pollution, including contamination of the air, land, and water [1]. Heavy metals, radioactive waste, chemical fertilizers, pesticides, hydrocarbons, and pharmaceutical by-products are only a few of the harmful compounds that contribute to pollution and seriously damage the ecosystem [2]. This issue is very difficult for science to solve and calls for in-depth understanding and technological advancements. Numerous biological and physicochemical treatment techniques have been created to eliminate or purify pollutants from impacted areas. Membrane filtration, ion exchange, electrochemical treatment, osmosis, precipitation, and evaporation are common physicochemical remediation techniques for wastewater treatment [3]. Nevertheless, the majority of these techniques are not environmentally sustainable nor commercially viable. To cut expenses and energy use, a new integrated technology is therefore required [4]. Therefore, in recent years, biological wastewater treatment has been favored over chemical treatments. Despite being the quickest, chemical wastewater treatment involves synthetic chemicals

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that harm living organisms and the environment in various ways. Thus, the most ecologically friendly choice is biological wastewater treatment [5].

One of the most promising methods is biological remediation, often known as bioremediation, because of its long-term efficacy, low cost, and ecological friendliness. Microorganisms are used in bioremediation to detoxify or lower environmental concentrations of organic or inorganic contaminants [6]. To eliminate pollutants from the environment, bioremediation has employed a variety of microorganisms, such as bacteria, fungi, and microalgae [7]. Specifically, bio-sorption and bioaccumulation are the two primary mechanisms through which bioremediation occurs. Living organisms absorb toxins via their cell walls in a process known as bioaccumulation, which is an active form of bioremediation [8]. In the meantime, biosorption is a novel method that uses inert biomass or living algae to remove heavy metal ions from acidic liquids [9].

The sorption mechanism is critical to algal development. Adsorption, influenced by environmental variables, is a complex process in which algae cells absorb heavy metal ions during their growth stages [6]. Passive bioremediation, on the other hand, is based on physicochemical processes carried out by living or dead microbial cells. The search for resources that may be utilized to lower heavy metal levels in the environment has resulted in the identification of novel materials that can serve as cost-effective, dependable, and safe wastewater treatment solutions [10, 11]. In this context, biological materials have emerged as eco-friendly and cost-effective alternatives. The use of microalgae as biosorbents has received attention due to their aptitude and versatility to resist polluted water [12].

Despite extensive study into the bioremediation of polluted environments by various microorganisms, microalgae-based bioremediation technology has attracted significant attention as a feasible solution due to its benefits [6, 13]. Bioremediation with microalgae can eliminate contaminants while also converting the biomass produced into other value-added bio-products [14]. The biological technique is the most promising method for the long-term remediation of industrial waste. It could also help promote the adoption of more circular economic processes [15].

The concept of using green algae as a feedstock for biofuel production has sparked widespread interest, owing to rising oil costs, the rapid depletion of natural oil supplies, and, most crucially, the detrimental impacts of fossil fuel use on global warming [16]. The World Oil Outlook Report of Petroleum Exporting Countries (OPEC) for 2020 predicts that oil will continue to be the primary fuel in the future, with global demand increasing from nearly 100 million barrels per day (mb/day) in 2019 to approximately 109 mb/day in 2045. However, OPEC members' oil reserves are rapidly depleting [17].

Fossil fuel supplies will be unavailable in the future. Renewable energy supplies that emit little or no carbon dioxide (CO_2) can meet a major fraction of the world's energy needs at a cost comparable to current petroleum prices [18]. First-generation biofuels are produced using soybeans, sugarcane, and vegetable oils. Concerns regarding future food production versus energy needs have turned attention to second-generation biofuels [19]. Non-food biomass sources, including grass straws, wood, jatropha, switchgrass, and organic waste, generate more net energy per acre than maize and sugarcane. However, the complex thermochemical and biochemical processes necessary to manufacture biofuel from these resources continually yield low yields and expensive prices [20].

Photosynthetic thallophytes may serve as the final source of third-generation biofuels. Microalgae provide more environmental and economic benefits than other feedstocks, and there is enough supply to meet rising demand while reducing environmental effects [19]. Microalgae have previously been utilized to produce biodiesel, bioethanol, and bio-hydrogen [19]. Alternative fuels are increasingly significant in a variety of industries, particularly transportation. Biofuels from microalgae have piqued the public's interest as a potential solution to these issues, both in terms of production and use [21]. The advantages of microalgal biomass as a source of biofuel and value-added bio-products have been extensively studied [22].

2. Pollutants in Industrial Waste Water

Distillery businesses are important contributors to the global economy, but they are also substantial sources of environmental pollution due to the discharge of large amounts of dark-colored wastewater [23]. This dark-colored wastewater has a high biological oxygen demand, chemical oxygen demand, total solids, sulfate, phosphate, phenolics, and other hazardous metals [23]. Distillery wastewater also contains a variety of organic and inorganic pollutants, including melanoidins, di-n-octyl phthalate, di-butyl phthalate, benzenepropanoic acid, and 2-hydroxysocaproic acid, as well as toxic metals that have been shown to be genotoxic, carcinogenic, mutagenic, and endocrine-disrupting [22]. It causes major environmental concerns in aquatic resources by reducing sunlight penetration, photosynthetic activity, and dissolved oxygen concentration [24]. In agricultural land, however, it inhibits seed germination and depletes vegetation by lowering soil alkalinity and manganese availability if discharged without proper treatment [25]. Thus, this review paper provides a comprehensive understanding of distillery wastewater pollutants, the various methodologies used to analyze them, and the toxicological impacts on the environment, human, and animal health. Furthermore, numerous physicochemical, biological, and developing treatment techniques for environmental, human, and animal health protection have been reviewed [22].

On the basis of previous studies, India has approximately 319 distilleries that produce 3.25 × 10^9 L of alcohol and 40.4 × 10^10 L of wastewater annually. Bioethanol production increased from 50 billion liters in 2007 to approximately 60 billion liters in 2008, accounting for over 4% of global gasoline use [22]. DIs generate a large volume of dark-colored wastewater characterized by its dark brown color, acidic pH (5.4-4.5), high BOD (40,000-50,000 mg/L), COD (80,000-100,000 mg/L), total dissolved solids (TDS), total solids (TS), total suspended solids (TSS), with high nitrogen, potassium, phosphates, calcium, and sulfate content [22, 23]. DWW's high BOD and COD values are mostly attributable to the presence of high organic content, which includes proteins, reduced sugars, polysaccharides, lignin, melanoidins, and waxes, as well as a complex mixture of refractory organic pollutants [22].

Lead and sodium benzoate are the primary pollutants in industrial wastewater, posing substantial environmental and health risks to humans and animals. Lead is the cause of various cancers and other neurodegenerative diseases. This lead, after exiting from the industries, combines with small water bodies, which are the main sources for irrigation, domestic usage in homes, and other small industries. This wastewater then causes various allergies and disorders amongst the population [24, 25].

Aside from lead, other hazardous compounds found in industrial wastewater include di-n-octyl phthalate, di-butyl phthalate, benzenepropanoic acid, and 2-hydroxysocaproic acid [25]. These toxic chemicals, particularly phthalates, have been well documented as endocrine-disrupting compounds (EDCs), causing hormonal imbalance and a variety of physiological and metabolic disorders that affect human and animal reproductive fitness [26, 27].

However, the properties of industrial wastewater are mostly determined by the raw materials, chemicals, and methods utilized by Dis. Various researchers in 2014 discussed in detail the various phases involved in wastewater creation in these chemical industries that use sodium benzoate, lead, sulfur, nitrates, nitrites, etc., as shown in Figure 1 [28]. The production process is divided into four steps: feed preparation, fermentation, distillation, and packaging [29].

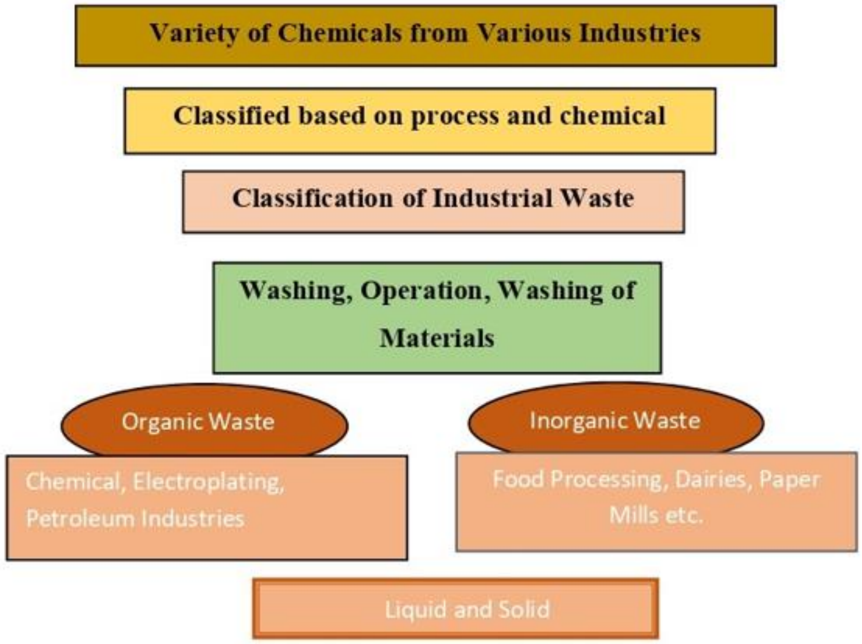

Figure 1.
Types of industrial wastewater.
Source: Xiong et al. [25].

When untreated or inadequately treated industrial wastewater is dumped into the environment, it poses significant ecotoxicological and health risks. In water bodies, it limits the penetration strength of sunlight, resulting in decreased photosynthetic activity and dissolved oxygen (DO) depletion [30]. However, in soil systems, it reduces agricultural land fertility. Due to these environmental and health risks, industrial wastewater should be properly treated to degrade and detoxify organic and inorganic pollutants before being discharged into the environment [31]. Various physicochemical approaches proposed for the treatment of industrial wastewater are insufficient to meet the discharge standards established by various environmental protection organizations [31]. Conversely, biological approaches such as aerobic/anaerobic treatment processes have been found to be relatively capable of reducing BOD/COD load in industrial wastewater, but the significant concentration of organic and inorganic pollutants and dark color remaining requires additional treatment [31].

3. Techniques for Waste Water Treatment

Industries require clean water, but they also produce large amounts of effluent tainted with numerous harmful substances. Such a condition high demand for clean water and wastewater production, was previously only seen in the developed world, but it is now becoming a rising problem in the developing world as a result of increased industrialization. For example, China, one of the world's fastest-expanding industrial countries, has produced more than 20 billion m^3/year of wastewater in recent times [31].

The requirement to deliver a large amount of clean water for industrial activity exacerbates the difficulty that humans confront in providing the same clean water to an ever-increasing human population [32]. Because freshwater supplies are limited, particularly in countries with limited rainfall patterns such as North Africa, the Middle East, Southern Europe, Australia, and the Southern and Western states of the United States, the reuse of both domestic and industrial wastewater remains the most viable long-term solution to this problem [33].

Prior to reuse or discharge into the environment, contaminated wastewater must be treated to eliminate or reduce the concentration of pollutants to safe levels. As people become more conscious of the effects of pollutants on human health and the environment, legislation governing pollution discharge is tightening around the world [33]. As a result, solutions for increasing the efficiency of treatment plants used to clean industrial wastewater are being developed [32]. The initial phases of an industrial water treatment plant include physicochemical treatments to remove organic or inorganic pollutants, as well as biological treatments (to remove organic pollutants), followed by secondary treatment [33].

This subsequent treatment generates backwash effluent, sludge, and membrane concentrates. Backwash effluents can be released or transported to a nearby sewage treatment plant if the discharge standards are met [34]. Depending on the type of contamination, the products of physicochemical and biological treatments will be subjected to purification and disinfection before reuse [35]. Advanced oxidation, nanofiltration, reverse osmosis filtration, and activated carbon filtration are among the methods employed in physicochemical treatment to remove contaminants; however, these procedures are still expensive, particularly in the context of full-scale treatment [33, 34]. Furthermore, several of these technologies produce hazardous byproducts in the environment, as shown in Figure 2.

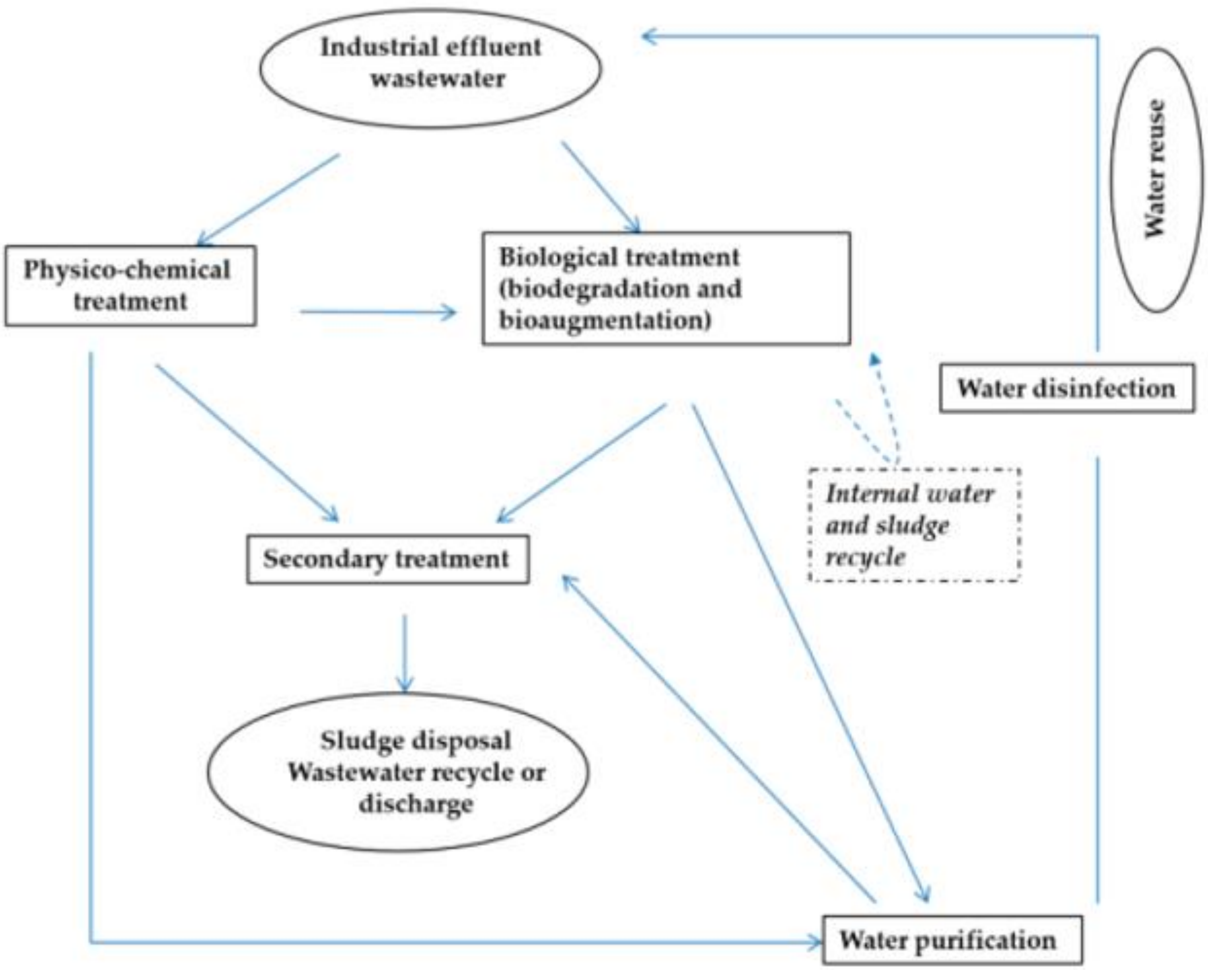

Figure 2.
Generic flow of an industrial wastewater treatment plan.
Source: Khan and Malik [34].

Biological treatment involves the biodegradation of organic contaminants by microorganisms found in wastewater or activated sludge. However, many pollutants, particularly highly complex chemicals, are inefficiently biodegraded by microbes; they may be resistant to biodegradation and hence remain in wastewater, degrading water quality [1]. To address these constraints, bioaugmentation strategies may be employed. Bioaugmentation is the inclusion of microorganisms capable of degrading refractory compounds in contaminated environments. This strategy is less expensive and more environmentally friendly than physicochemical approaches [36]. The literature has reported numerous examples of this strategy for pollutant removal in soil, and we direct readers to the following outstanding studies on the subject. Bioaugmentation approaches were reviewed with a focus on operational difficulties and wastewater plant management [1]. The current review focuses solely on the application of bioaugmentation in industrial wastewater, with a particular emphasis on microbiological characteristics of bioaugmentation and the biodegradation of refractory organic contaminants found in industrial wastewater. We also plan to identify knowledge gaps for future research endeavors. Pollutants covered include chlorinated molecules, quinolines, dyes, polyaromatic chemicals, glycol ethers, cyanide, and nitrogen heterocyclic compounds [1]. This evaluation excludes common pollutants found in home wastewater, such as carbohydrates, lipids, proteins, and nitrates. Furthermore, limitations of bioaugmentation tactics are described, as well as crucial elements that determine biodegradation efficiency and prospective new domains, such as nanotechnology and quorum sensing, which might be exploited to improve industrial success [1]

4. Bio-augmentation to Remove Recalcitrant Pollutants in Industrial Wastewater

Wastewater activated sludge contains naturally occurring microorganisms that biodegrade a variety of contaminants; nevertheless, as previously stated, some pollutants are resistant to biodegradation. Several variables contribute to this resistance, including high toxicity, low water solubility, limited bioavailability, high stability, and low biodegradability [37]. Some chemicals may not be effectively utilized as substrates by microbial metabolic enzymes. Certain pollutants' chemical structures may be so complicated that biodegradation requires consortia of various bacteria, or all of the essential microorganisms may not be present at the same time in the environment. In many circumstances, refractory substances may be novel, thus bacteria may not have yet adapted to use them as substrates [36].

Bio-augmentation can overcome these obstacles because one of its primary benefits is the ability to personalize therapy to a specific pollutant that is prevalent in the environment. As a result, this strategy is appealing for treating both the growing number of developing pollutants and pollutants with high concentrations. Over the last decade, numerous studies have been conducted to investigate bioaugmentation techniques for wastewater treatment, with the majority focusing on recalcitrant compounds [36]. Examples of bioaugmentation for pollutant removal from industrial wastewater from the early 2000s to the present are provided below (refer to Table 1).

Table 1. Example of Bio-augmentation of industrial wastewaters for the remediation of important organic compounds.

Pollutant	Set Up	Medium for Bioaugmentation	Bioaugmented Bacteria
3-Chloroaniline	Semi-continuous activated sludge (SCAS) (1 L)	Synthetic influent consisting of skim milk powder	Comamonas testosteroni
4-Fluoroaniline	Batch reactor (BR) (250 mL)	Inorganic salt medium	Acinetobacter sp.
2,4-Dichlorophenol (2,4-DCP)	Laboratory-scale continuous flow complete-mixed reactors (CFSTRs) (16 L)	Synthetic wastewater (SW)	Consortium of bacteria
2,4,6-Trichloro-phenol	Fluidized bed biofilm reactor (FBBR) and expanded granular sludge bed (EGSB)	Industrial wastewater (IW)	Desulfotobacterium sp.
Quinoline	Sequential Batch reactor (SBR) (250 mL)	Petroleum refinery wastewater	Bacillus sp.
Quinoline	SBR (2–7 L)	Coke plant wastewater	Burkholderia pickettii
Pyridine and quinolone	BR (100 mL)	Inorganic medium and wastewater	Paracoccus sp. and Pseudomonas sp.
Quinoline and Pyridine	BR (250 mL) with modified zeolite	Coke wastewater	Paracoccus sp. and Pseudomonas sp.

Source: Khan and Malik [34] and Gastaldi et al. [38].

5. Applications of Bio-augmentation

5.1. Chlorinated and Fluorinated Compounds Removal

Halogenated chemicals are employed in a variety of applications, including plastic components, lubricants, adhesives, solvents, degreasing agents, insecticides, fungicides, and wood preservatives. For example, in 2012, the total volume of chlorinated solvents used worldwide was projected to be 764,000 metric tons [36]. Such widespread use in both business and homes pollutes wastewater, and bioaugmentation has proven to be an effective approach for removing it. Acinetobacter sp. TW and Comamonas testosteroni I2 were found to decompose 4-fluoroaniline and 3-chloroaniline in a synthetic wastewater medium supplemented with AS, respectively. Furthermore, the scientists identified optimal conditions that encouraged colonization and consequently biofilm development, resulting in dramatically higher biodegradation [1]. The biodegradation of 2,4-dichlorophenol by bioaugmentation with a bacterial consortium has been reported in a laboratory-scale setup utilizing synthetic wastewater supplemented with activated sludge (AS). A recent study employing a fluidized bed biofilm reactor (FBBR) and an extended granular sludge bed (EGSB) found that bioaugmentation with Desulfitobacterium sp. increased the biodegradation of 2,4,6-trichlorophenol. However, it is worth noting that the aforementioned investigations were only conducted on a laboratory scale. As a result, the removal of chlorinated compounds by bioaugmentation has yet to be studied in the setting of a full-scale wastewater treatment plant [1].

5.2. Bioaugmentation for Lignin Degradation

Another effective bioaugmentation study was conducted for wastewater treatment in the paper sector. The pulp and paper industry produces significant amounts of effluent containing a high lignin content, known as black liquor. For example, it is predicted that one ton of pulp produces seven tons of black liquor. Black liquor is a complex mixture of lignin, polysaccharides, and resinous substances. Natural biological treatment with activated sludge (AS) cannot effectively remove these chemicals because lignin-biodegrading bacteria are uncommon in wastewater. Thus, selecting and adding lignin-biodegrading microbes to wastewater offers an appealing technique for removing particular contaminants derived from black liquor. The study evaluated a consortium of lignocellulosebiodegrading bacteria isolated from AS in a sequencing batch reactor (SBR) [34]. This mix of microorganisms, which was previously reported, included Comamonas B-9 and Pandoraea B-6 (bacteria) and Aspergillus F-1 (fungus) [39]. The results revealed that bioaugmentation significantly improved lignin removal (>50%) in a laboratory setup containing an SBR with a maximum operating volume of 2 L. All of these studies demonstrate that bioaugmentation is a viable alternative technique for improving the biological treatment of wastewater with a high lignin content. However, scaling up this method in the setting of a wastewater treatment plant is currently being evaluated [36].

5.2.1. Quinoline and Pyridine

Quinolines and pyridines are N-heterocyclic aromatic compounds that are often found in industrial and medicinal raw materials, as well as solvents for dyes, paints, and wood treatment chemicals, making them present in industrial effluent. Quinolines are also found in coal tar and petroleum products. They persist in the environment due to their limited biodegradability and carcinogenic properties. A study reported that utilizing Bacillus sp. isolated from soil in a 250 mL batch reactor loaded with petroleum refinery wastewater improved quinoline biodegradation. One study showed the biodegradation of quinoline in wastewater bioaugmented with Burkholderia pickettii, and another successfully evaluated the biodegradation of quinoline and pyridine using wastewater medium bioaugmented with Paracoccus sp. and Pseudomonas sp [40].

Although the amounts of quinoline and pyridine were lower in the subsequent investigation, the nitrogen content remained high [40]. To address this constraint, the same mixed biodegrading bacteria were evaluated in a 250-mL SBR reactor with a modified zeolite. Zeolites help to remove nitrogen content by adsorption. The results indicated a decrease in quinoline and pyridine concentrations, as well as nitrogen content in the medium [36]. The elimination of the two N-heterocyclic chemicals, pyridine and quinoline after bioaugmentation of four bacterial strains (Paracoccus sp. BW001, Shinella zoogloeoides, Pseudomonas sp. BW001, and Pseudomonas sp. BC003) in coking effluent was also investigated. Recent studies have shown that bioaugmentation of industrial wastewater with Rhizobium sp., utilizing an SBR, and Paracoccus denitrificans in a membrane batch reactor improves pyridine removal rates. There has been no report to date on the use of this technique in field circumstances to remove pyridine and quinoline [40].

5.2.2. Synthetic Dyes

Synthetic dyes, principally made of azo- and anthraquinone-based compounds, are widely utilized in textiles and cosmetics, with about 7×10^5 tons manufactured annually. It is believed that between 2% and 10% of the ecosystem is contaminated, mostly from industrial effluent [41]. Azo dyes, the largest and most diversified category of dyes, are largely resistant to biodegradation under standard AS conditions. The elimination of an azo dye, Acid Orange 7, by bioaugmentation with Shewanella sp. XB was tested in a 2 L membrane-aerated biofilm reactor and yielded promising results. The manufacture of anthraquinone dyes involves bromoamine acid (BAA) as the main synthetic step [36]. This chemical is poisonous and resistant to biodegradation; a BAA-biodegrading Sphingomonas sp. strain was identified and bioaugmented in a laboratory procedure that combined microelectrolysis with biological aerated filtering of polluted wastewater [42]. Another strain of the Sphingomonas genus, Sphingomonas xenophaga, was identified and effectively employed at laboratory scale for BAA removal in bioaugmentation investigations using synthetic wastewater medium [41]. However, research is still needed to determine whether these promising results on the removal of synthetic dyes could be expanded to full-scale treatment plants [36].

5.2.3. Cyanides

Cyanides are among the most harmful chemicals generated by coal during the coking process in the steel industry. Thus, industrial effluent must be treated before it is discharged into the environment [43]. To improve the effectiveness of biological cyanide removal, a full-scale coke wastewater treatment

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process was bioaugmented using cyanide-degrading yeast Cryptococcus humicolus and unidentified cyanide-degrading bacteria in wastewater containing ferric cyanide [36].

However, this procedure had limited efficacy due to the poor settling ability of microbial flocs and the sluggish biodegradation rate of ferric cyanide in wastewater. This is one of the first papers on the evaluation of bioaugmentation in full-scale treatment plants, and further research is certainly required to make this technique effective in the context of cyanide removal [33].

5.2.4. Nicotine

The tobacco industry is responsible for the discharge of large amounts of wastewater containing a variety of harmful compounds, one of which is nicotine, a potential carcinogen [40]. For every ton of cigarettes produced, 60 tons of toxic effluent are released. For example, more than five trillion cigarettes were generated globally in 2009, and with a weight of 1 g per cigarette, the total amount of wastewater created was more than 300 million tons in 2009 [44]. Bioaugmentation has been investigated as a solution for removing these contaminants. Studies have discovered many bacteria capable of digesting nicotine, including Acinetobacter sp. and Sphingomonas sp. Used a 2-L synthetic wastewater reactor containing COD (3200 mg/L), nicotine (1 g/L), and AS from a wastewater treatment facility to investigate the effect of bioaugmentation with Acinetobacter sp. on nicotine biodegradation [45]. The bioaugmented reactor removed nicotine at a rate of 98%, compared to approximately 10% in the control reactor. Interestingly, the elimination of nicotine was linked to a large increase in total bacteria and a decrease in COD in the bioaugmented reactor [46]. Nicotine is poisonous to microorganisms; thus, removing it encourages bacterial development, which helps the overall biodegradation process [1]. These studies demonstrate the effectiveness of bioaugmentation in removing nicotine. However, the aforementioned experiments were conducted on a small scale, and there is currently no report on the application of this approach in a tobacco wastewater treatment plant [33].

5.2.5. Diethylene Glycol Monobutyl Ether (DGBE)

Glycol ethers, particularly ethylene glycol monobutyl ether and diethylene glycol monobutyl ether (DGBE), are polar solvents that are miscible with both organic compounds and water. They are widely used in paints and cleaners [47]. These chemicals are hazardous in animal models and resistant to biodegradation, thus they persist in the environment after being discharged in industrial effluent [48]. Various researchers investigated the ability of a Serratia sp. strain to remove DGBE in the context of bioaugmentation of contaminated wastewater from the silicon plate industry. The results demonstrated an increase in DGBE elimination at both laboratory and full-scale levels [1].

5.2.6. Polycyclic Aromatic Hydrocarbons and Heterocyclic Compounds

Polycyclic aromatic hydrocarbons (PAHs) are another major contaminant found in industrial effluent. They are most commonly found in petroleum products, but they can also be present in many waste streams from other industrial processes, such as coal conversion and organic chemical synthesis [47]. These polycyclic aromatic compounds are resistant to biodegradation, thus they remain in the environment for longer periods, with negative effects on animal and environmental health [49]. One of the PHAs is naphthalene [36]. Its removal has been evaluated in the context of bioaugmentation in coal gasification wastewater, using a strain of Streptomyces sp. in a membrane bioreactor, which demonstrated considerable naphthalene removal [50]. A similar investigation was conducted on the bioaugmentation of coking wastewater using a consortium of Paracoccus denitrificans and five Pseudomonas sp. strains. The bioaugmentation helped to remove naphthalene, phenol, pyridine, quinoline, and carbazole from the coking wastewater [51].

Another bioaugmentation experiment was reported for the removal of phenols, naphthalenes, carbazole, dibenzofuran, and dibenzothiophene, all of which are present in genuine coking wastewater [40]. In this study, zeolite-biological aerated filters (Z-BAFs) containing Arthrobacter sp. (free and immobilized) were used, and the results revealed a considerable increase in pollutant removal in bioaugmented batch reactors, with a greater removal rate recorded with immobilized bacteria [52]. A study revealed that a combination of phenol-degrading bacteria could remove phenol from coal gasification effluent using a biological contact oxidation reactor. However, this investigation did not provide information on the species of bacteria [53].

6. Conclusion

At the end, the development of environmentally friendly wastewater treatment technology represents a significant step forward in achieving sustainable water management for industrial and municipal uses. These eco-friendly technologies enhance wastewater treatment efficiency while drastically reducing environmental impacts by incorporating innovative treatment procedures, resource recovery techniques, and renewable energy sources. The advantages of implementing these advanced designs extend beyond improved water quality; they promote economic sustainability, public health, and regulatory compliance. Toxic pollutants and contaminants must be removed from the environment because they cause illness and disrupt ecosystem dynamics. The algae-bacteria consortium for wastewater treatment is a green technology that has been effectively used to remove hazardous pollutants and toxins from the environment. The recovery rate of valuable resources from wastewater highlights the potential for transforming waste into assets, contributing to a circular economy that emphasizes sustainability. Furthermore, involving local communities in the planning and implementation of eco-friendly systems fosters awareness and engagement, reinforcing the importance of responsible water management. Finally, the integration of eco-friendly wastewater treatment technologies.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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References

[1] N. Jahan *et al.*, "A comprehensive review on the sustainable treatment of textile wastewater: Zero liquid discharge and resource recovery perspectives," *Sustainability*, vol. 14, no. 22, p. 15398, 2022. https://doi.org/10.3390/su142215398

[2] A. Ahmad, F. Banat, H. Alsafar, and S. W. Hasan, "Algae biotechnology for industrial wastewater treatment, bioenergy production, and high-value bioproducts," *Science of The Total Environment*, vol. 806, p. 150585, 2022. https://doi.org/10.1016/j.scitotenv.2021.150585

[3] M. Gavrilescu, "Environmental biotechnology: achievements, opportunities and challenges," *Dynamic Biochemistry, Process Biotechnology and Molecular Biology*, vol. 4, no. 1, pp. 1-36, 2010.

[4] J. W. Dobrowolski *et al.*, *Integrated innovative biotechnology for optimization of environmental bioprocesses and a green economy. In Optimization and applicability of bioprocesses.* Singapore: Springer Singapore, 2018.

[5] Y. Lokko, M. Heijde, K. Schebesta, P. Scholtès, M. Van Montagu, and M. Giacca, "Biotechnology and the bioeconomy—Towards inclusive and sustainable industrial development," *New Biotechnology*, vol. 40, pp. 5-10, 2018. https://doi.org/10.1016/j.nbt.2017.06.005

[6] B. Gaonkar, R. Roopashree, and V. Swarupa, *Application of biotechnology tools in agrarian and industrial wastewater treatment. In A. Pourhashemi, K. H. Asli, A. R. Abraham & A. K. Haghi (Eds.), Sustainable Water Engineering: Smart and Emerging Technologies.* Palm Bay, FL, USA: Apple Academic Press, 2024.

[7] C. S. Ezeonu, R. Tagbo, E. N. Anike, O. A. Oje, and I. N. Onwurah, "Biotechnological tools for environmental sustainability: Prospects and challenges for environments in Nigeria—a standard review," *Biotechnology Research International*, vol. 2012, no. 1, p. 450802, 2012. https://doi.org/10.1155/2012/450802

[8] A. A. Kiss, J. Grievink, and M. Rito-Palomares, "A systems engineering perspective on process integration in industrial biotechnology," *Journal of Chemical Technology & Biotechnology*, vol. 90, no. 3, pp. 349-355, 2015. https://doi.org/10.1002/jctb.4584

[9] J. J. J. Y. Yong, K. W. Chew, K. S. Khoo, P. L. Show, and J.-S. Chang, "Prospects and development of algal-bacterial biotechnology in environmental management and protection," *Biotechnology Advances*, vol. 47, p. 107684, 2021. https://doi.org/10.1016/j.biotechadv.2020.107684
[10] M. Farid *et al.*, *Principles and applications of environmental biotechnology for sustainable future. In M. Hasanuzzaman (Ed.), Climate-Resilient Agriculture, Vol. 1: Crop Responses and Agroecological Perspectives.* Cham, Switzerland: Springer International Publishin, 2023.
[11] S. A. Razzak *et al.*, "A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater," *Environmental Advances*, vol. 7, p. 100168, 2022. https://doi.org/10.1016/j.envadv.2022.100168
[12] T. P. C. Ezeorba, E. S. Okeke, M. H. Mayel, C. O. Nwuche, and T. C. Ezike, "Recent advances in biotechnological valorization of agro-food wastes (AFW): Optimizing integrated approaches for sustainable biorefinery and circular bioeconomy," *Bioresource Technology Reports*, vol. 26, p. 101823, 2024. https://doi.org/10.1016/j.biteb.2024.101823
[13] N. Kuppan, M. Padman, M. Mahadeva, S. Srinivasan, and R. Devarajan, "A comprehensive review of sustainable bioremediation techniques: Eco friendly solutions for waste and pollution management," *Waste Management Bulletin*, vol. 2, no. 3, pp. 154-171, 2024. https://doi.org/10.1016/j.wmb.2024.07.005
[14] S. Arora, A. Kumar, S. Ogita, and Y. Y. Yau, *Innovations in environmental biotechnology*. Singapore: Springer Nature, 2022.
[15] R. Rame, P. Purwanto, and S. Sudarno, "Biotechnological approaches in utilizing agro-waste for biofuel production: An extensive review on techniques and challenges," *Bioresource Technology Reports*, vol. 24, p. 101662, 2023. https://doi.org/10.1016/j.biteb.2023.101662
[16] M. K. Awasthi *et al.*, "Microbial biotechnology approaches for conversion of pineapple waste in to emerging source of healthy food for sustainable environment," *International Journal of Food Microbiology*, vol. 373, p. 109714, 2022. https://doi.org/10.1016/j.ijfoodmicro.2022.109714
[17] V. Venugopal and A. Sasidharan, "Seafood industry effluents: Environmental hazards, treatment and resource recovery," *Journal of Environmental Chemical Engineering*, vol. 9, no. 2, p. 104758, 2021. https://doi.org/10.1016/j.jece.2020.104758
[18] A. Rai, V. K. Yadav, D. Ali, and M. Fulekar, "Unlocking bioremediation potential: Harnessing an indigenous bacterial consortium from effluent treatment plants for industrial wastewater treatment," *Environmental Research Communications*, vol. 6, no. 9, p. 095005, 2024. https://doi.org/10.1088/2515-7620/ad6dbd
[19] M. Rizwan, G. Mujtaba, S. A. Memon, K. Lee, and N. Rashid, "Exploring the potential of microalgae for new biotechnology applications and beyond: A review," *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 394-404, 2018. https://doi.org/10.1016/j.rser.2018.04.034
[20] A. A. Juwarkar and H. P. Jambhulkar, "Phytoremediation of coal mine spoil dump through integrated biotechnological approach," *Bioresource Technology*, vol. 99, no. 11, pp. 4732-4741, 2008. https://doi.org/10.1016/j.biortech.2007.09.060
[21] Y. V. Nancharaiah and M. Sarvajith, "Aerobic granular sludge process: A fast growing biological treatment for sustainable wastewater treatment," *Current Opinion in Environmental Science & Health*, vol. 12, pp. 57-65, 2019. https://doi.org/10.1016/j.coesh.2019.09.011
[22] J. M. Kwakye, D. E. Ekechukwu, and A. D. Ogbu, "Challenges and opportunities in algal biofuel production from heavy metal-contaminated wastewater," *Renewable Sustainable Energy Rev*, vol. 135, p. 110209, 2024.
[23] P. Pattnaik, G. Dangayach, and A. K. Bhardwaj, "A review on the sustainability of textile industries wastewater with and without treatment methodologies," *Reviews on Environmental Health*, vol. 33, no. 2, pp. 163-203, 2018. https://doi.org/10.1515/reveh-2018-0013
[24] S. Mani and R. N. Bharagava, *Textile industry wastewater: environmental and health hazards and treatment approaches. In Recent advances in environmental management*. Boca Raton, FL, USA: CRC Press, 2018.
[25] J.-Q. Xiong, M. B. Kurade, and B.-H. Jeon, "Can microalgae remove pharmaceutical contaminants from water?," *Trends in Biotechnology*, vol. 36, no. 1, pp. 30-44, 2018.
[26] C. Wells, D. Render, and P. Rose, "Integrated algal ponding systems and the treatment of domestic and industrial wastewaters Part 3C: Chloride saline systems: The use of saline waters for the reticulation," Report to the Water Research Commission (WRC Report No. TT 403/09). Water Research Commission, Pretoria, South Africa, 2009.
[27] K. Singh *et al.*, "Microalgae from wastewaters to wastelands: Leveraging microalgal research conducive to achieve the UN Sustainable Development Goals," *Renewable and Sustainable Energy Reviews*, vol. 188, p. 113773, 2023. https://doi.org/10.1016/j.rser.2023.113773
[28] P. Sharma, S. Tripathi, D. Purchase, and R. Chandra, "Integrating phytoremediation into treatment of pulp and paper industry wastewater: Field observations of native plants for the detoxification of metals and their potential as part of a multidisciplinary strategy," *Journal of Environmental Chemical Engineering*, vol. 9, no. 4, p. 105547, 2021. https://doi.org/10.1016/j.jece.2021.105547
[29] T. Shindhal *et al.*, "A critical review on advances in the practices and perspectives for the treatment of dye industry wastewater," *Bioengineered*, vol. 12, no. 1, pp. 70-87, 2021. https://doi.org/10.1080/21655979.2020.1863034

[30] B. Chaudhary and V. Kumar, "Emerging technological frameworks for the sustainable agriculture and environmental management," *Sustainable Horizons*, vol. 3, p. 100026, 2022. https://doi.org/10.1016/j.horiz.2022.100026

[31] A. Srivastava, R. M. Rani, D. S. Patle, and S. Kumar, "Emerging bioremediation technologies for the treatment of textile wastewater containing synthetic dyes: a comprehensive review," *Journal of Chemical Technology & Biotechnology*, vol. 97, no. 1, pp. 26-41, 2022. https://doi.org/10.1002/jctb.6891

[32] A. A. Owodunni and S. Ismail, "Revolutionary technique for sustainable plant-based green coagulants in industrial wastewater treatment—A review," *Journal of Water Process Engineering*, vol. 42, p. 102096, 2021. https://doi.org/10.1016/j.jwpe.2021.102096

[33] P. Rajasulochana and V. Preethy, "Comparison on efficiency of various techniques in treatment of waste and sewage water–A comprehensive review," *Resource-Efficient Technologies*, vol. 2, no. 4, pp. 175-184, 2016. https://doi.org/10.1016/j.reffit.2016.09.004

[34] S. Khan and A. Malik, *Environmental and health effects of textile industry wastewater. In Environmental deterioration and human health: Natural and anthropogenic determinants*. Dordrecht: Springer Netherlands, 2013.

[35] P. Kehrein, M. Van Loosdrecht, P. Osseweijer, M. Garfí, J. Dewulf, and J. Posada, "A critical review of resource recovery from municipal wastewater treatment plants–market supply potentials, technologies and bottlenecks," *Environmental Science: Water Research & Technology*, vol. 6, no. 4, pp. 877-910, 2020. https://doi.org/10.1039/C9EW00905A

[36] G. Yadav, S. K. Dash, and R. Sen, "A biorefinery for valorization of industrial waste-water and flue gas by microalgae for waste mitigation, carbon-dioxide sequestration and algal biomass production," *Science of the Total Environment*, vol. 688, pp. 129-135, 2019. https://doi.org/10.1016/j.scitotenv.2019.06.024

[37] T. Terlouw, C. Bauer, R. McKenna, and M. Mazzotti, "Large-scale hydrogen production via water electrolysis: A techno-economic and environmental assessment," *Energy & Environmental Science*, vol. 15, no. 9, pp. 3583-3602, 2022. https://doi.org/10.1039/D2EE01023B

[38] E. Gastaldi *et al.*, "Degradation and environmental assessment of compostable packaging mixed with biowaste in full-scale industrial composting conditions," *Bioresource Technology*, vol. 400, p. 130670, 2024. https://doi.org/10.1016/j.biortech.2024.130670

[39] R. Al-Tohamy *et al.*, "A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety," *Ecotoxicology and Environmental Safety*, vol. 231, p. 113160, 2022. https://doi.org/10.1016/j.ecoenv.2021.113160

[40] I. Michalak, *The application of seaweeds in environmental biotechnology. In Advances in botanical research*. London, UK: Elsevier, 2020.

[41] S. Sridhar, *Membrane technology: sustainable solutions in water, health, energy and environmental sectors*. Boca Raton, FL, USA: CRC Press, 2018.

[42] H. V. Oral *et al.*, "A review of nature-based solutions for urban water management in European circular cities: A critical assessment based on case studies and literature," *Blue-Green Systems*, vol. 2, no. 1, pp. 112-136, 2020. https://doi.org/10.2166/bgs.2020.932

[43] M. Smol, C. Adam, and M. Preisner, "Circular economy model framework in the European water and wastewater sector," *Journal of Material Cycles and Waste Management*, vol. 22, pp. 682-697, 2020. https://doi.org/10.1007/s10163-019-00960-z

[44] N. N. Tran, M. Escriba-Gelonch, M. M. Sarafraz, Q. H. Pho, S. Sagadevan, and V. Hessel, "Process technology and sustainability assessment of wastewater treatment," *Industrial & Engineering Chemistry Research*, vol. 62, no. 3, pp. 1195-1214, 2023. https://doi.org/10.1021/acs.iecr.2c03471

[45] H. Abyar and M. Nowrouzi, "A comprehensive framework for eco-environmental impact evaluation of wastewater treatment plants: Integrating carbon footprint, energy footprint, toxicity, and economic assessments," *Journal of Environmental Management*, vol. 348, p. 119255, 2023. https://doi.org/10.1016/j.jenvman.2023.119255

[46] M. He *et al.*, "Waste-derived biochar for water pollution control and sustainable development," *Nature Reviews Earth & Environment*, vol. 3, pp. 444-460, 2022. https://doi.org/10.1038/s43017-022-00306-8

[47] U. Ejairu, A. T. Aderamo, H. C. Olisakwe, A. E. Esiri, U. M. Adanma, and N. O. Solomon, "Eco-friendly wastewater treatment technologies (concept): Conceptualizing advanced, sustainable wastewater treatment designs for industrial and municipal applications," *Comprehensive Research and Reviews in Engineering and Technology*, vol. 2, no. 1, pp. 083-104, 2024.

[48] J. Qu *et al.*, "Municipal wastewater treatment in China: Development history and future perspectives," *Frontiers of Environmental Science & Engineering*, vol. 13, p. 88, 2019. https://doi.org/10.1007/s11783-019-1172-x

[49] K. Obaideen, N. Shehata, E. T. Sayed, M. A. Abdelkareem, M. S. Mahmoud, and A. Olabi, "The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline," *Energy Nexus*, vol. 7, p. 100112, 2022. https://doi.org/10.1016/j.nexus.2022.100112

[50] E. Khaki, H. Boleydei, H. Abyar, and M. Nowrouzi, "Integrating eco-environmental assessment with energy recovery for petrochemical wastewater treatment technologies: A transition towards green and sustainable management," *Journal of Water Process Engineering*, vol. 55, p. 104103, 2023. https://doi.org/10.1016/j.jwpe.2023.104103

[51] A. Saravanan *et al.*, "Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development," *Chemosphere*, vol. 280, p. 130595, 2021. https://doi.org/10.1016/j.chemosphere.2021.130595

[52] X. Xiang, Q. Li, S. Khan, and O. I. Khalaf, "Urban water resource management for sustainable environment planning using artificial intelligence techniques," *Environmental Impact Assessment Review*, vol. 86, p. 106515, 2021. https://doi.org/10.1016/j.eiar.2020.106515

[53] M. P. Shah, "Environmental bioremediation: A low cost nature's natural biotechnology for environmental clean-up," *Journal of Petroleum & Environmental Biotechnology*, vol. 5, no. 4, p. 1, 2014.

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