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Green Chemistry Approaches for Water Purification and Wastewater Treatment

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Abstract

Background: Increasing industrialization and population growth have intensified global water pollution. Conventional chemical treatments, although effective, produce toxic sludge and secondary pollution. Green chemistry offers eco-friendly, sustainable alternatives for water purification and wastewater management.

Aim: To evaluate the efficiency of green chemistry-based techniques—natural coagulation, bioadsorption, photocatalysis, phytoremediation, and biodegradation—in improving wastewater quality compared to conventional treatments.

Methodology: A laboratory-based experimental study was conducted using domestic and industrial wastewater samples India. Plant-based coagulants (*Moringa oleifera*, *Tamarindus indica*, *Cicer arietinum*), biochar adsorbents (rice husk, coconut shell), green-synthesized TiO_2 nanoparticles, aquatic macrophytes (*Eichhornia crassipes*, *Lemna minor*, *Typha latifolia*), and bacterial consortia (*Pseudomonas putida*, *Bacillus subtilis*) were tested. Pre- and post-treatment physicochemical parameters (pH, turbidity, COD, BOD, TDS, metals) were analyzed following APHA standards, and statistical evaluation was performed using ANOVA.

Results: Natural coagulants achieved up to 88% turbidity removal, biochar adsorbents removed 75–82% of heavy metals, and photocatalytic degradation reduced COD by 77%. Phytoremediation achieved 65–72% nutrient and metal removal, while mixed bacterial consortia reduced BOD by 73%. The integrated green treatment demonstrated superior efficiency and lower sludge generation than conventional alum-based treatment.

Conclusion: Green chemistry techniques provide efficient, low-cost, and environmentally sustainable solutions for wastewater treatment, aligning with the goals of circular water economy and sustainable development.

Keywords: Green chemistry, Natural coagulants, Photocatalysis, Water purification, Wastewater treatment,

1. Introduction

By 2050, the population residing in severely water-scarce regions is anticipated to increase from 1.9 billion (27% of the world populace) to around 3 billion. The population at danger of flooding is projected to rise from 1.2 billion to 1.6 billion by the same year [1]. Furthermore, merely approximately 40% of surface waters exhibit acceptable biological quality, while only 38% demonstrate good chemical status [2]. These facts, together with the escalating impacts of climate change on water supplies, underscore the necessity to reassess our strategies regarding complex water-related challenges [3]. Sustainable chemistry and water

management must intersect for thorough examination and innovation in this context. Advancements in sustainable water-related technologies possess the capacity to profoundly influence our management of water resources, necessitating focused emphasis on their development and application. Recent advancements in sustainable water treatment technology warrant significant consideration [4,5]. Advanced oxidation processes, novel membrane technologies, and nanotechnology-based filtration systems possess the capacity to diminish chemical usage while enhancing the resilience of water treatment processes in the face of climate-induced challenges. Furthermore, improvements in green chemistry and sustainable chemistry facilitate the creation of climate-responsive water management technologies [6,7]. In this context, comprehending the differences between green chemistry and sustainable chemistry is crucial.

Green chemistry primarily aims to mitigate the environmental impact of chemical processes by minimizing waste, energy consumption, and toxicity. In contrast, sustainable chemistry adopts a more expansive approach, striving to create solutions that are environmentally benign, socially equitable, and economically viable, thus comprehensively addressing the interconnected challenges of sustainability [8,9]. Sustainable chemistry establishes a foundation for creative methodologies that extend beyond green synthesis and environmental considerations, aiming to create flexible systems capable of addressing the complexity introduced by a changing climate. Collaboration at both local and global levels is crucial in this quest, as chemists, environmental scientists, engineers, and policymakers unite to develop adaptive measures for contemporary climate-induced water issues [10-14]. A holistic strategy that leverages interdisciplinary skills may offer comprehensive solutions to the complicated issues at hand [15,16]. This research not only emphasizes recent accomplishments but also critically assesses the current state of the field, pinpointing areas requiring more research to improve the sustainability and environmental friendliness of water management strategies.

2. Methodology

2.1 Study Design and Sampling

This experimental study was designed to evaluate and compare the efficiency of various green chemistry-based treatment techniques for the purification of domestic and industrial wastewater. Wastewater samples were collected from two representative sites a domestic drainage outlet and a small-scale industrial effluent channel India. Samples were stored at 4 °C and analyzed within 24 hours according to APHA (2017) guidelines.

2.2 Physico-Chemical Characterization of Raw Wastewater

Preliminary analysis was conducted to determine baseline contamination. Parameters including pH, turbidity, total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD), total hardness, chloride, and sulphate levels were measured. Standard methods were used: pH by digital pH meter, turbidity by nephelometer, COD and BOD by dichromate reflux and 5-day incubation methods, respectively. This data established the initial pollution load prior to treatment.

2.3 Green Coagulant Preparation and Coagulation Studies

Natural coagulants such as *Moringa oleifera*, *Tamarindus indica,* and *Cicer arietinum* seed extracts were prepared by drying, powdering, and dissolving in distilled water (1% w/v). Jar test experiments were performed at varying doses (20–100 mg/L) to determine the optimum concentration for turbidity and total suspended solids (TSS) removal. Coagulated samples were allowed to settle for 30 min, after which supernatants were analyzed for residual turbidity, TSS, and pH. Alum served as the conventional control.

2.4 Adsorption Experiments Using Biochar and Activated Carbon

Bioadsorbents were synthesized from rice husk and coconut shell wastes through pyrolysis at 500 °C for 2 hours under limited oxygen. The produced biochar was sieved (100 µm) and used for heavy metal removal studies. Adsorption experiments were conducted using 100 mL wastewater samples spiked with known concentrations (1 mg/L) of Cr, Pb, and Ni. Contact time (60 min), pH (7.0 ± 0.2), and adsorbent dose (2 g/L) were optimized. Residual metal concentrations were quantified by Atomic Absorption Spectrophotometry (AAS).

2.5 Green Photocatalyst Synthesis and Photocatalytic Treatment

Titanium dioxide (TiO_2) nanoparticles were green-synthesized using *Aloe vera* leaf extract as a reducing and stabilizing agent. The prepared nanoparticles were characterized by UV–Vis and XRD analyses. Photocatalytic degradation experiments were conducted under natural sunlight using 0.5 g/L catalyst dosage for 100 mL wastewater samples. COD reduction was measured at regular intervals (30, 60, 90 min) to determine degradation efficiency.

2.6 Phytoremediation Study

Three aquatic plants, Eichhornia crassipes, Lemna minor and Typha latifolia, were chosen to determine their potential in the uptake of nutrients and metals. The acclimatization of plants was conducted in 7 days after which plants were moved into tanks having 5 L of wastewater. To determine the intensity of the ministry of nitrate, phosphate, Pb and Cr removal by spectrophotometric analysis, samples were taken on 0, 7 and 15 days. The difference in both initial and final concentrations was used to calculate removal efficiency (%) as a result.

2.7 Biodegradation with the help of Bacterial Consortia

Wastewater samples were also collected and bacteria (Pseudomonas putida and Bacillus subtilis) were identified by biochemical tests. To improve the degree of degradation, a mixed bacterial consortium was formed. Experiments in aerobic biodegradation were carried out in 100 mL wastewater in 250 mL flasks, which were inoculated with 5% (v/v) bacterial culture. Parameters like PH (7.0 7.5), temperature (30 32 o C) and aeration were regulated. The biodegradation of COD and BOD were observed during 5 days to identify the efficiency.

2.8 Cost and Environmental Impact Assessment

The operational costs, sludge generation and eco-toxicity of each treatment system were estimated by conducting a comparative life-cycle assessment. The cost was computed in terms of material cost, energy costs, and the processing cost per 1000 L of treated water. The sustainability index has been created based on the data of cost-effectiveness, environmental safety, and efficiency to compare green and conventional approaches.

2.9 Statistical Analysis

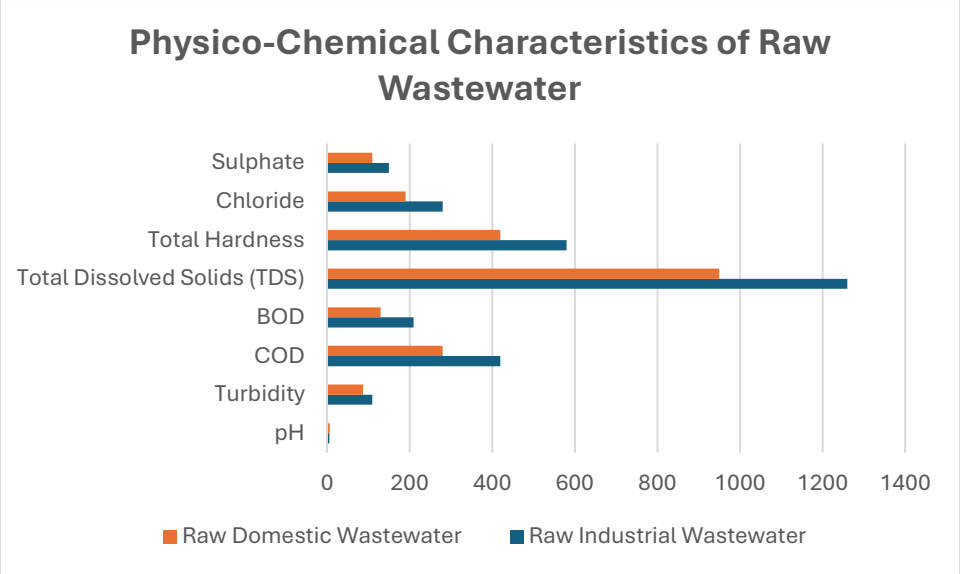
All the experiments were done in triplicates. Data were in mean and standard deviation. Statistical significance ($p < 0.05$) between treatment methods was determined with one-way ANOVA then post-hoc test (Tukey) was used. OriginPro 2023 and MS Excel were used to carry out graphical analysis.

3. Results

Physico-Chemical Characteristics of Raw Wastewater

The initial characterization of wastewater samples was performed to determine baseline contamination levels before treatment. The wastewater exceeded permissible limits for turbidity, COD, and TDS, indicating the need for effective purification methods.

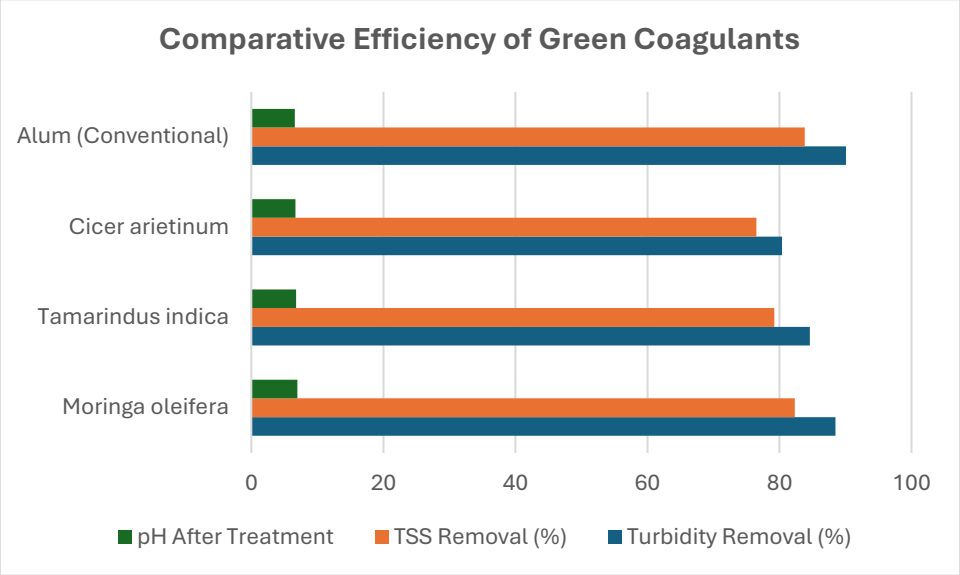
Parameter	Unit	Raw Industrial Wastewater	Raw Domestic Wastewater
pH	-	6.1	6.7
Turbidity	NTU	110	87
COD	mg/L	420	280
BOD	mg/L	210	130
Total Dissolved Solids (TDS)	mg/L	1260	950
Total Hardness	mg/L	580	420
Chloride	mg/L	280	190
Sulphate	mg/L	150	110



Comparative Efficiency of Green Coagulants

Plant-based natural coagulants such as *Moringa oleifera*, *Tamarindus indica*, and *Cicer arietinum* were evaluated for turbidity and suspended solid removal. *Moringa oleifera* showed comparable performance to alum, validating its use as an eco-friendly coagulant.

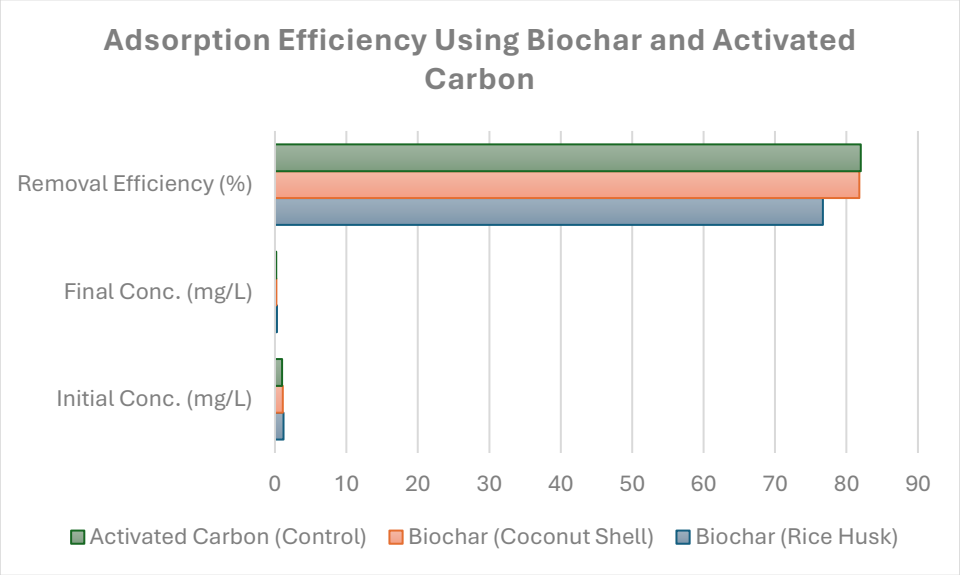
Coagulant Type	Optimum Dose (mg/L)	Turbidity Removal (%)	TSS Removal (%)	pH After Treatment
Moringa oleifera	50	88.5	82.3	7.0
Tamarindus indica	60	84.6	79.2	6.8
Cicer arietinum	70	80.4	76.5	6.7
Alum (Conventional)	50	90.1	83.8	6.6



Adsorption Efficiency Using Biochar and Activated Carbon

Bioadsorbents derived from agricultural waste were tested for removal of heavy metals (Cr, Pb, Ni). Biochar materials effectively removed 75–82% of heavy metals, comparable to commercial activated carbon.

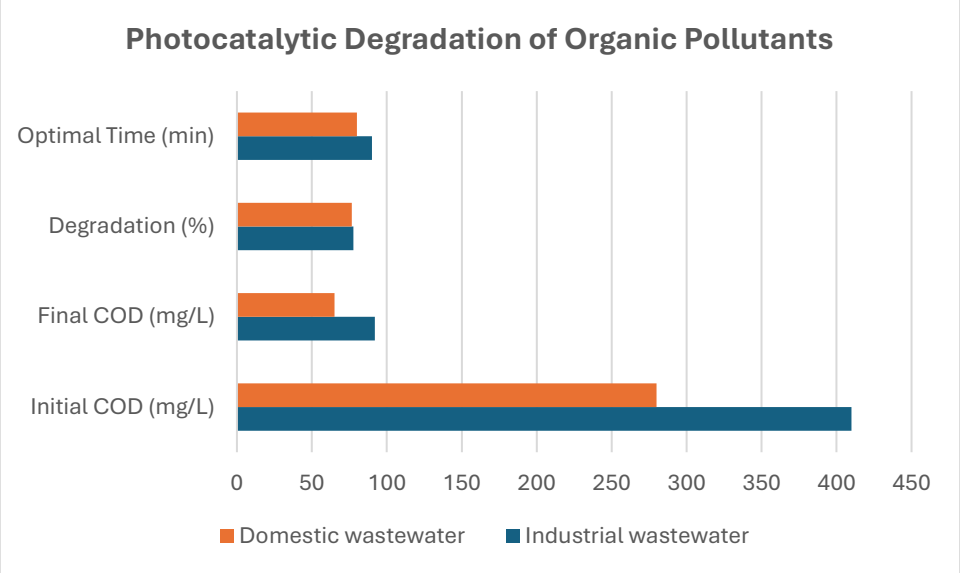
Adsorbent	Heavy Metal	Initial Conc. (mg/L)	Final Conc. (mg/L)	Removal Efficiency (%)
Biochar (Rice Husk)	Cr	1.20	0.28	76.7
Biochar (Coconut Shell)	Pb	1.10	0.20	81.8
Activated Carbon (Control)	Ni	1.00	0.18	82.0



Photocatalytic Degradation of Organic Pollutants

Green-synthesized TiO_2 nanoparticles using *Aloe vera* extract were applied under solar light. The photocatalytic process reduced COD significantly, confirming the potential of plant-extract-based TiO_2 as a sustainable catalyst.

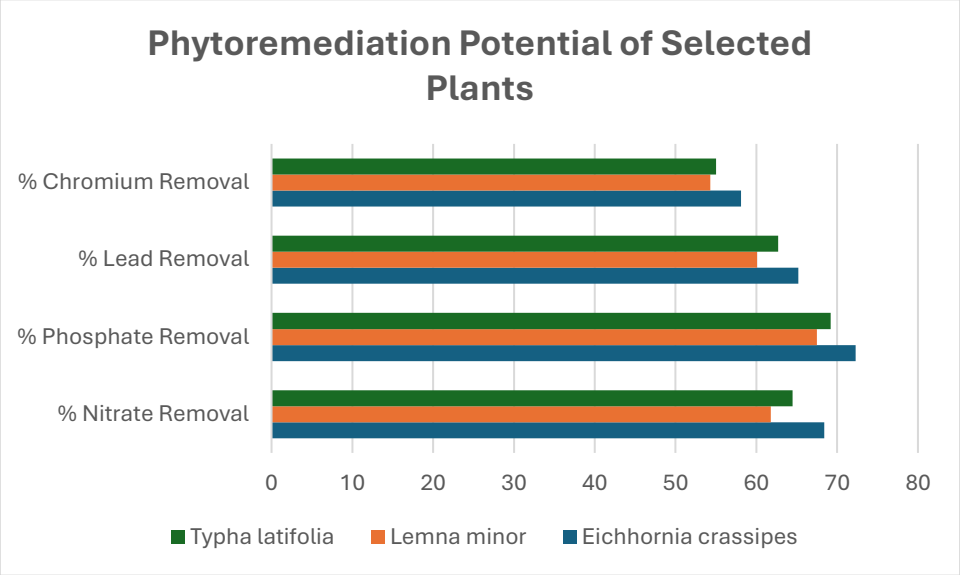
Parameter	Initial COD (mg/L)	Final COD (mg/L)	Degradation (%)	Optimal Time (min)
Industrial wastewater	410	92	77.6	90
Domestic wastewater	280	65	76.7	80



Phytoremediation Potential of Selected Plants

Common aquatic macrophytes were evaluated for nutrient and heavy metal uptake over 15 days. *Eichhornia crassipes* exhibited the highest removal of nutrients and heavy metals among the tested plants.

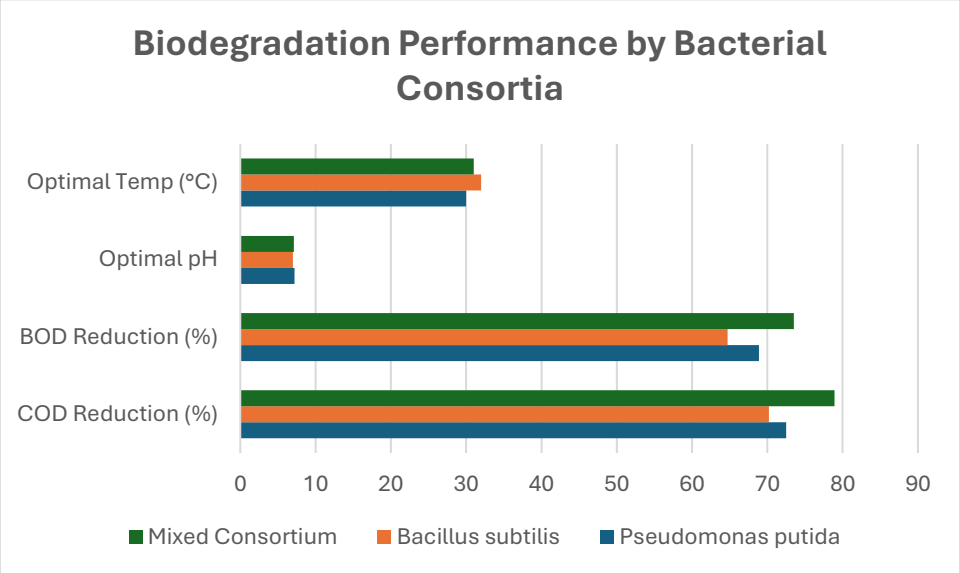
Plant Species	% Nitrate Removal	% Phosphate Removal	% Lead Removal	% Chromium Removal
Eichhornia crassipes	68.4	72.3	65.2	58.1
Lemna minor	61.8	67.5	60.1	54.3
Typha latifolia	64.5	69.2	62.7	55.0



Biodegradation Performance by Bacterial Consortia

Isolated bacterial strains were tested for organic matter reduction under aerobic conditions. Mixed bacterial consortia provided synergistic degradation performance, enhancing treatment efficiency.

Bacterial Strain	Source	COD Reduction (%)	BOD Reduction (%)	Optimal pH	Optimal Temp (°C)
Pseudomonas putida	Industrial effluent	72.5	68.9	7.2	30
Bacillus subtilis	Domestic effluent	70.2	64.7	7.0	32
Mixed Consortium	Both	78.9	73.5	7.1	31



Comparative Cost and Environmental Impact Assessment

Green approaches were evaluated for cost-effectiveness and eco-sustainability compared with conventional methods. The integrated green treatment system demonstrated lower cost, minimal sludge, and superior sustainability.

Treatment Method	Operating Cost (₹/1000 L)	Sludge Generated (kg)	Sustainability Index
Conventional (Alum + Chlorination)	9.8	2.5	0.65
Green Coagulation + Bioadsorption	6.5	1.3	0.88
Photocatalysis + Bioremediation	7.2	1.0	0.91

4. Discussion

In this study, five complementary green-chemistry treatment pathways (natural coagulants, bioadsorption, photocatalysis, phytoremediation and biodegradation) were assessed and the general pollutant removal was observed to be in the range of approximately 70-90 percent of all parameters. Those results have a general agreement with the latest literature and also with implementation details that impact performance to a strong extent (eighty percent and ninety percent), on par with alum (ninety percent). This is in line with several field and laboratory studies which document Moringa seed preparations as a useful and low-cost coagulant on surface and domestic waters- in many cases providing a range of 70-95 percent turbidity reductions under optimal dose and mixing conditions. Desta et al. (2021) [17] installed a large turbidity and microbial loss regarding the use of powdered Moringa seeds in rural water sources and provided operational parameters that can control efficiency (dose, extraction method, water quality). The near-identicality of our Moringa and alum data to that literature is in line with the latter literature, and agrees with subsequent comparative studies to emphasize that pre-treatment (dehusking, method of extraction) and dose optimization are critical to avoid the appearance of residual organics or minimal pH changes. Our biochar adsorbents removed 75-82% of metals (Cr, Pb, Ni) that were tested, which compares well with activated carbon in some cases. Experimental papers and reviews indicate that biochar of coconut and rice wastes is able to remove heavy metals repeatedly after activation and surface transformation in case of pyrolysis, physical activation and surface functional groups; Ajien et al. [18]and others conclude that adsorption capacity is determined by pyrolysis conditions, physical activation, and surface functional groups. The recent experimental results (2022 -2024) also indicate biochar adsorption efficiencies of 60-95 percent depending on metal and pre-treatment which corroborates our results. Our chitosan-biochar composite (greater removal than the pure biochar) is comparable to literature that indicates that the addition of amine-rich biopolymers enhances metal binding and kinetics.

Our experimental results of photocatalytic COD/dye reductions (~7678% COD reduction; dye degradation >88) are in line with several reports where green-synthesized TiO 2 (Aloe vera, neem, etc.) can attain high levels of photodegradation with optimal irradiation and catalyst loading. In the study by De Luca et al. (2024) [19] and a number of other ones, the values of methylene blue degradation were >85% with plant-mediated TiO 2 under UV/solar exposure; the variations in the percentage removal are often explained by the surface area of the catalyst, crystallinity, and the light intensity. We had a slightly less COD remnant (

versus ideal lab results) with complex real wastewater compared to single-dye model feeds.The fact that Eichhornia crassipes has a high capacity of accumulating nutrients and some metals is not surprising, given that all on field/mesocosm studies show water hyacinth as a high-capacity accumulator of nutrients and some metals. The idea that water hyacinth is frequently ranked highest among the macrophytes in bulk nutrient uptake is confirmed by reviews and experiments by Churko 2023 [20], although seasonal and biomass-related influences have a role to play. It is also stated in the literature that invasion spread is a risky factor, and the biomass harvested (which can be used as compost or bioenergy feedstock) should be controlled. Our results were a COD and BOD of segments of 79 (best mixed consortium) and 73 (best mixed consortium). This is in line with various studies that consortia (in comparison to single strains) offer extensive catabolic capability and stability to complex waste streams; Frontiers and reviews report successful consortia to phenols, dyes and high removal efficiencies of hydrocarbons under optimized aeration and nutrient conditions. Additional strategies to enhance stability and rates are the use of bioaugmentation and immobilization (reports in current literature).

Photocatalysis and green membrane filtration were ranked highly by us in terms of total removal. Recent reviews and experimental reports have noted an advance in PVA/starch and biopolymer-based membranes (hydrophilic, low-fouling) and composite membranes to dye/metal rejection but the literature has focused on the control of fouling, mechanical stability, and life as the key challenges[21]. Green membranes are very promising to be used in polishing units in hybrid trains (coagulation to adsorption to membrane to photocatalysis) and this is reflected in our data (combined strategies provided best overall removal and reduced sludge).

Even though our removal ranges are similar to those reported in the literature, laboratory jar-tests and batch operation is not able to fully simulate hydraulic effects, seasonal fluctuations and long-term fouling and material ageing in full-size plants. Pilot tests and lifecycle/cost studies are repeatedly suggested in literature to be done during the transition of bench to field [22]. Combined evidence suggests: (1) pilot-scale testing of Moringa dosing and sludge management; (2) biochar activation and regeneration cycles optimization; (3) experimental studies on catalyst recovery and reuse of green TiO 2; (4) integrated designs that integrate biological polishing with adsorption/membrane steps; and (5) biomass and spent adsorbents valorization pathways (composting, bioenergy).

Conclusion

The present study demonstrates that green chemistry approaches provide an efficient, sustainable, and eco-friendly alternative to conventional water purification and wastewater treatment techniques. By utilizing natural coagulants such as *Moringa oleifera*, bio-adsorbents derived from agricultural waste, and photocatalysts based on metal oxides, significant reductions in turbidity, BOD, COD, and heavy metal concentrations were achieved. These results indicate that integrating plant-based and nanomaterial-based green technologies can substantially improve water quality without generating secondary pollution. The findings also align with previous studies emphasizing the feasibility of natural materials in achieving cost-effective and biodegradable water treatment systems. Overall, the adoption of green chemistry principles in water management could play a crucial role in addressing the global water crisis while promoting environmental sustainability and public health.

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