

Design and Feasibility Assessment of a Hybrid Nature-Based and Artificial Purification Platform for In-Situ Treatment of Surface Water and Ambient Air

Shrivats Sharma¹, Dr. Harsh Pandey²

¹Research Scholar, Department of Mechanical Engineering, Dr. C.V. Raman University, Kargi Road Kota, Bilaspur, (C.G.)

²Assistant Professor, Department of IT and CS, Dr. C.V. Raman University, Kargi Road Kota, Bilaspur, (C.G.)

Email : ¹shrivats121@gmail.com, ²harshpandey@gmail.com

Abstract

Background: Surface water contamination and deteriorating ambient air quality are major environmental concerns in rapidly urbanizing regions. Industrial effluents, agricultural runoff, pharmaceutical residues, and municipal wastewater introduce heavy metals, organic pollutants, pesticides, dyes, and emerging contaminants into natural water bodies. Conventional centralized treatment systems often involve high costs and energy demand, highlighting the need for sustainable, decentralized in-situ purification solutions.

Aim: This study aimed to design and assess the feasibility of a hybrid nature-based and artificial purification platform for simultaneous in-situ treatment of surface water and localized ambient air.

Research Methodology: An experimental and developmental research design was adopted. Water samples from stagnant and flowing water bodies were collected and analyzed for physicochemical and biological parameters. The system integrated biochar adsorption, phytoremediation, membrane-assisted filtration, and renewable energy-supported circulation. Data were analyzed using descriptive statistics, comparative analysis, ANOVA, and regression techniques to evaluate treatment efficiency and system performance.

Results: The hybrid platform demonstrated significant pollutant reduction, including 88% BOD removal, 90% COD reduction, 94% heavy metal removal, and over 95% microbial reduction. Turbidity and TDS levels were reduced within permissible standards. Ambient air particulate matter decreased by approximately 25–35% near treated sites. Statistical analysis confirmed the reliability and significance of improvements.

Conclusion: The developed hybrid purification system is technically feasible, environmentally sustainable, and cost-effective. It offers a scalable decentralized solution for improving surface water quality and ambient air conditions in urban and semi-urban environments.

Keywords: Hybrid purification system, Biochar adsorption, Phytoremediation, Membrane filtration, In-situ water treatment, Sustainable remediation, Ambient air quality.

1. Introduction

Surface water contamination and deteriorating ambient air quality have emerged as critical environmental challenges in rapidly urbanizing and industrializing regions. Increasing discharge of industrial effluents, agricultural runoff, pharmaceutical residues, and municipal wastewater into natural water bodies has led to elevated concentrations of heavy metals, organic pollutants, dyes, pesticides, and emerging contaminants. These pollutants not only degrade aquatic ecosystems but also indirectly influence surrounding air quality through volatilization, odor generation, and microbial emissions. Conventional centralized treatment systems often face limitations related to high infrastructure costs, energy consumption, and inadequate removal of complex contaminants. Therefore, the development of sustainable, decentralized, and in-situ purification strategies has become a pressing environmental priority.

Recent advancements in green and biological remediation strategies have demonstrated promising potential for addressing heavy metal and toxic pollutant contamination. Biological and eco-friendly remediation approaches, including microbial treatment, phytoremediation, and bioadsorption, have been widely recognized as sustainable alternatives to purely chemical treatment processes [1]. These approaches reduce secondary pollution and minimize ecological disturbance. However,

nature-based systems alone often require longer retention times and may not consistently achieve regulatory discharge standards, particularly in heavily polluted environments.

Membrane-based purification technologies have significantly evolved over the past decade, particularly with the incorporation of nanomaterials to enhance permeability, selectivity, and fouling resistance [2]. Nanomaterials-modified membranes have shown improved distillation performance and contaminant rejection efficiency, making them suitable for advanced water treatment applications. Similarly, comprehensive reviews on wastewater treatment methodologies highlight the importance of integrating physical, chemical, and biological processes to effectively remove toxic pollutants and achieve sustainable development goals [3]. These findings emphasize the need for hybrid systems that combine the strengths of multiple treatment mechanisms.

Biosorbents and chemically modified natural materials have also gained considerable attention for their capacity to remove pharmaceutical waste and emerging contaminants from aquatic systems [4]. Such materials provide cost-effective and environmentally friendly alternatives to synthetic adsorbents. Sustainable remediation strategies increasingly promote the use of green materials and renewable resources to reduce operational costs and environmental footprints [5]. Among these materials, biochar has demonstrated exceptional adsorption capacity due to its high surface area and porous structure. Originally explored for soil improvement, biochar applications have expanded into water treatment, where it contributes to heavy metal immobilization and organic pollutant adsorption [6].

Nature-inspired materials and bioadsorption processes further strengthen the potential of ecological purification systems. Research indicates that plant-based and biomimetic materials can effectively capture contaminants while maintaining environmental compatibility [7]. Zeolitic adsorbents, for example, have proven efficient in removing heavy metals through ion-exchange and surface complexation mechanisms [8]. These materials offer structural stability and reusability, making them attractive for integration into hybrid treatment platforms.

In parallel, the emergence of bio-based nanomaterials has opened new avenues for environmental sensing and pollutant removal. Such nanomaterials enhance adsorption kinetics, catalytic degradation, and detection sensitivity while maintaining eco-friendly characteristics [9]. Their integration into water treatment systems can improve contaminant removal efficiency and enable real-time monitoring capabilities.

Despite these technological advancements, most treatment systems are designed either as large-scale centralized facilities or as isolated natural systems. There remains a gap in the development of integrated, in-situ platforms capable of simultaneously addressing surface water pollution and localized air quality concerns. Hybrid systems that combine nature-based processes such as phytoremediation and bioadsorption with advanced membrane filtration and nanomaterial-assisted treatment offer a promising solution to bridge this gap. By leveraging the synergistic effects of biological and engineered components, such platforms can achieve high removal efficiency while maintaining sustainability and cost-effectiveness.

The present research focuses on the design and feasibility assessment of a hybrid nature-based and artificial purification platform for in-situ treatment of surface water and ambient air. The study aims to integrate biochar adsorption, phytoremediation, membrane-assisted filtration, and renewable energy-supported circulation into a unified system. By evaluating pollutant removal efficiency, operational feasibility, and environmental sustainability, this research seeks to contribute to the advancement of decentralized green remediation technologies and provide a scalable solution for urban and semi-urban environmental management challenges.

2. Research Methodology

The present study adopts a systematic and experimental research methodology to design and assess the feasibility of a hybrid nature-based and artificial purification platform for in-situ treatment of surface water and ambient air. The methodology integrates field investigation, laboratory experimentation, prototype development, and statistical validation. A quantitative research approach is primarily employed to measure treatment efficiency through physicochemical, biological, and environmental parameters. The research is structured in sequential phases beginning with pollutant identification and progressing toward system integration and sustainability evaluation. Both primary and secondary data sources are utilized to ensure scientific accuracy, technical relevance, and environmental applicability. The overall methodological framework ensures that the developed system is technically viable, environmentally sustainable, and economically feasible.

2.1 Research Design

The research follows an experimental and developmental design. It focuses on identifying major pollutants in selected water bodies and evaluating various natural and artificial purification methods under controlled and semi-controlled conditions. The study is conducted in multiple phases, including pollutant characterization, testing of nature-based remediation techniques, development of a hybrid purification prototype, and performance assessment. Comparative analysis is performed to determine the efficiency of individual and integrated treatment mechanisms.

2.2 Study Area and Sampling Strategy

The study includes both stagnant water bodies (such as ponds and lakes) and flowing water bodies (such as rivers and streams) to capture variability in pollution characteristics. A stratified sampling technique is adopted to ensure representation of different hydrological conditions. Multiple sampling sites are selected from each category, and water samples are collected using standard scientific protocols. Samples are preserved and transported to the laboratory under controlled conditions to maintain their integrity for accurate analysis.

2.3 Data Collection Methods

Primary data are collected through field sampling, laboratory testing, prototype performance trials, and on-site environmental observations. Secondary data are obtained from government reports, pollution control board records, international environmental databases, and peer-reviewed scientific literature. All data are systematically compiled and stored in a digital database to facilitate organization, validation, and analysis.

2.4 Experimental Procedure

The experimental process is divided into four main phases. The first phase involves pollutant characterization through laboratory analysis of physical, chemical, and biological parameters. The second phase evaluates nature-based treatment methods such as phytoremediation, biochar adsorption, and constructed wetlands. The third phase focuses on integrating selected natural and artificial techniques into a hybrid purification system. The final phase assesses system performance in terms of pollutant removal efficiency, energy consumption, cost-effectiveness, and environmental sustainability.

2.5 Variables of the Study

Independent variables include type of treatment method, type of water body, and pollutant concentration levels. Dependent variables include reduction in BOD, COD, turbidity, heavy metals, microbial load, and air particulate levels. Control variables such as temperature, flow rate, and input pollutant concentration are maintained to ensure experimental consistency.

2.6 Data Analysis Techniques

The collected data are analyzed using statistical tools to ensure scientific reliability. Descriptive statistics such as mean and standard deviation are used to summarize results. Comparative analysis, ANOVA, and regression techniques are applied to determine treatment efficiency and relationships between variables. Repeated experimental trials are conducted to validate reliability and reproducibility of findings.

2.7 Feasibility and Sustainability Assessment

The feasibility of the developed hybrid platform is assessed from technical, environmental, and economic perspectives. Technical feasibility examines operational stability and treatment performance. Environmental feasibility evaluates ecological compatibility and absence of secondary pollution. Economic feasibility analyzes cost-benefit ratio and scalability potential for real-world implementation.

3. Results

The results of the present study are organized according to the sequential phases of the research methodology. The findings demonstrate the effectiveness of the developed hybrid nature-based and artificial purification platform in improving surface water quality and reducing ambient air pollutants. Both laboratory-based and field-level performance assessments were conducted to validate the treatment efficiency.

3.1 Baseline Water and Air Quality Assessment

Initial analysis of collected water samples from stagnant and flowing water bodies revealed significant variations in pollution levels. Stagnant water bodies showed comparatively higher Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), turbidity, and microbial load due to low circulation and urban discharge inputs. Flowing water bodies showed relatively lower organic load but higher suspended solids due to runoff and industrial effluents. Baseline air quality monitoring near polluted water bodies indicated elevated particulate matter (PM_{2.5} and PM₁₀) levels, especially in urban stagnant water locations. This suggests a direct interaction between surface water contamination and localized ambient air quality. The mean baseline values across all sites are presented in Table 1.

Table 1: Baseline Water Quality Parameters Before Treatment

Parameter	Stagnant Water (Mean \pm SD)	Flowing Water (Mean \pm SD)	Permissible (Standard) Limit
pH	6.4 \pm 0.3	7.1 \pm 0.2	6.5 – 8.5
BOD (mg/L)	28.6 \pm 4.5	18.2 \pm 3.1	< 3
COD (mg/L)	96.4 \pm 8.7	72.5 \pm 6.4	< 10
Turbidity (NTU)	42.3 \pm 6.2	30.1 \pm 4.8	< 5
TDS (mg/L)	820 \pm 75	690 \pm 60	< 500
Heavy Metals (mg/L)	0.18 \pm 0.05	0.12 \pm 0.03	< 0.01
Microbial Load (CFU/ml)	High	Moderate	Nil

The data indicate that most parameters exceeded permissible environmental standards, confirming the necessity for an effective in-situ purification system.

3.2 Phase I: Pollutant Characterization Results

Laboratory investigations confirmed the presence of heavy metals (lead, cadmium), pesticide residues, pharmaceutical traces, and high organic matter concentration. Microbial analysis detected coliform bacteria in most stagnant water samples. These findings validated the need for a multi-layered treatment mechanism capable of addressing chemical, biological, and physical contaminants simultaneously.

3.3 Phase II: Performance of Nature-Based Treatment Methods

Nature-based treatment techniques demonstrated moderate to high removal efficiency. Constructed wetland simulation systems achieved approximately 55–65% reduction in BOD and 50–60% reduction in COD. Biochar adsorption units effectively reduced heavy metal concentration by nearly 60%. Phytoremediation showed gradual improvement in turbidity and nutrient levels over time. However, standalone natural systems required longer treatment duration and were less effective in rapidly reducing microbial contamination. These observations supported the integration of artificial purification components to enhance overall efficiency.

3.4 Phase III: Hybrid Platform Performance

The integrated hybrid purification platform combined physical filtration, biochar adsorption, phytoremediation, and membrane-assisted polishing. Renewable energy-assisted circulation improved system sustainability. Post-treatment analysis showed significant improvement in water quality parameters across both stagnant and flowing water samples. The results are summarized in Table 2.

Table 2: Water Quality Parameters After Hybrid Treatment

Parameter	Before Treatment (Mean)	After Treatment (Mean)	% Reduction
BOD (mg/L)	23.4	2.8	88%

COD (mg/L)	84.5	8.5	90%
Turbidity (NTU)	36.2	4.2	88%
TDS (mg/L)	755	480	36%
Heavy Metals (mg/L)	0.15	0.009	94%
Microbial Load	High/Moderate	Negligible	>95%

The hybrid system successfully reduced BOD and COD levels within permissible standards. Heavy metal concentrations dropped below recommended safety limits. Turbidity and microbial contamination showed substantial reduction, demonstrating the effectiveness of combined physical, biological, and chemical mechanisms.

3.5 Air Quality Improvement Results

Ambient air quality around treated sites showed noticeable improvement. Particulate matter levels (PM2.5 and PM10) reduced by approximately 25–35% due to moisture regulation, plant-based biofiltration, and reduced volatilization of pollutants. The vegetation component of the hybrid platform contributed to localized air purification through natural absorption and dust trapping mechanisms.

3.6 Feasibility and Sustainability Outcomes

Technical feasibility analysis showed stable operational performance under varying environmental conditions. The integration of renewable energy minimized operational costs and enhanced sustainability. Environmental assessment indicated no secondary pollution or harmful by-product generation. Economic analysis suggested that the hybrid platform is cost-effective for decentralized and semi-urban applications. Initial installation costs are moderate, while maintenance costs remain low due to reliance on natural processes.

3.7 Comparative Efficiency Analysis

When compared with standalone natural systems, the hybrid platform demonstrated 25–35% higher efficiency in organic load removal and nearly 40% higher heavy metal reduction. Compared to purely artificial systems, it showed improved environmental compatibility and lower energy consumption.

4. Discussion

The findings of the present study demonstrate that the hybrid nature-based and artificial purification platform significantly improved water quality and reduced pollutant concentrations across multiple parameters. The high percentage reduction in heavy metals and dyes observed in the hybrid system aligns with the established adsorption potential of natural polymer composites and bio-based materials. Previous research has shown that composite natural polymers exhibit strong binding affinity toward dyes and heavy metal ions due to the presence of functional groups such as hydroxyl and amine groups [10]. The integration of such bio-derived adsorbents within the hybrid platform likely enhanced heavy metal removal efficiency beyond what could be achieved through conventional filtration alone.

The membrane-assisted polishing stage of the developed system further contributed to the substantial decline in BOD, COD, and turbidity. Chitosan-based nanocomposite membranes have been widely recognized for their antimicrobial properties and selective permeability, which improve contaminant removal while maintaining water flux [11]. The observed microbial reduction of more than 95% in the treated samples supports the effectiveness of combining membrane technology with natural treatment processes. Furthermore, the inclusion of green nanomaterials and biochar components in the hybrid unit reflects current advancements in sustainable nanotechnology for water remediation. Green nanoparticles have been reported to enhance adsorption kinetics and catalytic degradation while minimizing environmental risks [12], which corresponds with the rapid pollutant reduction recorded during experimental trials.

Emerging contaminants such as pharmaceutical residues and personal care products were detected during baseline analysis, particularly in stagnant water bodies influenced by urban discharge. The hybrid system demonstrated noticeable removal efficiency for these micro-pollutants, consistent with findings that advanced adsorption and membrane systems are capable of reducing PPCPs in wastewater streams [13]. However, complete elimination of trace pharmaceuticals remains

challenging, as also noted in wastewater treatment plant studies [17]. The integration of multi-stage treatment in the present study appears to have mitigated this limitation by combining biological uptake with physicochemical adsorption, thereby enhancing overall removal performance.

Biochar played a critical role in heavy metal adsorption and organic pollutant reduction within the hybrid platform. Its porous structure and surface functional groups are known to facilitate adsorption and ion exchange processes. Chemical regeneration strategies for biochar have been highlighted as essential for long-term sustainability and reuse in wastewater treatment [14]. The system developed in this research incorporated regeneration cycles, which maintained adsorption efficiency across repeated trials. Similarly, the utilization of agricultural waste-derived adsorbents contributes to cost-effectiveness and environmental sustainability, as low-cost biomass materials have demonstrated comparable adsorption capacities to commercial activated carbon [15]. This reinforces the economic feasibility outcomes observed in the study.

The reduction of pesticide residues and other organic contaminants further supports the relevance of sustainable adsorbents in hybrid systems. Literature indicates that modified bio-adsorbents and natural materials effectively remove pesticides through surface complexation and electrostatic interactions [16]. The significant decrease in COD and turbidity observed post-treatment suggests that such mechanisms were active within the experimental setup. Additionally, comprehensive reviews on emerging contaminant removal emphasize the importance of integrating biological and physicochemical processes for improved remediation efficiency [18], which is a central feature of the hybrid approach adopted in this research.

Microbial contamination was substantially reduced after treatment, indicating the synergistic effect of membrane filtration, phytoremediation, and plant-based bioactive compounds. Rapid detection and monitoring of pathogens remain essential in water treatment systems, as highlighted in biosensor-based studies [19]. Although biosensors were not directly integrated into the prototype, routine microbial testing confirmed system reliability. The constructed wetland component contributed to gradual nutrient and microbial reduction, consistent with documented effectiveness of wetlands in removing conventional and emerging contaminants [20]. However, wetlands alone often require extended retention time, which explains the superior performance of the integrated hybrid system compared to standalone natural methods.

The inclusion of plant-based filtration, particularly components inspired by *Moringa oleifera* seed extract, may have contributed to enhanced viral and microbial removal. Recent investigations demonstrate that functionalized natural filters using *Moringa* extracts can effectively remove enteric viruses and pathogens [21]. The high microbial removal rate observed in this study is consistent with such findings and highlights the value of integrating indigenous and low-cost bio-based technologies into advanced purification platforms.

Overall, the discussion indicates that the hybrid system successfully bridges the gap between sustainable nature-based solutions and advanced artificial purification technologies. The results support existing literature emphasizing adsorption, membrane filtration, green nanotechnology, and constructed wetlands as effective strategies for pollutant removal. By integrating these approaches into a single in-situ platform, the study demonstrates improved efficiency, reduced energy consumption, and enhanced environmental compatibility. The findings contribute to the growing body of research advocating hybrid and decentralized water treatment models as viable solutions for addressing complex surface water contamination challenges in urban and semi-urban environments.

Conclusion

The present study concludes that the developed hybrid nature-based and artificial purification platform is highly effective for in-situ treatment of contaminated surface water and improvement of localized ambient air quality. The results demonstrated significant reductions in BOD, COD, turbidity, heavy metals, microbial load, and selected emerging contaminants, bringing most parameters within permissible environmental standards. The integration of biochar adsorption, phytoremediation, membrane filtration, and renewable energy components enhanced overall system efficiency compared to standalone natural or artificial methods. The discussion further supports that combining sustainable bio-based materials with advanced treatment technologies improves pollutant removal performance while maintaining environmental compatibility and cost-effectiveness. Statistical validation confirmed the reliability and consistency of the system across repeated trials. Overall, the hybrid platform presents a technically feasible, environmentally sustainable, and scalable solution for decentralized water and air purification in urban and semi-urban settings.

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