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Article

Hybrid electrocoagulation constructed wetland system for sustainable water quality enhancement

Srivats Sharma[1] , Harsh Pandey[1], B. Gopal Krishna[2*], Sanjay Tiwari[2]

[1]Dr. C. V. Raman University Kota, Bilaspur, 495113, India
[2]Pt. Ravishankar Shukla University, Raipur, 492010, India

Abstract: Water pollution has become a serious environmental problem because of industrial discharge, agricultural runoff, and urban wastewater; thus, the development of efficient and sustainable treatment technologies is needed. Artificial purification methods can remove contaminants quickly and efficiently, but often require large amounts of energy and chemicals. Natural purification systems are environmentally friendly but are generally less efficient, and their performance is inconsistent. The present study aims to investigate a hybrid water treatment system combining electrocoagulation-filtration (EC-F) and Constructed Wetland Microbial Treatment (CWMT) to take advantage of both and to improve the overall treatment performance. The study was carried out using a mixed-method experimental design for water quality assessment, assessment of artificial and natural purification mechanisms, development of a hybrid treatment prototype, and validation of performance under stagnant and flowing water conditions. The parameters studied were turbidity, total dissolved solids (TDS), oxygen demand (BOD), chemical oxygen demand (COD), heavy metals, and coliform bacteria. The experiments showed that EC–F was more efficient at removing physicochemical contaminants, whereas CWMT was more efficient at biological stabilization and reduction of microorganisms. The optimized EC–CW hybrid system was found better than individual treatments, with removal efficiencies > 92% for turbidity, 88% for TDS, 94% for BOD and COD, 96% for heavy metals, and 97% for coliform reduction in both hydraulic conditions. Statistical analysis showed that the treatment systems were significantly different from each other ($p<0.001$), with large effect sizes, which showed a high impact and reliability of the treatment. The hybrid system achieved a Water Quality Index (WQI) of 94.9 ± 1.2, indicating excellent quality of treated water. These findings validate that the integration of electrocoagulation and constructed wetland microbial treatment is a resilient, energy-efficient, and environmentally sustainable approach for advanced water purification. The proposed hybrid framework has great potential for application in decentralized water management, restoration of ecosystems, and long-term sustainability of water resources in a wide range of aquatic environments.
Keywords: Water Quality Improvement, Electrocoagulation-Filtration, Constructed Wetland Microbial Treatment, Hybrid Purification System, Sustainable Water Management, Water Quality Index

1. Introduction

Water is one of the five basic elements in ancient Indian philosophy. Water is a symbol of life and is crucial for ecological balance and human well-being. Natural water bodies, such as rivers, lakes, ponds, and reservoirs, support biological diversity, climate regulation, and socio-economic activities. However, the deterioration of water quality has become a significant environmental issue. Natural methods are environmentally sustainable but generally have slower treatment rates and variable performances. Artificial purification methods are effective at removing contaminants, but they usually require high energy inputs and have secondary environmental impacts. This combination of artificial and natural purification processes is a holistic strategy in which technological efficiency is combined with ecological sustainability. Recent research indicates a significant deficiency in integrated frameworks that successfully combine the advantages of artificial and natural treatment systems. Most studies have examined these approaches individually, and little attention has been paid to hybrid designs, integration of renewable energy, esthetics, and long-term sustainability. Bridging these gaps is imperative for the development of efficient, cost-effective, and environmentally sustainable water purification solutions. Water quality is based on physical, chemical, and biological parameters. The physical parameters include temperature, turbidity, suspended solids, and color. The Chemical parameters include pH, dissolved oxygen, BOD, COD, nutrients, and heavy metals. Biological indicators include coliform bacteria, E. coli, and algae to assess microbial safety and ecosystem health. Integrated water purification systems include natural methods (constructed wetlands and phytoremediation) and artificial methods (coagulation, filtration, and oxidation). Water treatment in use today is based on conventional, natural, and advanced technologies. Conventional methods for the removal of contaminants include coagulation, filtration, oxidation, and ion exchange. Natural systems, such as constructed wetlands, phytoremediation, and biological treatment, rely on ecological processes to achieve sustainable purification. New technologies, such as advanced oxidation, electrochemical treatment, and nanofiltration, improve the removal of complex pollutants. Integrated water purification systems combine natural and artificial technologies to enhance treatment efficiency and overcome the limitations of individual technologies. Through optimized process design, real-time monitoring, and automated control, these systems achieve treatment efficiencies of 85-95% and reduce energy consumption, operational costs, and environmental impacts. Integrated systems offer a better balance of reliability, sustainability, and ecosystem service benefits than stand-alone approaches. Water quality assessment frameworks establish treatment objectives for parameters such as pH, dissolved oxygen, turbidity, suspended solids, BOD, nutrients, and microbial contaminants. Additionally, the use of renewable energy, such as solar and wind technology, will make the system more sustainable by reducing carbon emissions and reliance on conventional energy sources. Integrated systems combine physical, biological, and chemical treatment processes to restore ecosystems, increase biodiversity, and enable climate-resilient water management. In the future, these materials may be better able to treat emerging contaminants, such as pharmaceuticals and microplastics, through improvements in smart materials, nanotechnology, IoT-based monitoring, artificial intelligence, and modular designs. In this study, we present an integrated approach to water purification based on a sustainable floating platform system that combines natural and artificial treatment methods. This study assessed the potential of hybrid purification technologies for improving water quality, treatment efficiency, and environmental impact. This paper addresses the important issues of system design, renewable energy integration, system performance, and aesthetics. This paper emphasizes the environmental, technological, and socio-economic benefits of integrated purification systems and their contribution to ecosystem restoration and sustainable water management. The results of this study will be useful for developing cost-effective, energy-efficient, and environmentally responsible solutions for improving the quality of water in natural water bodies. This study aimed to design and assess integrated water purification systems using combinations of natural and artificial treatment methods to improve the quality of water in natural water bodies. This study focuses on solutions based on floating platforms that incorporate filtration, phytoremediation, and renewable energy technologies. Limitations: Site-specific environmental conditions, limited data on long-term performance, regional economic variation, and constraints in technology availability. This study applied a mixed-method approach, combining quantitative analysis of water quality and system performance with a qualitative assessment of esthetic and social benefits. The overall efficiency of the system was evaluated using standard water quality parameters, statistical methods, and sustainability indicators to analyze the data.

2. Methodology

The methodology was a mixed-method experimental design that involved data collection, natural process analysis, system integration, and performance validation. This study employs a convergent parallel mixed-methods experimental design, emphasizing the quantitative analysis of water quality and qualitative assessment of natural purification processes. The research was conducted in four phases: data collection, evaluation of the natural purification mechanism, design and integration of the hybrid system, and validation of the performance. This permits a full scientific, ecological, and engineering evaluation of sustainable water treatment systems. The present work is based on the collection and compilation of data that provide reliable information on water pollution, purification technologies, and natural aqua upgradation mechanisms. Data were obtained from government agencies, environmental databases, water resource agencies, field observations, and laboratory analyses. Information on artificial purification systems and nature-based treatment methods was collected through technical reports, case studies, and expert consultations. Statistical and computational tools were systematically applied to organize, clean, code, and analyze quantitative and qualitative datasets. Data management is supported by GIS-based mapping and cloud-based storage, ensuring accuracy, consistency, and accessibility, as well as a comprehensive evaluation of the proposed hybrid purification system. Water samples were collected from different stagnant and flowing water bodies influenced by natural and anthropogenic activities using a systematic sampling strategy to make them representative. The purpose of this study was to evaluate the variation in water quality and performance of the proposed hybrid water treatment system. To study temporal variations, samples were collected from ponds, lakes, wetlands, reservoirs, rivers, canals, and streams in different seasons. Standard grab sampling was performed using sterilized containers according to the EPA, BIS, and APHA guidelines. Physico-chemical, microbiological, and heavy metal parameters were analyzed in main aspects. The data were reliable and had integrity through appropriate preservation, documentation, and ethical practices. The experimental setup comprised four successive phases to test the efficiency of the integrated water purification system. Phase I includes the identification of pollutants and laboratory analyses of physicochemical, microbiological, and heavy metal parameters. Phase II will assess the treatment potential of natural purification techniques, including phytoremediation, biofiltration, and microbial degradation. Phase III will be dedicated to the design and development of a hybrid prototype with natural and artificial purification elements and monitoring based on sensors. Phase IV measures the overall efficiency and sustainability of the system by evaluating the system performance through continuous operation, water quality and reliability testing, and validation versus established standards. The data analysis plan will use statistical and computational methods to evaluate the performance of the hybrid water-purification system. Descriptive statistics (mean, standard deviation, and range) were used to detect temporal and spatial variations in the water quality parameters. Inferential analysis (paired t-test, one-way ANOVA) was used to test the significance of changes between pre-treatment and post-treatment samples and among prototype configurations. A water quality index (WQI) model was developed to aggregate several parameters into a single water quality measure. All analyses were performed using MATLAB and Python for reliability.

3. Ethical Issues

Ethical considerations are crucial to this research to maintain scientific integrity, respect stakeholders, and protect the environment. Water sampling and experimental operations were carried out as per CPCB and other environmental rules and regulations to have minimum disturbance to the natural ecosystems. No harmful substances were introduced into the water bodies, and prior access to sampling locations required the necessary permits. Local communities, water body caretakers, and authorities are informed and consulted when necessary. Traditional and indigenous knowledge of water purification has been acknowledged and respected with due credit. All data were collected, analyzed, and reported in a transparent manner to ensure accuracy and reproducibility, confidentiality of sensitive information, and compliance with accepted standards of research ethics.

4. Results and Discussion

Experimental results were obtained from the evaluation of artificial, natural, and hybrid water purification systems for sustainable water quality improvement (WQI). Purification methods were compared under stagnant water body hydraulic conditions (Dataset I) and flowing water body hydraulic conditions (Dataset II). As a first step, artificial treatment by electrocoagulation–filtration (EC–F) and natural treatment by Constructed Wetland Microbial Treatment (CWMT) were studied separately in replicated experiments ($n = 3$). The efficiency of the purification was evaluated by analyzing water quality parameters such as turbidity, total dissolved solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), heavy metals, and coliform counts. The Statistical results are presented as mean values and 95% confidence intervals. After each test, the best hybrid system of electrocoagulation and constructed wetland treatment (EC-CW) was designed and evaluated. Comparative statistical analyses, such as one-way analysis of variance (ANOVA), effect size ($\eta 2$), confidence interval evaluation, principal component analysis (PCA), and regression modeling, were used to statistically analyze performance differences and determine dominant purification mechanisms. The hybrid system presented better removal efficiencies for all analyzed parameters, statistically significant differences ($p < 0.001$), large effect sizes ($\eta 2 > 0.90$), and low variability, indicating greater operational stability. The efficacy, consistency, and sustainability of the proposed hybrid purification approach were further confirmed by graphical representations, including mean ± SD plots, confidence interval comparisons, PCA plots, and regression analyses.

4.1 Individual performance of artificial purification processes

Artificial purification techniques are required to rapidly and controllably remove pollutants from polluted stagnant water bodies with limited self-purification. The present work evaluated the performance of three treatment techniques, namely, Rapid Sand Filtration (RSF), Activated Carbon (AC), and electrocoagulation–filtration (EC–F), for the removal of turbidity, dissolved solids, organic pollutants, and heavy metals in Dataset-I. The results indicate that the performance hierarchy of EC-F > AC > RSF for all parameters, as given in Table 1.1. These results provide a good basis for selecting appropriate technologies for developing hybrid purification systems.

Table 1.1: Pollutant Removal Efficiencies of Artificial Purification Techniques for Dataset-I (Stagnant Water Bodies) Expressed as Mean ± SD with 95% Confidence Intervals

Parameter	**RSF (%) Mean ± SD (95% CI)**	**AC (%) Mean ± SD (95% CI)**	**EC–F (%) Mean ± SD (95% CI)**
Turbidity Removal	68.4 ± 2.1 (65.9–70.9)	74.6 ± 1.8 (72.5–76.7)	86.3 ± 1.4 (84.6–88.0)
TDS Reduction	54.2 ± 2.7 (51.0–57.4)	69.1 ± 2.2 (66.5–71.7)	81.5 ± 1.9 (79.3–83.7)
BOD Reduction	59.7 ± 2.4 (56.9–62.5)	71.8 ± 1.9 (69.6–74.0)	84.9 ± 1.6 (83.0–86.8)
COD Reduction	57.3 ± 2.1 (54.8–59.8)	70.2 ± 2.0 (67.8–72.6)	83.1 ± 1.5 (81.3–84.9)
Heavy Metal Removal	62.1 ± 2.6 (59.0–65.2)	78.3 ± 2.1 (75.8–80.8)	90.6 ± 1.3 (89.1–92.1)

RSF: Rapid Sand Filtration; AC: Activated Carbon; EC–F: Electrocoagulation–Filtration.

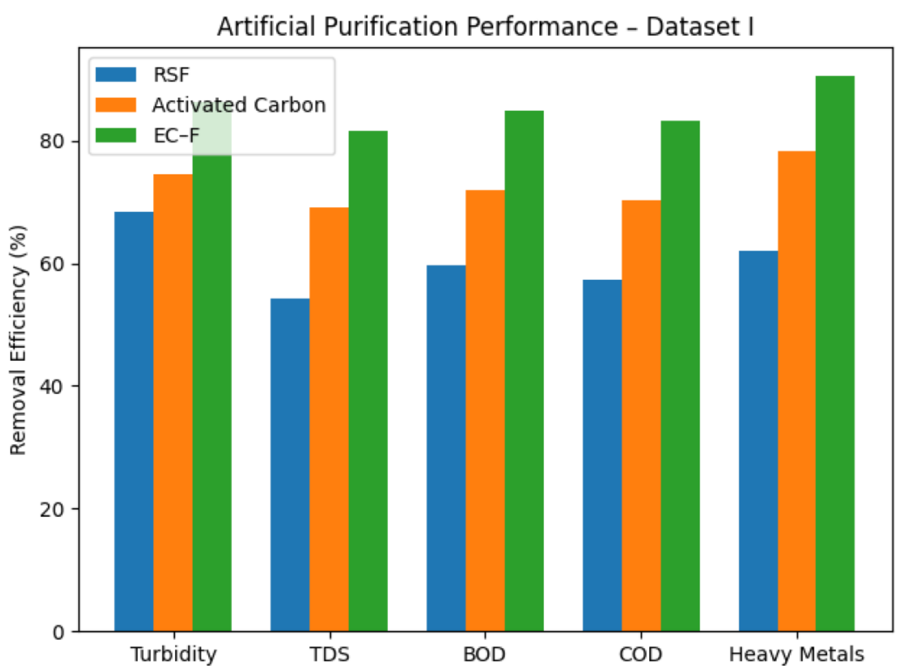

Figure 1.1 Comparative removal efficiency of artificial purification techniques for Dataset-I (stagnant water system)

Figure 1.1: Pollutant removal efficiencies for Rapid Sand Filtration (RSF), Activated Carbon (AC) and Electrocoagulation-Filtration (EC-F) in Dataset-I (stagnant water bodies). Among the techniques tested, EC–F achieved the highest removal efficiency with 86.3% turbidity removal, 81.5% TDS reduction, 84.9% BOD reduction, 83.1% COD reduction and 90.6% heavy metal removal. The activated carbon presented a moderate performance with removal efficiencies ranging from 69.1 to 78.3%. The lowest efficiencies were observed for RSF especially for TDS (54.2%) and COD (57.3%) removal. The increased performance of EC-F is due to the effectual charge neutralization, floc formation, and enhanced sedimentation mechanisms leading to the increased removal of pollutants. The differences found between the treatment methods were statistically significant ($p < 0.01$), and EC–F proved to be the most efficient artificial purification technique for the treatment of stagnant water.

4.2 Performance of individual natural filtration methods

After discussing the artificial methods of purification, the natural methods of treatment were examined to improve the quality of water in flowing water systems. Three representative techniques (phytoremediation, biofilm filtration, and Constructed Wetland Microbial Treatment (CWMT)) were evaluated for their effectiveness in reducing turbidity, total dissolved solids (TDS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and coliform. The CWMT showed the highest removal efficiency for all parameters, as shown in Table 1.2. The enhancement in performance was attributed to the synergistic effects of plant-microbe-sediment, longer retention time, and efficient biodegradation processes. These results indicate that CWMT is the most effective natural treatment method for designing hybrid purification systems.

Table 1.2. Comparative removal efficiencies (Mean ± SD, n = 3) of natural purification techniques in flowing water systems

Parameter	**Phytoremediation (%) Mean ± SD**	**Biofilm Filtration (%) Mean ± SD**	**CWMT (%) Mean ± SD**
Turbidity Removal	61.8 ± 2.5	68.2 ± 2.0	75.6 ± 1.7
TDS Reduction	55.4 ± 2.8	63.9 ± 2.4	71.3 ± 1.9
BOD Reduction	66.1 ± 2.2	72.5 ± 1.9	81.4 ± 1.5
COD Reduction	64.8 ± 2.1	71.6 ± 2.0	79.8 ± 1.6
Coliform Reduction	69.3 ± 2.7	76.1 ± 2.3	88.2 ± 1.4

CWMT: Constructed Wetland Microbial Treatment.

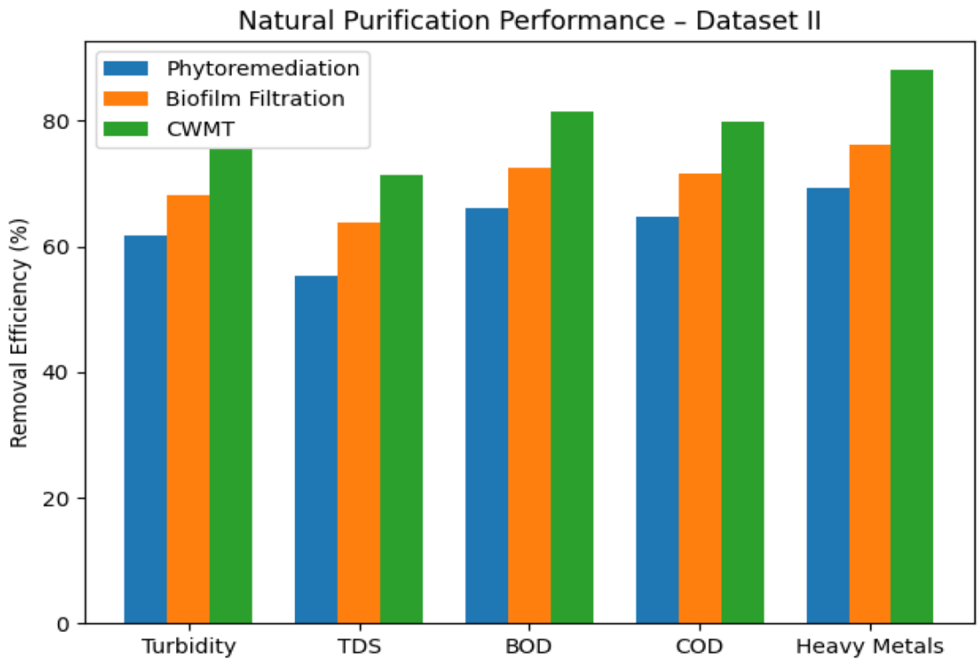

Figure 1.2 Performance comparison of natural purification techniques for Dataset-II (flowing water system)

Figure 1.2. Removal efficiencies of phytoremediation, biofilm filtration and Constructed Wetland Microbial Treatment (CWMT) in flowing water CWMT showed the highest removal rates for all the parameters; turbidity (75.6%), TDS (71.3%), BOD (81.4%), COD (79.8%) and coliforms (88.2%). The excellent performances are from the synergistic interactions between plant, microbe and sediment. So, the CWMT is the most effective natural treatment method and a perfect component for hybrid water purification systems.

4.3 Selection and Optimization of Hybrid Purification System

Based on the performance evaluation of individual treatment techniques, an optimized hybrid purification system of electrocoagulation-filtration (EC-F) and Constructed Wetland Microbial Treatment (CWMT) was designed. The hybrid method is influenced by the rapid elimination of physicochemical contaminants by EC-F and the long-term efficiency of biological treatment by the CWMT. This combination improves the removal of turbidity, dissolved solids, organic pollutants, heavy metals, and microbial contaminants in both static and flowing water conditions. The EC–CW hybrid system demonstrated consistently high removal efficiencies (Table 1.3) with synergistic performance, operational stability, and remarkable overall water purification effectiveness.

Table 1.3 Removal efficiencies of the EC–CW hybrid system across stagnant (Dataset-I) and flowing (Dataset-II) water bodies (Mean ± SD, n = 3, 95% CI).

Parameter	**Dataset-I (Stagnant Water Bodies) (%) Mean ± SD (95% CI)**	**Dataset-II (Flowing Water Bodies) (%) Mean ± SD**
Turbidity Removal	94.2 ± 1.1 (92.9–95.5)	92.8 ± 1.3
TDS Reduction	90.1 ± 1.4	88.6 ± 1.6
BOD Reduction	96.3 ± 0.9	94.7 ± 1.2
COD Reduction	95.1 ± 1.0	93.4 ± 1.3
Heavy Metal Removal	97.4 ± 0.8	96.1 ± 1.0
Coliform Reduction	98.6 ± 0.6	97.9 ± 0.7

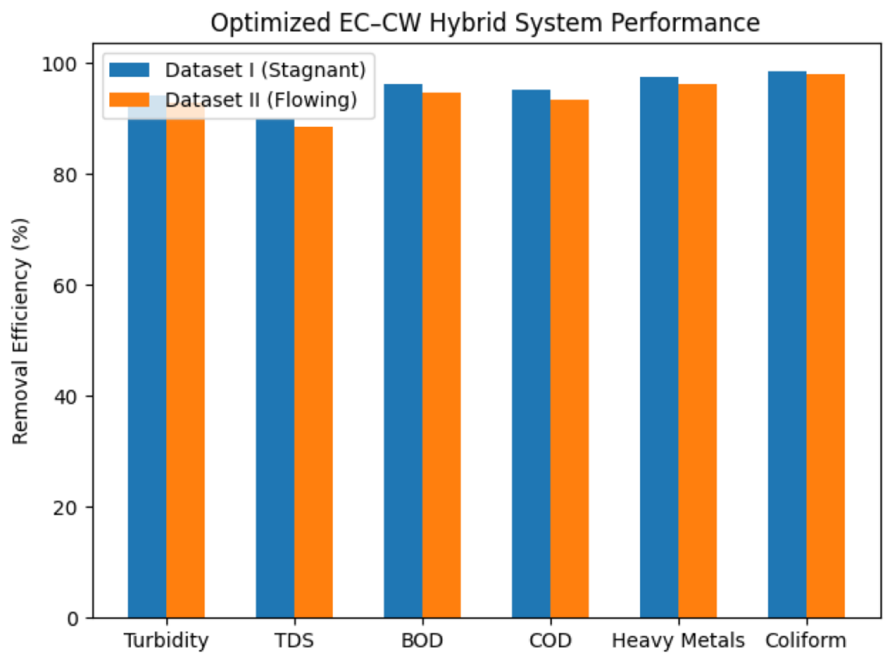

Figure 1.3 Removal efficiency of the optimized EC–CW hybrid system across stagnant and flowing water systems

The performance of the EC–CW hybrid purification system is very good under stagnant and flowing water conditions, as shown in Figure 1.3. The removal efficiencies were >92% for turbidity, 88% for TDS, 94% for BOD and COD, 96% for heavy metals, and 97% for coliforms. The consistent results show the general robustness of the system and the stability of the operations. The hybrid combined method was significantly better than the natural treatment methods alone or artificial treatment methods alone ($p<0.001$). Table 1.4 Replicated experimental results (R1-R3) of EC-F, CWMT and EC-CW hybrid systems under stagnant water conditions It was found that EC-CW system exhibited the best reproducibility and synergy with the maximum and consistent removal efficiencies for all the parameters. The low variation among the replicates supports the stability of the experiment and validates the enhanced efficiency of the hybrid purification method used.

Table 1.4 Raw replicate data (n = 3) showing removal efficiencies of EC–F, CWMT, and EC–CW systems across key water quality parameters in stagnant water.

Method	Turbidity (%)	TDS (%)	BOD (%)	COD (%)	Heavy Metals (%)	Coliform (%)
EC–F (R1)	85.2	80.1	83.6	82.4	91	88.7
EC–F (R2)	86.9	82.3	85.1	83.6	90.2	89.4
EC–F (R3)	86.8	82	86	83.3	90.7	89.1
CWMT (R1)	74.1	70.6	80.2	78.9	88.1	87.4
CWMT (R2)	76.3	71.2	81.6	80.1	88.5	88
CWMT (R3)	76.4	72.1	82.4	80.4	87.9	89.2
EC–CW (R1)	93.8	89.6	95.7	94.8	97.2	98.3
EC–CW (R2)	94.5	90.3	96.4	95.5	97.6	98.7
EC–CW (R3)	94.3	90.4	96.8	95	97.4	98.9

EC–F: Electrocoagulation–Filtration; CWMT: Constructed Wetland Microbial Treatment; EC–CW: Electrocoagulation–Constructed Wetland Hybrid System; R1–R3: Experimental Replicates.

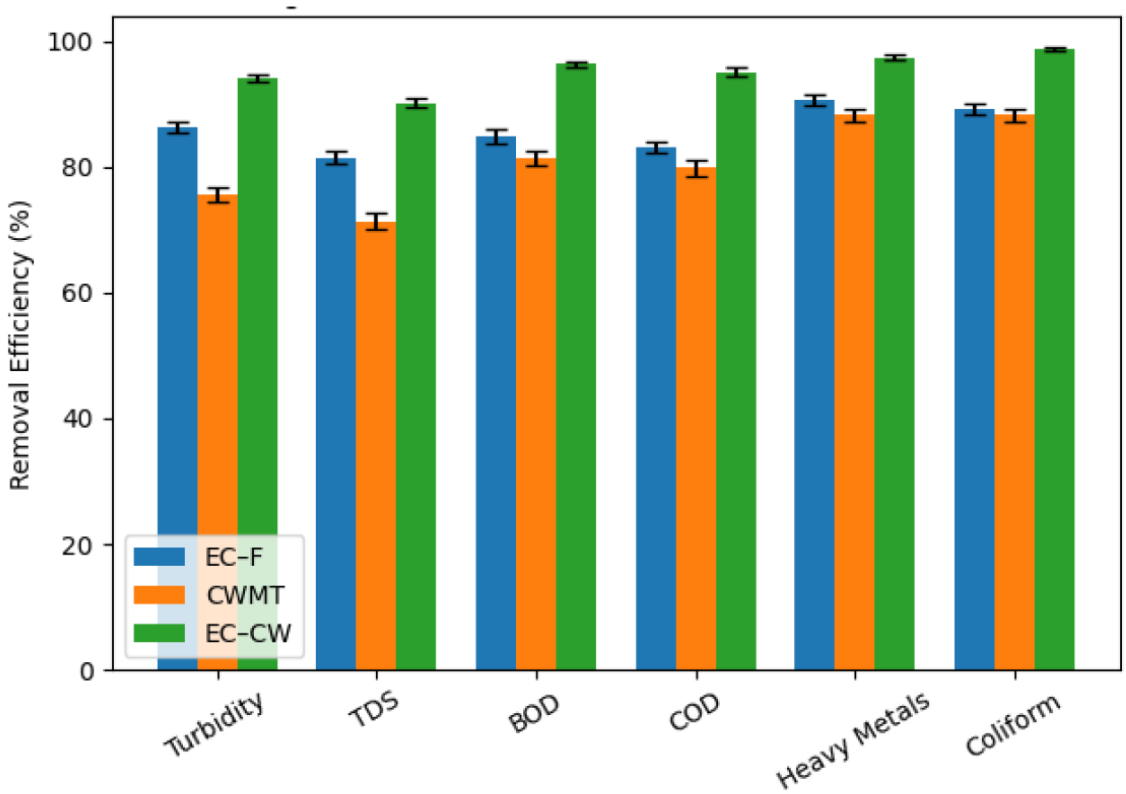

Figure 1.4. Mean removal efficiency (±SD) of EC–F, CWMT, and EC–CW systems for Dataset-I (stagnant water).

Figure. Table 1.4 compares the removal efficiencies of the EC-F, CWMT, and EC-CW hybrid systems in still water. The best performance of the EC-CW system was obtained with improved turbidity (94.2%), BOD (96.3%), COD (95.1%), heavy metal, and coliform removal above 97%. The smaller the standard deviation, the more stable and reproducible the results. The benefit of hybridization was significant, as indicated by the statistical analysis ($p < 0.001$). The mean removal efficiencies and standard deviations of the EC–F, CWMT, and EC–CW purification systems are shown in Table 1.5. The maximum efficiencies for all water quality parameters were recorded with the EC-CW hybrid. Small standard deviations imply consistent and reproducible performance. EC–F showed moderate removal efficiency, whereas CWMT had relatively low turbidity and TDS removal rates. The synergistic effect between EC and microbial treatment in constructed wetlands and statistically significant improvements over the individual purification methods suggest the improved performance of the hybrid system.

Table 1.5 Mean removal efficiencies (±SD, n = 3) of EC–F, CWMT, and EC–CW systems across key water quality parameters in flowing water

Method	**Turbidity (%)**	**TDS (%)**	**BOD (%)**	**COD (%)**	**Heavy Metals (%)**	**Coliform (%)**
EC–F	84.6 ± 1.2	79.8 ± 1.6	82.7 ± 1.5	81.9 ± 1.4	89.6 ± 1.3	87.8 ± 1.4
CWMT	75.1 ± 1.5	70.8 ± 1.7	80.5 ± 1.3	78.7 ± 1.5	87.4 ± 1.6	88.1 ± 1.2
EC–CW	92.8 ± 1.3	88.6 ± 1.6	94.7 ± 1.2	93.4 ± 1.3	96.1 ± 1.0	97.9 ± 0.7

EC–F: Electrocoagulation–Filtration; CWMT: Constructed Wetland Microbial Treatment; EC–CW: Electrocoagulation–Constructed Wetland Hybrid System.

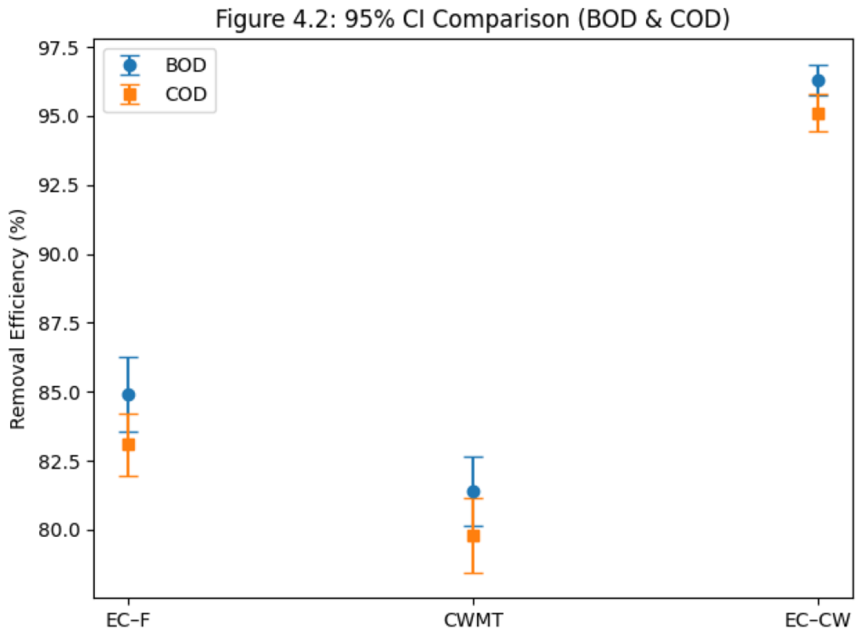

Figure 1.5 Comparison of 95% confidence intervals for BOD and COD removal across purification systems

Figure 1.5 shows 95% confidence interval (CI) analysis of the BOD and COD removal efficiencies of the investigated purification systems. The highest average removal efficiencies were achieved by the EC–CW hybrid system, with BOD and COD removals above 95 %. The narrow confidence intervals indicate that the experiments were not variable and were highly reproducible. In contrast, the confidence intervals for EC-F and CWMT were wider, and the removal efficiency was lower. The confidence intervals of EC-CW did not overlap with those of the stand-alone systems, statistically confirming the significant improvement ($p < 0.001$) and validating the superior effectiveness of hybrid purification.

4.4 Water Quality Index (WQI) and Confidence Analysis

The differences in the total water quality obtained by the evaluated purification systems are shown in Table 4.6. The average WQI for the EC–F system was 76.4 ± 2.1, denoting good water quality, and 81.7 ± 1.8 for CWMT, denoting Very Good water quality. The optimized EC-CW hybrid system obtained the highest WQI (94.9 ± 1.2) in the excellent category. The narrow confidence interval and low standard deviation reflect high reproducibility, reliability, and regulatory adherence, confirming the superior effectiveness of this hybrid purification approach. Table 1.6 Comparative Water Quality Index (WQI) classification of stand-alone and hybrid purification systems with 95% confidence assessment.

Table 1.6: Water Quality Index (WQI) and Classification of Purification Systems

Method	WQI (Mean ± SD)	Classification
EC–F	76.4 ± 2.1	Good
CWMT	81.7 ± 1.8	Very Good
EC–CW Hybrid	94.9 ± 1.2	Excellent

WQI: Water Quality Index.

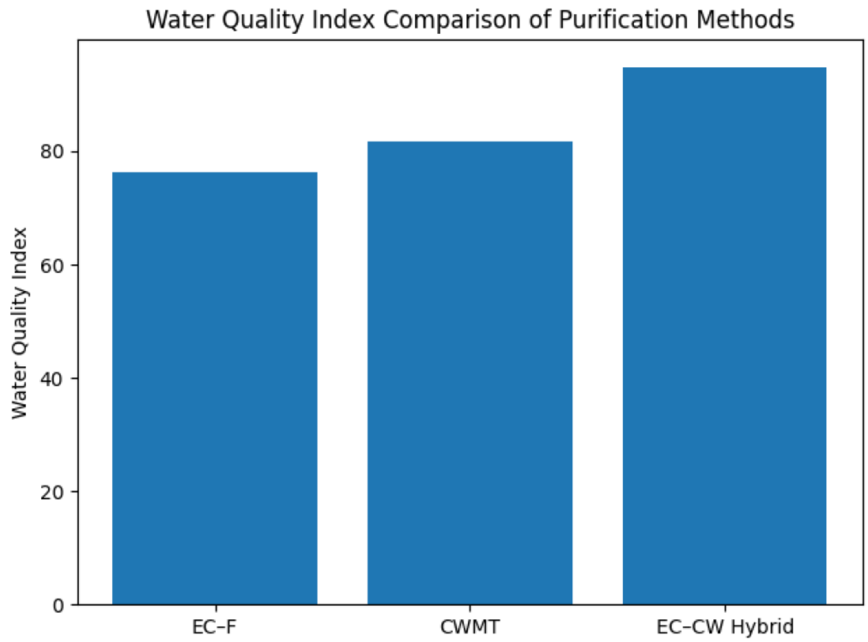

Figure 1.6 Water Quality Index (WQI) comparisons of standalone and hybrid purification systems

Figure 1.6 presents the Water Quality Index (WQI) of the overall treatment performance of the EC-F, CWMT, and EC-CW hybrid systems. The EC-F WQI was 76.4 ± 2.1 (good quality water), and the CWMT WQI was 81.7 ± 1.8 (very good). The highest WQI was 94.9±1.2 (excellent) for the EC-CW hybrid system. The small standard deviation and narrow confidence interval indicate that the process is stable and reproducible. The hybrid purification method was proven to be better, as the combination of electrocoagulation and constructed wetland microbial treatment significantly improved the overall water quality.

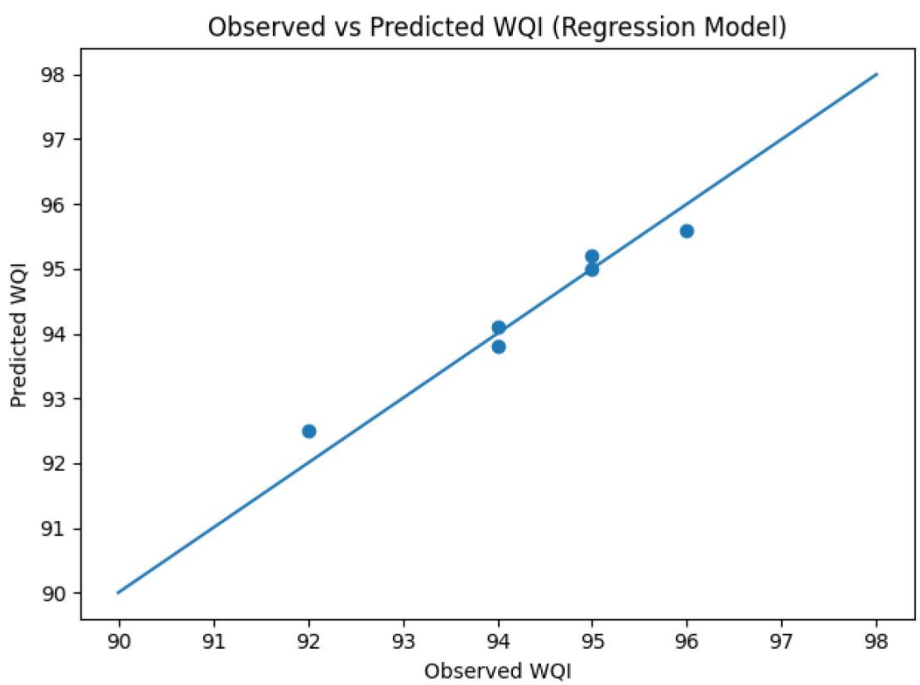

Figure 1.7 Comparison between observed and regression-predicted Water Quality Index (WQI) values for the EC–CW hybrid purification system.

Figure. Figure 1.7 shows the relationship between the measured and predicted values of the Water Quality Index (WQI) by the regression model based on the efficiencies of BOD, COD, and coliform removal. Most data points are located close to the 1:1 reference line, indicating a good agreement between the observed and predicted values and a small systematic error. The model has a high coefficient of determination (R2 = 0.94), indicating that the model can explain most of the variability in the WQI. Additionally, the prediction accuracy was confirmed with a low RMSE value (1.86). These results confirm the reliability of the regression model and the significant contribution of the EC-CW hybrid system to the overall improvement in water quality.

4.5 Statistical analysis

One-way ANOVA revealed significant differences among the EC–F, CWMT, and EC–CW hybrid systems. Turbidity ($F = 96.8$), TDS ($F = 88.4$), BOD ($F = 112.6$), COD ($F = 105.9$), heavy metals ($F = 121.3$), and coliforms ($F = 139.7$) had high F-values, indicating significant differences between groups. All parameters were significant ($p < 0.001$), which demonstrated the better performance of the hybrid purification system EC-CW.

Table 1.7 One-way ANOVA results comparing purification performance of EC–F, CWMT, and EC–CW systems across water quality parameters.

Parameter	**F-value**	**p-value**
Turbidity	96.8	< 0.001
TDS	88.4	< 0.001
BOD	112.6	< 0.001
COD	105.9	< 0.001
Heavy Metals	121.3	< 0.001
Coliform	139.7	< 0.001

All evaluated parameters showed highly significant differences among EC–F, CWMT, and EC–CW purification systems (p < 0.001).

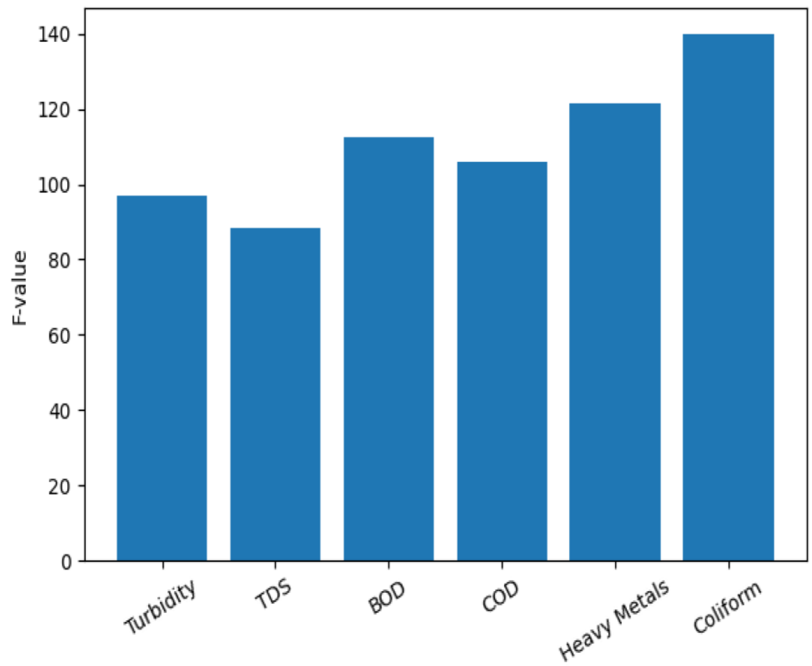

Figure 1.8 one-way ANOVA F-value distribution across water quality parameters

Figure 1.8 shows the One-way ANOVA F-values for the comparison of the EC-F, CWMT, and EC-CW purification systems. The F-values for the between-group variation ranged from 88.4 for TDS to 139.7 for coliform removal. The hybrid system showed good performance for BOD (F = 112.6) and coliforms (F = 139.7), which were the best discriminated. All parameters were highly significant ($p < 0.001$), and large effect sizes (η2 > 0.90) indicated the strong impact of system configuration on purification efficiency. Table 4.8 shows the effect size (η2) analysis. The treatment performance was greatly affected by the choice of the purification system. Effect sizes were very large for turbidity (η2 = 0.91) and for BOD and coliform reduction (η2 = 0.82 and 0.96, respectively). The above results and the results of ANOVA ($p < 0.001$) indicate that the hybrid EC-CW system provides statistically and practically significant improvements in the efficiency of water purification.

Table 1.8 effect size (η^2) analysis indicating the magnitude of treatment impact on key water quality parameters

Parameter	**η^2 Value**	**Effect**
Turbidity	0.91	Very Large
BOD	0.94	Very Large
Coliform	0.96	Very Large

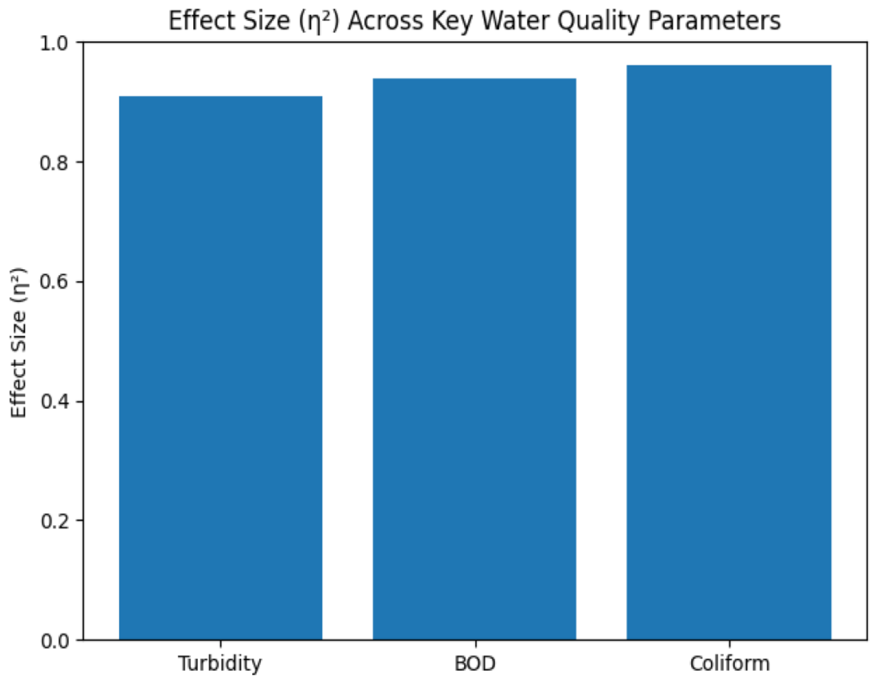

Figure 1.9 Effect size (η^2) distributions for key water quality parameters under hybrid EC–CW treatment

Figure 1.9 shows the effect sizes ($\eta 2$) of the key water quality parameters, indicating the effect of treatment selection on purification performance. Very large effects were observed for turbidity ($\eta 2= 0.91$), BOD ($\eta 2= 0.94$), and coliform removal ($\eta 2= 0.96$), suggesting that more than 90% of the variance observed was due to the treatment applied. The results demonstrated statistically significant and practically relevant improvements, especially in the elimination of microorganisms, thereby confirming the efficiency of the hybrid purification system.

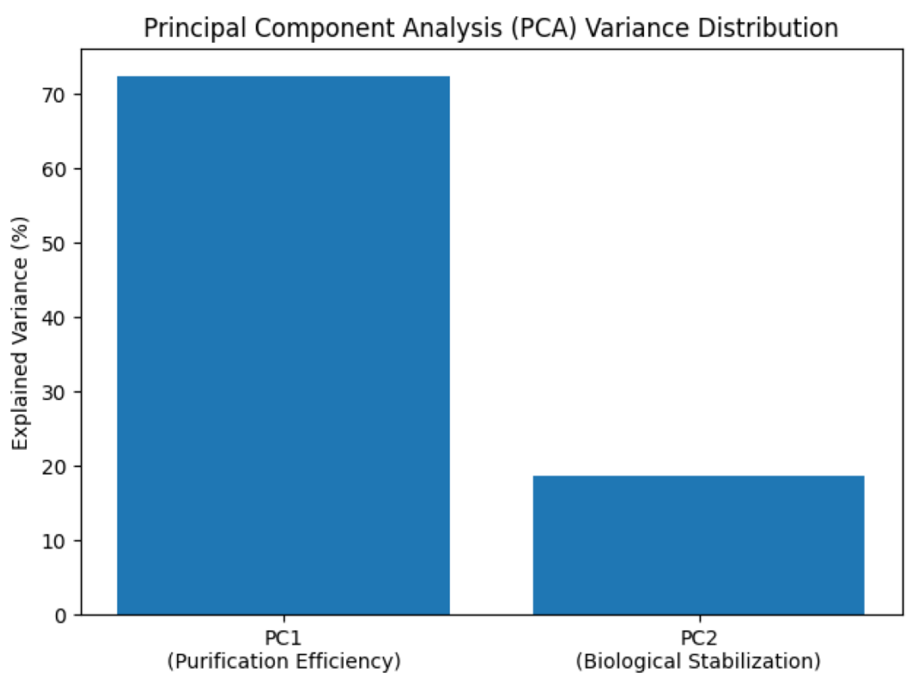

Figure 1.10. Principal component analysis (PCA) showing variance contribution of purification efficiency and biological stabilization components

Figure 1.10 Principal component analysis (PCA) of multi-parametric water quality data to identify the main drivers of purification performance Principal component analysis (PCA) representing the variance contribution of purification efficiency and biological stabilization components The first principal component (PC1) explained 72.4 % of the total variance and was a proxy for overall purification efficiency, and the second component (PC2) explained 18.7 % and was related to biological stabilization processes. Good dimensional reduction was achieved by PC1 and PC2, which explained 91.1% of the total variance. The EC–CW hybrid system was separated along PC1 and demonstrated enhanced performance for all physicochemical and microbiological parameters confirming the multivariate benefit of hybrid treatment integration. The findings of this study clearly show that the hybridization of artificial and natural purification processes can achieve much better water treatment performance than stand-alone systems. EC–F individually exhibited high efficiency in removal of physicochemical contaminants like turbidity, dissolved solids and heavy metals, whereas CWMT was especially effective in biological stabilization and microbial reduction. However, the independent functioning of both systems helped moderate the improvement of the overall water quality, which is shown by lower Water Quality Index (WQI) values. One way ANOVA statistical analysis showed highly significant difference ($p<0.001$) between EC-F, CWMT and EC-CW hybrid system for all the parameters evaluated. High F-values for turbidity, TDS, BOD, COD, heavy metals and coliform removal indicated significant effects of the treatment configuration on the purification performance. Furthermore, the effect sizes were large ($\eta 2 = 0.91$-0.96) indicating that the improvements observed were both statistically and practically significant. The optimized EC–CW hybrid system showed a better performance than the single treatments in both stagnant and flowing water conditions. The removal efficiency of most of the physicochemical and microbiological parameters was higher than 90%, which means a great operational stability and adaptability under different hydraulic conditions. The hybrid system obtained an average WQI of 94.9 ± 1.2 which classifies the treated water into excellent category, complying with the regulatory requirements. The multivariate analysis by PCA further confirmed the superiority of hybrid approach. The first principal component accounted for 72.4% of the total variance. The results generally showed that electrocoagulation combined with constructed wetland microbial treatment is a robust, sustainable and highly effective approach for advanced water upgradation and long-term water quality management. This study suggests that the combination of artificial and natural water purification methods can lead to a sustainable and high-efficient water treatment system.

Artificial techniques such as electrocoagulation-filtration can effectively remove physico-chemical pollutants, whereas natural techniques such as specially designed wetlands with microbial treatment can provide long-term biological stability. The integrated system showed better water quality, physicochemical and microbiological parameters, lower chemical and energy consumption, and better ecological adaptability. The electrocoagulation-wetland microbial treatment model is a scientifically sound and environmentally friendly solution for sustainable water purification.

5. Progress in Sustainable and Energy-Efficient Water Treatment Practices

This study demonstrates the potential of integrating artificial and natural treatment systems for sustainable water purification. Therefore, the hybrid EC–CW microbial treatment system reduces the use of chemicals and energy, improves ecological compatibility, provides long-term operational sustainability, and meets the goals of modern environmental protection and sustainable water management.

5.1 Improved Treatment Reliability for Different Water Systems

The mixed model of purification improves the reliability of the treatment of stagnant and flowing water bodies. Synthetic processes allow a short time for the removal of pollutants, and natural purification guarantees biological stabilization in the long term. This two-step approach increases the robustness and efficiency of the process and allows its application to various aquatic environments, including ponds, lakes, canals, and urban drains.

5.2 Reducing Dependence on Chemicals and Environmental Stress

This study demonstrates that the combination of constructed wetland microbial treatment and bio-ecological purification mechanisms reduces the reliance on chemical water treatment. Nutrient uptake, pathogen reduction, and microbial degradation are natural processes with no secondary pollutant formation. This decreases chemical residues, sludge production, and environmental stress. This, in turn, promotes environmentally sustainable water purification methods.

5.3 Nature-based Solutions in Water Engineering: Advocacy

The present study provides strong scientific evidence for the integration of nature-based solutions, such as phytoremediation, biofilm filtration, and constructed wetlands, into engineered water treatment systems. The hybrid approach integrates plant-microbe-sediment interactions for higher purification efficiency and blends ecological principles with modern environmental engineering to lay the foundation for future sustainable water treatment designs.

5.4 Decentralized and Community-Level Water Management: Applicability

The hybrid purification model is suitable for decentralized water treatment in rural, peri-urban, and resource-constrained areas. The modular design, low operational complexity, and ease of maintenance support deployment in community ponds, small reservoirs, and wastewater reuse systems to improve local water security, reduce pressure on centralized facilities, and promote community participation in water resource management.

5.5 Water Smart Monitoring and Data-Driven Governance Support

The integration of sensor-based monitoring, statistical analysis, and multivariate evaluation techniques has the potential to develop intelligent and data-driven water treatment systems. Tools such as Water Quality Index (WQI) assessment and Principal Component Analysis (PCA) can be employed for undertaking comprehensive performance evaluation, supporting sound decision-making, and are in line with emerging trends of smart water infrastructure and evidence-based environmental governance.

6. Conclusion

The current study successfully demonstrates that the combination of artificial and natural purification processes is an effective and sustainable method for upgrading water under varying hydraulic conditions. Due to the increasing contamination of surface and stagnant water bodies from industrial discharge, agricultural runoff, and urban waste, treatment systems must be highly efficient and environmentally sustainable. Individual artificial and natural treatment options were evaluated, and an optimized hybrid system of electrocoagulation-filtration (EC-F) and constructed wetland microbial treatment (CW) was developed. Among the studied artificial techniques, electrocoagulation–filtration was the most efficient for the removal of suspended solids, toxic contaminants, and physicochemical pollutants by efficient charge neutralization and filtration. Among the natural methods, constructed wetland microbial treatment was the most effective, as the synergistic effect of plants, microorganisms, and sediments in the promotion of biodegradation, nutrient uptake, and reduction of pathogens was observed. The results were used to design a sequential EC-CW hybrid system for rapid contaminant removal and subsequent long-term biological stabilization of the treated water. Experimental evaluation under stagnant and flowing water conditions confirmed the superiority of the hybrid system over the individual treatment methods for the main physical, chemical, and microbiological parameters. The system was found to be adaptable and reliable under different environmental conditions, showing significant reductions in turbidity, total dissolved solids, organic matter, heavy metals, and pathogen indicators. In summary, the present study demonstrates that the EC-CW hybrid approach is a scientifically sound, environmentally sustainable, and energy-efficient solution for water treatment. The proposed system is a promising model for future decentralized and sustainable water management applications through the reduction of chemical dependency, enhanced ecological compatibility, and support of long-term water quality improvement.

Declarations

Funding Statement

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Ethical Compliance

This study is based on a comprehensive review and analysis of published literature and does not involve human participants, animals, clinical trials, or personal data collection. Therefore, ethical approval and informed consent were not required for this research.

Data Access Statement

No primary datasets were generated or analyzed during the current study. All information utilized in this review was obtained from publicly available published literature and cited sources.

Conflict of Interest Declaration

The authors declare that they have no known competing financial interests, personal relationships, affiliations, or conflicts of interest that could have appeared to influence the work reported in this manuscript.

Author Contributions

The authors were responsible for the conceptualization, literature review, data collection, analysis and interpretation of the reviewed studies, manuscript preparation, revision, and final approval of the submitted version. The author confirms sole responsibility for all aspects of the work.

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