# A Phytoremediation Approach Using *Chrysopogon zizanioides* and *Eichhornia crassipes* for Water Quality Restoration in Tiruchirappalli District, India

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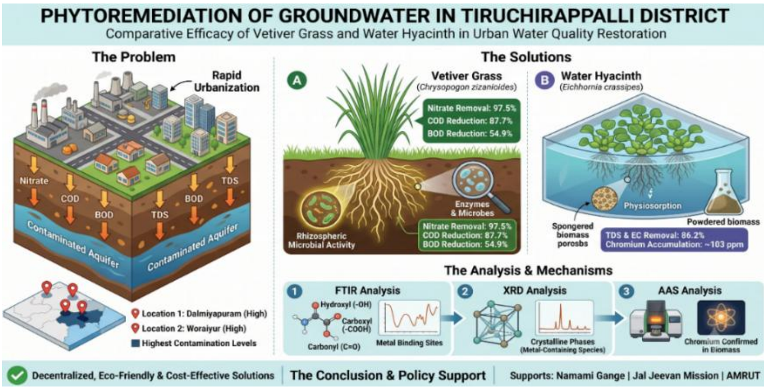
**Abstract**
Groundwater contamination has emerged as a critical environmental and public health concern in rapidly urbanizing regions of India. This study investigates the effectiveness of two plant based remediation systems, *Chrysopogon zizanioides* (Vetiver grass) and *Eichhornia crassipes* (Water hyacinth), for improving water quality in Tiruchirappalli district, Tamil Nadu. Groundwater samples collected from four locations were analyzed for physicochemical parameters, with Dalmiyapuram and Woraiyur exhibiting the highest contamination levels. Vetiver treatment demonstrated significant reductions in nitrate (97.5%), COD (87.7%), and BOD (54.9%), while Water hyacinth powder achieved exceptional TDS and EC removal (up to 86.2%). FTIR analysis confirmed the presence of carboxyl and carbonyl functional groups responsible for metal binding, while XRD revealed crystalline phases associated with metal containing species. AAS analysis confirmed chromium accumulation (approximately 103 ppm) in the biomass. The Exhausted Water hyacinth biomass with adsorbed heavy metals was safely disposed via controlled landfilling, preventing secondary contamination and completing the sustainable cycle. The study demonstrates that Vetiver excels at biological degradation of organic pollutants through rhizospheric microbial activity, while Water hyacinth functions as an effective physicochemical biosorbent. Both approaches offer cost effective, eco-friendly, and sustainable solutions for decentralized water purification, supporting government initiatives such as Namami Gange, Jal Jeevan Mission, and AMRUT.

**Keywords:** Phytoremediation, Vetiver grass, Water hyacinth, Groundwater quality, Biosorption, Sustainable water treatment.




## 1. Introduction

Water is one of the most essential natural resources for life and plays an important role in human survival, agriculture, industries, and maintaining ecological balance. Water bodies such as rivers, lakes, ponds, and groundwater are the main sources of freshwater used for drinking, farming, and domestic purposes. Nearly 70% of the Earth's surface is covered by water, but only 2.5% is freshwater, and less than 1% is directly available for human use. In India, groundwater provides nearly 85% of drinking water in rural areas and supports more than 60% of irrigation needs. However, water pollution has become a serious global and national issue. According to environmental studies, nearly 80% of wastewater generated worldwide is released into the environment without proper treatment, causing severe contamination of water bodies. In India, reports from pollution monitoring agencies have shown that more than 300 river stretches remain polluted, while a large percentage of groundwater sources are affected by excess nitrates, dissolved salts, and heavy metal contamination. Increasing industrial growth, rapid urbanization, population increase, agricultural chemicals, and improper waste disposal are continuously reducing water quality. Pollutants such as chlorides, nitrates, organic waste, sewage discharge, and industrial effluents enter water bodies and make the water unsafe for drinking and daily use. This has created major environmental and public health concerns in many parts of the country, including urban and semi-urban

regions of Tamil Nadu.
In order to control this growing problem, the Government of India has introduced important water restoration programs. The Namami Gange Programme, launched as a flagship initiative for the rejuvenation of river Ganga and its tributaries. The National River Conservation Plan has contributed to the reduction in polluted river stretches from 351 in 2018 to 296 in 2025. The Jal Jeevan Mission aims to provide safe drinking water to rural households, with more than 15.68 crore rural households provided with tap water connections. The Atal Mission for Rejuvenation and Urban Transformation and AMRUT 2.0 focus on urban water supply and sewerage Because of this, scientists are increasingly focusing on sustainable and low-cost natural treatment methods such as phytoremediation, where plants help remove pollutants from contaminated water. Among these, Vetiver Grass (*Chrysopogon zizanioides* ) and Water Hyacinth (*Eichhornia crassipes*) have shown strong potential for water purification. Vetiver grass, scientifically known as *Chrysopogon zizanioides* , has attracted considerable attention for phytoremediation applications due to its extensive root network, high tolerance to environmental stress, and ability to accumulate various contaminants. Native to India, this perennial grass can develop roots reaching depths of up to 3 meters, creating an extensive subsurface filtration system. The salient features of Vetiver include its remarkable tolerance to extreme climatic variations, including prolonged drought, flood, submergence, extreme temperature, high levels of salinity, sodicity, acidity, alkalinity, and a wide range of toxic metalloids and organic contaminants. The plant possesses a dense, deep, and fibrous root system that penetrates the soil profile, providing mechanical strength and excellent hydraulic conductivity. Vetiver is also known for its rapid growth rate, high biomass production, and ability to thrive in nutrient poor soils. Water hyacinth, scientifically known as *Eichhornia crassipes*, is a free-floating aquatic plant widely distributed in tropical and subtropical regions of the world. Despite being one of the world's most problematic invasive aquatic weeds, it possesses remarkable properties that can be harnessed for water purification. The salient features of Water hyacinth include its exceptionally rapid growth rate, enabling it to dominate water bodies within a short period, and its ability to reproduce predominantly through vegetative propagation, with each mature plant producing one or two daughter plants through stolons. The plant possesses long, swollen stalks that aid buoyancy, and its seeds remain viable for several years, contributing to long term persistence even after removal efforts. Water hyacinth thrives in optimum temperature range of 25 to 30 degrees Celsius and when salinity levels remain below approximately 5 grams per liter.The main objective is to study groundwater contamination, evaluate the individual treatment efficiency of both plants, analyze Water Hyacinth biomass properties using FTIR, XRD, and AAS, determine the best treatment conditions, and develop simple, cost-effective, and sustainable water treatment models for long-term environmental protection and safe water management.

## 2. Materials and Methods

### 2.1 Study Area

The study was conducted in Tiruchirappalli district, Tamil Nadu, India, where rapid urbanization and industrialization have contributed to significant groundwater contamination. These regions were selected because they represent diverse land use patterns, including industrial zones, residential areas, and agricultural belts, which are known to contribute varying types and levels of pollutants to groundwater resources. Dalmiyapuram is characterized by the presence of small-scale industries and commercial activities that discharge untreated effluents, while Thiruverumbur is situated near major industrial establishments and transportation corridors, contributing to elevated levels of dissolved salts and heavy metals. Sangiliyandapuram represents a densely populated residential and commercial area where sewage intrusion and domestic waste disposal are major concerns, and Woraiyur is an urbanized locality influenced by municipal waste discharge and agricultural runoff from surrounding farmlands. Four locations were selected for groundwater assessment based on preliminary surveys indicating varying levels of anthropogenic impact: Dalmiyapuram, Thiruverumbur, Sangiliyandapuram, and Woraiyur.

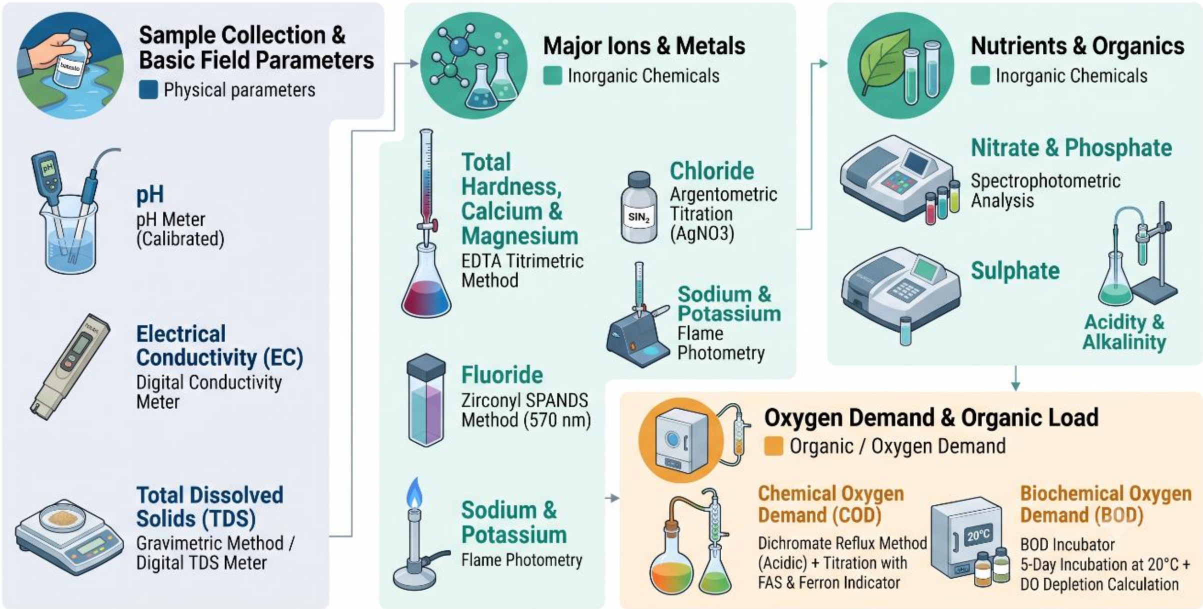
### 2.2 Sample Collection

Groundwater samples were collected between December 2024 and February 2025 using the grab sampling technique. Samples were collected in pre-cleaned polyethylene containers rinsed with distilled water prior to use. Temperature and pH were measured at the site to prevent alteration of physicochemical characteristics during storage. For drainage water analysis, samples were collected from the laboratory drainage outlet to represent wastewater conditions.

### 2.3 Physicochemical Analysis

The collected samples were analyzed for physicochemical parameters including pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness, Calcium, Magnesium, Chloride, Fluoride, Alkalinity, Sodium, Potassium, Phosphate, Nitrate, Iron, Sulphate, Acidity, Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD) using standard analytical methods. pH was measured using a calibrated digital pH meter, while EC was determined using a digital TDS/EC conductivity meter. TDS was determined using the gravimetric method and confirmed using a digital TDS meter. Total hardness, calcium, and magnesium were estimated by EDTA titrimetric method. Chloride was estimated by argentometric titration using silver nitrate, and fluoride was determined by the Zirconyl SPANDS spectrophotometric method at 570 nanometers. Sodium and potassium concentrations were measured using a flame photometer, while nitrate and phosphate were determined spectrophotometrically. COD was determined using the dichromate reflux method under acidic conditions, followed by titration with ferrous ammonium sulphate using Ferron indicator. BOD was measured by incubating diluted samples at 20 degrees Celsius for five days and calculating dissolved oxygen depletion. The diagrammatic representation of the procedure of physicochemical water quality assessment in shown in Figure 1.

**Figure 1. The diagrammatic representation of the procedure of physicochemical water quality assessment**




## 2.4 Preparation of Treatment Materials

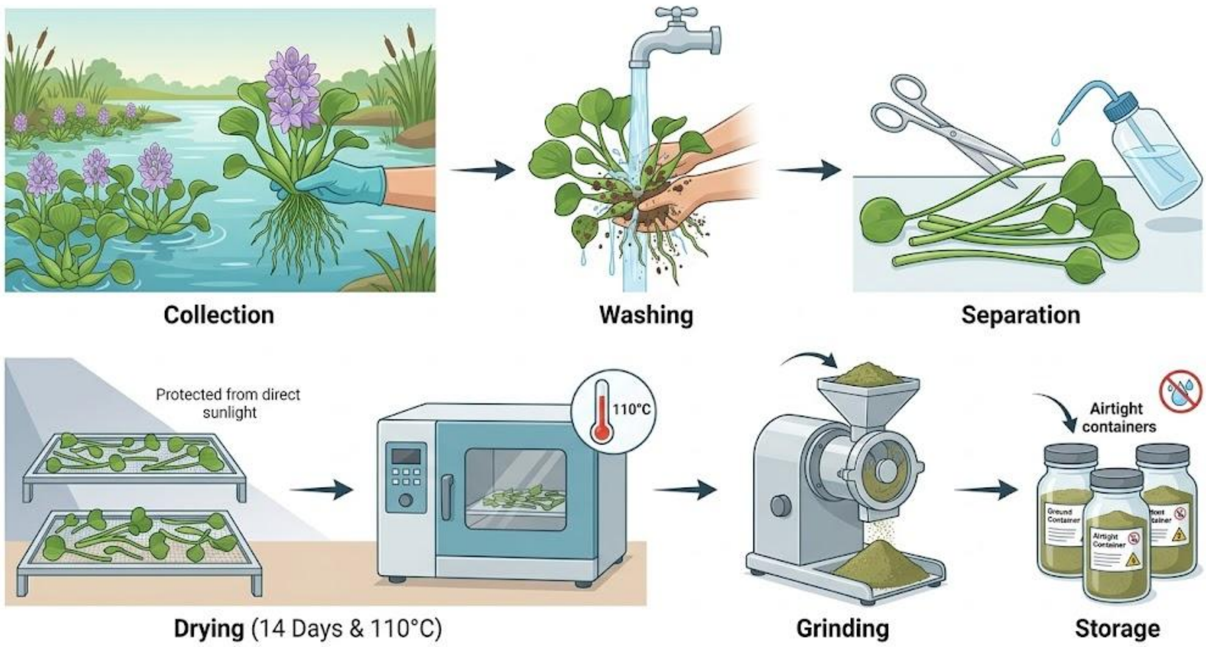
### 2.4.1 Vetiver Grass Preparation

Vetiver plants were collected from local nurseries and stored in controlled conditions. Healthy plants with well-developed root systems were selected for treatment experiments. Roots were carefully washed to remove soil particles before use in treatment applications.

### 2.4.2 Water Hyacinth Powder Preparation

Water hyacinth plants were collected from freshwater sources (ponds and canals) in and around Tiruchirappalli district where they grow abundantly. Healthy and mature plants were carefully uprooted manually to avoid damaging the roots. The plants were washed thoroughly with clean water to remove attached soil, debris, and other impurities. The stems and leaves were separated using clean stainless-steel scissors and washed again with distilled water. The plant parts were dried without sunlight for 14 days, followed by oven drying at 110°C until constant weight was achieved. The dried material was ground into a fine powder using a mechanical grinder and stored in clean, airtight containers to prevent moisture absorption and contamination. The schematic workflow of the step-by-step sample preparation procedure for water hyacinth (*Eichhornia crassipes*) is shown in Figure 2.

**Figure 2. Schematic workflow of the step-by-step sample preparation procedure for water hyacinth (*Eichhornia crassipes*)**



### 2.5 Experimental Procedure
#### 2.5.1 Initial Characterization
All collected water samples were analyzed for physicochemical parameters including pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness, Calcium, Magnesium, Chloride, Fluoride, Alkalinity, Sodium, Potassium, Phosphate, Nitrate, Iron, Sulphate, Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD) using standard analytical methods.

#### 2.5.2 Vetiver Treatment
Based on preliminary water quality analysis, groundwater samples collected from Dalmiyapuram and Woraiyur, identified as the most contaminated sites, were selected for phytoremediation treatment. Roots of *Chrysopogon zizanioides* (Vetiver grass) were immersed in the contaminated groundwater samples and maintained for a designated contact period to facilitate pollutant removal through root uptake, adsorption, and rhizospheric microbial degradation. Following treatment, the samples were filtered using Whatman filter paper and subjected to post-treatment analysis to evaluate contaminant removal efficiency.

#### 2.5.3 Water Hyacinth Biosorption
Measured quantities of powdered *Eichhornia crassipes* (Water hyacinth) at concentrations of 0.02 g, 0.05 g, and 0.10 g per 100 mL were separately introduced into groundwater and drainage water samples contained in reagent bottles. The samples were subjected to continuous agitation using a rotary shaker for 12 h per day over a treatment period of three days to ensure uniform mixing and effective contaminant–adsorbent interaction. Aliquots were collected at predetermined intervals of 6 h, 1 day, 2 days, and 3 days, followed by filtration and subsequent analysis of physicochemical parameters including pH, total dissolved solids (TDS), and electrical conductivity (EC) using calibrated analytical instruments to assess treatment efficiency. The pictorial representation of treatment of Groundwater and Drainage Water Using Powdered Water Hyacinth is depicted in Figure 3.

**Figure 3. Pictorial representation of Treatment of Groundwater and Drainage Water Using Powdered Water Hyacinth Leaves and Stem**


### 2.6 Analytical Techniques
#### 2.6.1 Fourier Transform Infrared Spectroscopy (FTIR)
FTIR analysis was performed on oven-dried Water hyacinth powder samples (leaf and stem, dried for 8 and 16 h) to identify functional groups and confirm moisture removal. The spectra were recorded in the wavenumber range of 4000-400 $cm^{-1}$.

#### 2.6.2 X-Ray Diffraction (XRD)
XRD analysis was conducted to investigate the crystalline structure of Water hyacinth powder and detect inorganic or metal-associated phases. The diffraction pattern was recorded using Cu-Kα radiation in the 2θ range of 10-80°.

#### 2.6.3 Atomic Absorption Spectroscopy (AAS)
AAS analysis was performed to quantify heavy metals (chromium and lead) in Water hyacinth powder. One gram of dried powder was acid-digested, made up to 60 mL volume, and analyzed using a calibrated AAS instrument with standard solutions for Cr and Pb.

# 3. Results and Discussion

## 3.1 Results

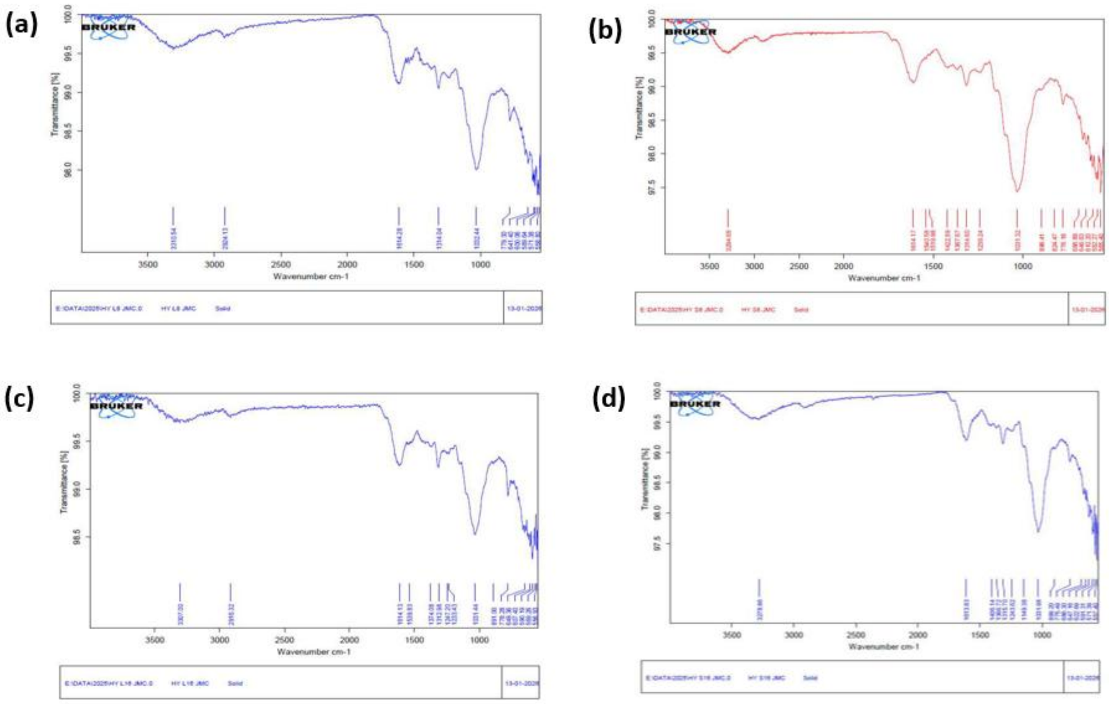
### 3.1.1 Groundwater Quality Before Treatment

Physicochemical analysis revealed considerable spatial variation in groundwater quality across the study locations. Dalmiyapuram exhibited the highest contamination levels, with EC of 2300 µS/cm, TDS of 1380 mg/L, total hardness of 525 mg/L, and chloride of 524.66 mg/L. Elevated EC and TDS indicate high ionic concentration and mineralization, typically linked to anthropogenic influences such as sewage intrusion, industrial discharge, and urban runoff. Hardness levels above 500 mg/L reflect excessive calcium and magnesium salts, which may impair potability and domestic usability. Organic pollution indicators were also elevated. BOD reached 10.2 mg/L in Dalmiyapuram, while COD values ranged up to 68 mg/L in Thiruverumbur. High BOD and COD levels indicate biodegradable organic matter and microbial contamination. Moderate nitrate levels (3.65 mg/L) suggest agricultural runoff and fertilizer leaching. Overall, pre-treatment data highlight groundwater deterioration due to rapid urbanization in the Tiruchirappalli district.

### 3.1.2 FTIR Analysis of Water Hyacinth Powder

FTIR analysis was performed to identify functional groups and confirm the absence of moisture in dried Water hyacinth powder samples. The spectra of all samples (leaf and stem, 8 h and 16 h drying) did not show characteristic water peaks, the broad O-H stretching band (3200-3600 cm$^{-1}$) and H-O-H bending peak (1630-1650 cm$^{-1}$), confirming complete drying. The spectra primarily displayed absorption bands corresponding to natural organic components of the plant material, carboxyl groups (-COOH) exhibiting characteristic absorption around 1700-1725 cm$^{-1}$ attributed to C=O stretching of carboxylic acids, and carbonyl groups (C=O) showing strong absorption bands in the region of 1600-1750 cm$^{-1}$. Additional absorption bands observed included C-H stretching vibrations of aliphatic groups in the region of 2850-2950 cm$^{-1}$, C-O stretching of alcohols and esters around 1000-1300 cm$^{-1}$, and aromatic skeletal vibrations characteristic of lignin at 1508, 1541, and 1559 cm$^{-1}$. These functional groups, particularly the carboxyl and carbonyl moieties, are responsible for metal binding and ion exchange through electrostatic interactions, hydrogen bonding, and complexation mechanisms. The absence of moisture-related peaks in both 8 h and 16 h dried samples indicates that oven drying was effective at both durations. The FTIR spectrum of the sample at different time intervals is shown in Figure 4.

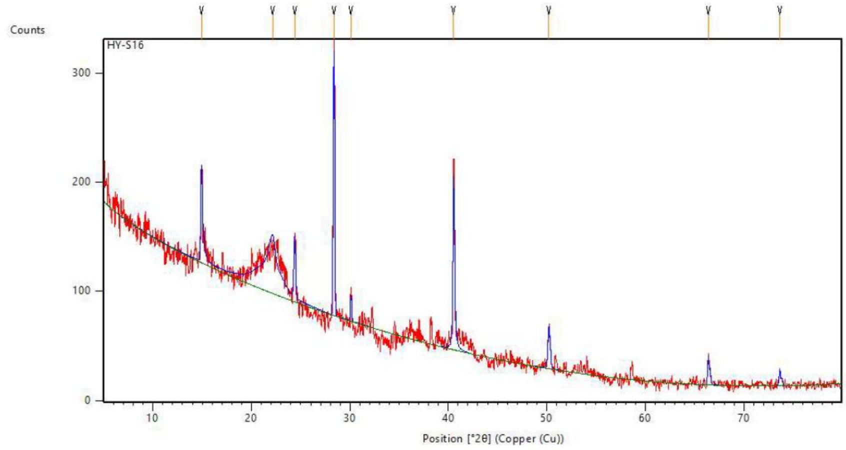
**Figure 4. (a) FTIR spectrum of Water Hyacinth Leaf powder dried in an oven for 8 h; (b) FTIR spectrum of Water Hyacinth Stem powder dried in an oven for 8 h; (c) FTIR spectrum of Water Hyacinth Leaf powder dried in an oven for 16 h; (d) FTIR spectrum of Water Hyacinth Stem powder dried in an oven for 16 h.**




### 3.1.3 XRD Analysis of Water Hyacinth Powder

The X-ray diffraction pattern showed a broad hump in the region of 15-25° (2θ), confirming the predominantly amorphous nature of the lignocellulosic biomass. In addition, several sharp diffraction peaks were observed at approximately 16-18°, 22-23°, 29-30°, 39-40°, 50°, 68-70°, and 73-75° (2θ), indicating the presence of crystalline phases. Since the biomass is largely amorphous, the appearance of distinct sharp peaks suggests the presence of crystalline inorganic components, possibly related to metal-containing species formed after adsorption. This finding supports the hypothesis that Water hyacinth accumulates metals and minerals from contaminated water. The XRD spectrogram is depicted in Figure 5.

**Figure 5. XRD spectrogram of Water hyacinth sample**




### 3.1.4 AAS Analysis for Heavy Metal Confirmation

AAS analysis was performed to confirm heavy metal presence in Water hyacinth powder. Chromium and lead were selected for investigation due to their widespread environmental contamination and potential health hazards. Analysis revealed that the calibration curve showed a concentration of 1.71 ppm in the digested solution. Based on the initial sample weight of 1 g and final volume of 60 mL, the chromium concentration in the plant powder was approximately 103 mg/kg. This confirms the presence of chromium in the biomass, supporting the XRD inference that crystalline inorganic components may be associated with metal species. No detectable absorbance corresponding to Pb was observed, indicating that lead was either absent or present below the instrument's detection limit. These results confirm that Water hyacinth effectively adsorbs heavy metals, particularly chromium, from contaminated water sources. The adsorption mechanism is attributed to the abundant functional groups on the biomass surface (as confirmed by FTIR) that bind metal ions through electrostatic interactions and complexation.

### 3.1.5 Vetiver Treatment Results

Treatment of groundwater samples collected from Dalmiyapuram using Vetiver grass (*Chrysopogon zizanioides* ) demonstrated significant reduction in multiple physicochemical contaminants, confirming its effectiveness as a phytoremediation agent for groundwater purification. Post-treatment analysis revealed a considerable decrease in electrical conductivity (EC) from 2300 to 1269 µS/cm, corresponding to a 44.8% reduction, indicating substantial removal of dissolved ionic species. Similarly, total dissolved solids (TDS) decreased from 1380.00 to 761.40 mg/L with an equivalent reduction efficiency of 44.8%, confirming uptake and adsorption of dissolved salts by the extensive vetiver root system. Chloride concentration was reduced from 524.66 to 301.32 mg/L, achieving 42.6% removal, while fluoride concentration decreased moderately from 0.920 to 0.670 mg/L with 27.2% removal efficiency. The most remarkable result was observed for nitrate, where concentration decreased drastically from 3.65 to 0.09 mg/L, corresponding to an exceptional removal efficiency of 97.5%, which is highly significant in reducing nitrate-associated health hazards such as methemoglobinemia. Chemical oxygen demand (COD) decreased substantially from 52 to 6.4 mg/L, resulting in 87.7% removal, indicating efficient degradation and elimination of organic pollutants through rhizospheric microbial activity associated with vetiver roots. Biological oxygen demand (BOD) was reduced from 10.2 to 4.6 mg/L with a 54.9% reduction, further supporting the role of microbial biodegradation in reducing biodegradable organic matter. However, hardness showed negligible change after treatment, suggesting that calcium and magnesium salts responsible for hardness are relatively resistant to biological uptake and are not readily removed through phytoremediation processes involving vetiver grass. The effect of Vetiver grass phytoremediation treatment on physicochemical parameters of Dalmiyapuram groundwater samples is shown in Table 1.

**Table 1. Effect of Vetiver grass phytoremediation treatment on physicochemical parameters of Dalmiyapuram groundwater samples.**

| Parameter | Before Treatment | After Treatment | % Removal |
|---|---|---|---|
| EC (µS/cm) | 2300 | 1269 | 44.8% |
| TDS (mg/L) | 1380.00 | 761.40 | 44.8% |
| Chloride (mg/L) | 524.66 | 301.32 | 42.6% |
| Fluoride (mg/L) | 0.920 | 0.670 | 27.2% |
| Nitrate (mg/L) | 3.65 | 0.09 | 97.5% |
| COD (mg/L) | 52 | 6.4 | 87.7% |
| BOD (mg/L) | 10.2 | 4.6 | 54.9% |

The results clearly indicate that Vetiver grass possesses strong phytoremediation potential for groundwater treatment, particularly for the removal of nitrates, dissolved salts, and organic contaminants, thereby demonstrating its applicability as an eco-friendly and sustainable water remediation system.

### 3.1.6 Water Hyacinth Biosorption Results

#### 3.1.6(a) Groundwater Treatment

Treatment of groundwater samples using powdered *Eichhornia crassipes* (Water hyacinth) resulted in significant reduction of dissolved ionic contaminants, demonstrating its effective biosorption potential for groundwater purification. The untreated groundwater sample exhibited an initial total dissolved solids (TDS) concentration of 477 ppm and electrical conductivity (EC) of 954 µS/cm. Following treatment for a period of three days with varying concentrations of water hyacinth powder (0.02%, 0.05%, and 0.10%), substantial contaminant removal was observed. At both 0.02% and 0.05% concentrations, TDS values decreased from 477 ppm to 87 ppm, corresponding to a high removal efficiency of 81.8%, while EC decreased from 954 µS/cm to 174 µS/cm with an identical removal efficiency of 81.8%, indicating highly effective adsorption of dissolved salts and ionic species by the biomass surface. At the higher concentration of 0.10%, comparatively lower treatment efficiency was observed, where TDS decreased to 162 ppm and EC decreased to 324 µS/cm, each corresponding to 66.0% removal efficiency. The reduced performance at higher adsorbent concentration may be attributed to particle aggregation and reduced accessibility of active adsorption sites, which can limit effective contaminant interaction. Overall, the results confirm that water hyacinth powder possesses strong adsorption capacity for reducing dissolved solids and conductivity in groundwater, with optimum remediation efficiency achieved at lower concentrations under the present experimental conditions.

**Table 2. Effect of powdered Water hyacinth treatment at different concentrations on TDS and electrical conductivity reduction in groundwater samples**

| Parameter | 0.02% Concentration | 0.05% Concentration | 0.10% Concentration |
|---|---|---|---|
| TDS after 3 days (ppm) | 87 | 87 | 162 |
| TDS Removal (%) | 81.8% | 81.8% | 66.0% |
| EC after 3 days (µS/cm) | 174 | 174 | 324 |
| EC Removal (%) | 81.8% | 81.8% | 66.0% |

#### 3.1.6(b) Drainage Water Treatment

Treatment of drainage water samples using powdered *Eichhornia crassipes* (Water hyacinth) demonstrated substantial reduction in dissolved ionic contaminants, confirming its effectiveness as a biosorbent material for wastewater purification. The untreated drainage water sample showed an initial total dissolved solids (TDS) concentration of 573 ppm and electrical conductivity (EC) of 1146 µS/cm. Following a treatment period of three days with varying concentrations of water hyacinth powder (0.02%, 0.05%, and 0.10%), considerable removal of dissolved contaminants was observed across all tested concentrations. The highest treatment efficiency was achieved at the lowest concentration of 0.02%, where TDS was reduced from 573 ppm to 79 ppm, corresponding to an excellent removal efficiency of 86.2%. Similarly, EC decreased from 1146 µS/cm to 158 µS/cm, also achieving 86.2% removal, indicating highly effective adsorption of dissolved ions onto the biomass surface. At 0.05% concentration, TDS decreased to 141 ppm and EC decreased to 282 µS/cm, each showing a removal efficiency of 75.4%. Further increase in adsorbent concentration to 0.10% resulted in comparatively lower treatment performance, with TDS reduced to 175 ppm and EC reduced to 350 µS/cm, corresponding to 69.5% removal efficiency. The progressive decline in removal efficiency at higher concentrations suggests that excessive biomass loading may promote particle clustering, thereby decreasing the effective surface area available for contaminant adsorption and limiting interaction between dissolved pollutants and active binding sites. These findings indicate the presence of an optimum adsorbent dosage under the present experimental conditions, with lower biomass concentration providing superior purification performance.

**Table 3. Effect of powdered Water hyacinth treatment at varying concentrations on TDS and electrical conductivity reduction in drainage water samples**

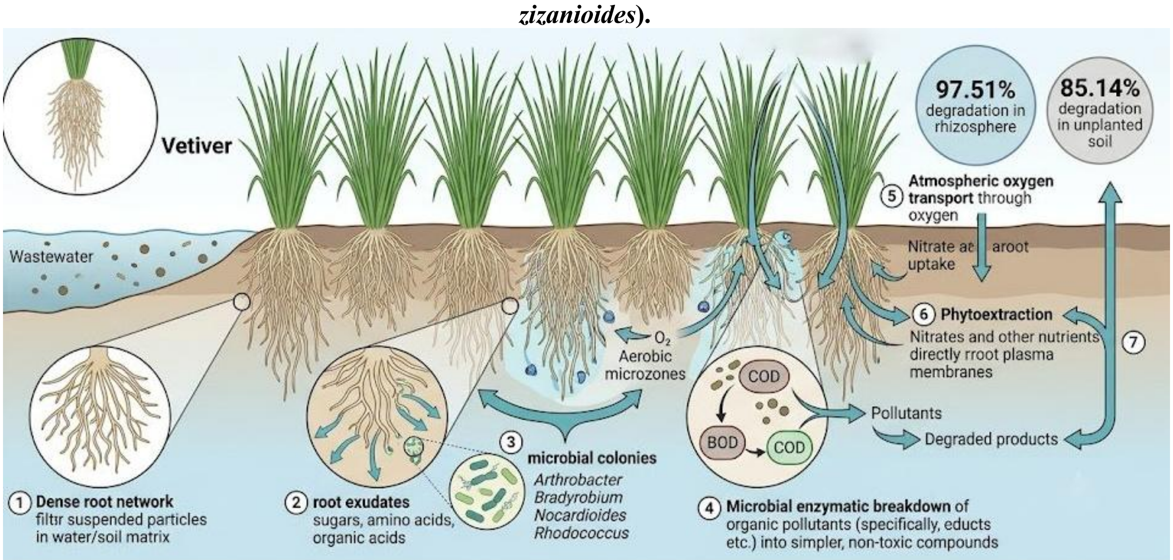
| Parameter | 0.02% Concentration | 0.05% Concentration | 0.10% Concentration |
|---|---|---|---|
| TDS after 3 days (ppm) | 79 | 141 | 175 |
| TDS Removal (%) | 86.2% | 75.4% | 69.5% |
| EC after 3 days (µS/cm) | 158 | 282 | 350 |
| EC Removal (%) | 86.2% | 75.4% | 69.5% |

### 3.2 Discussion

#### 3.2.1 Mechanisms of Contaminant Removal by Vetiver

Vetiver is effectiveness in organic pollutant removal is primarily attributed to its extensive root system and associated rhizosphere microbial colonies. The mechanism involves several interconnected processes that work synergistically to remove contaminants from water. Root exudates released by Vetiver roots include organic compounds such as sugars, amino acids, and organic acids that serve as substrates for rhizosphere microorganisms, stimulating their growth and metabolic activity. The rhizosphere bacteria and fungi produce extracellular enzymes that break down complex organic molecules including BOD and COD into simpler compounds through aerobic and anaerobic pathways. Research by Gupta and colleagues in 2012 documented that the mechanism of contaminant reduction by Vetiver in wastewater involves interactions between root released oxygen into the rhizosphere, root-based uptake of nutrients from wastewater, the existence of appropriate surface area for attached microbial growth, and root exuded organic carbon. The presence of specific bacterial genera such as Arthrobacter, Bradyrhizobium, Nocardioides, and Rhodococcus in the rhizosphere likely contributes to enhanced degradation of organic pollutants, as these have been identified as the major atrazine degrading bacterial genera responsible for enhanced degradation in the rhizosphere soil by researchers in 2023. The dense root network of Vetiver physically filters suspended particles and provides large surface area for microbial colonization, while the plant efficiently absorbs nitrates and other nutrients directly into plant tissues through phytoextraction, where pollutants are adsorbed by the channels and then transferred across the plasma membrane of the root.
The plant transports atmospheric oxygen to the rhizosphere, creating aerobic microsomes that support oxidative degradation of organic pollutants, while the organic carbon released from roots supports microbial growth and enhances contaminant degradation. Research has demonstrated that Vetiver can significantly promote the degradation of organic pollutants, with dissipation in rhizosphere soil reaching 97.51% compared to 85.14% in unplanted soil as reported in 2023. The augmentation of Vetiver with microbes amplifies its stress tolerance and remediation capacity, and understanding this potential enhancement through microbial associations could crucially help in advancing the role of Vetiver in sustainable ecological restoration as documented by researchers in 2026. The combination of physical filtration, nutrient uptake, oxygen transfer, and microbial degradation mechanisms collectively enables Vetiver to achieve remarkable removal of organic pollutants, nitrates, and dissolved contaminants from groundwater, making it a highly effective phytoremediation agent for decentralized water treatment applications in resource limited settings. Figure 6 portrays the Schematic illustration of the phytoremediation mechanism of Vetiver grass (*Chrysopogon zizanioides*).

**Figure 6: Schematic illustration of the phytoremediation mechanism of Vetiver grass (*Chrysopogon zizanioides*).**

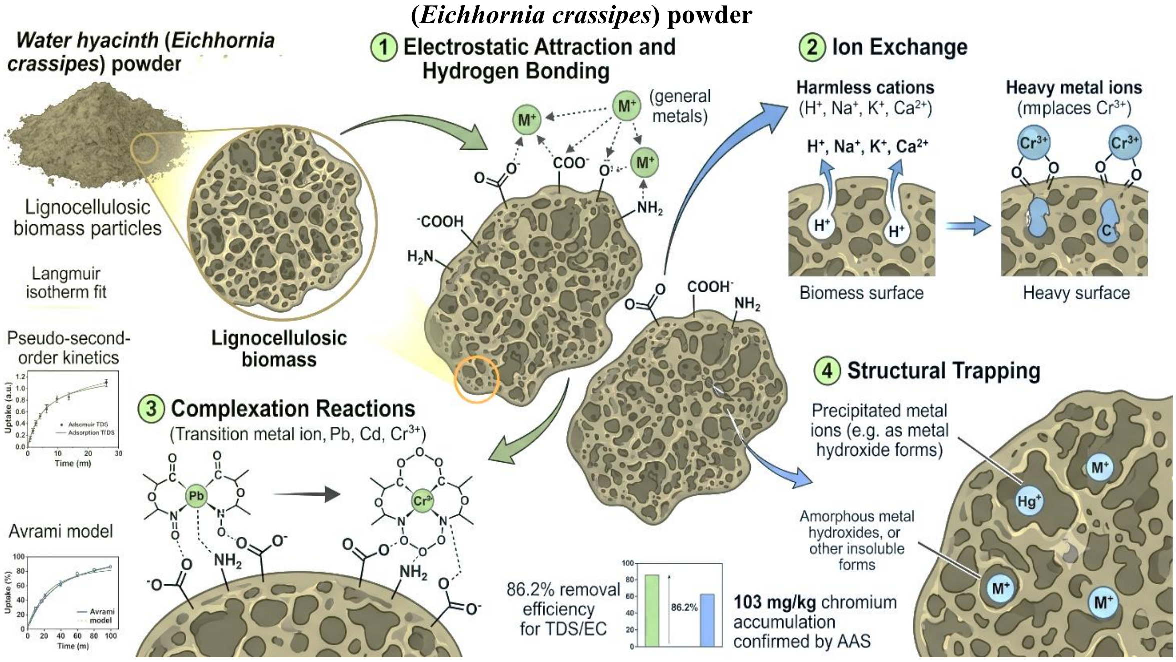



#### 3.2.2 Mechanisms of Contaminant Removal by Water Hyacinth

Water hyacinth powder removes ionic contaminants through a combination of physicochemical mechanisms that work together to achieve high removal efficiencies. The lignocellulosic biomass provides a large surface area with abundant functional groups including hydroxyl, carboxyl, and amino groups that bind metal ions and dissolved salts through electrostatic interactions and hydrogen bonding. FTIR analysis has identified functional groups involved in binding sites, with hydroxyl group from alcohol and carboxylic acid being prominent as documented by Muchanyereyi in 2016. The plant material releases harmless cations such as $H^+$, $Na^+$, $K^+$, and $Ca^{2+}$ in exchange for heavy metal ions and dissolved salts, effectively removing them from solution through ion exchange mechanisms. FTIR and XPS analysis imply that functional groups including amino, hydroxyl, and carboxyl are responsible for the adsorption process, in which coordination and ion exchange mechanisms could be involved as reported by researchers in 2016. Functional groups on the biomass surface form stable complexes with metal ions, particularly transition metals like chromium, through complexation reactions, while the crystalline phases detected by XRD may represent metal precipitates or adsorbed metal ions trapped within the biomass matrix.
The adsorption of heavy metals follows the Langmuir isotherm and pseudo second order kinetics, with the Avrami

model being most adequate in the kinetic study, revealing that the adsorption process is carried out by several mechanisms as documented by researchers in 2021. Studies have confirmed the root biomass to be amorphous with increased crystallinity upon treatment, and thermodynamic parameters have been determined for various adsorption processes, indicating that the biosorption process is spontaneous and endothermic in nature. The combination of surface adsorption, ion exchange, complexation, and structural trapping mechanisms enables Water hyacinth to achieve exceptional removal of dissolved ionic species and heavy metals from contaminated water, with maximum removal efficiencies reaching 86.2% for TDS and EC as demonstrated in the present study. The confirmation of chromium accumulation at approximately 103 mg/kg through AAS analysis further validates the effectiveness of Water hyacinth as a biosorbent material, supporting its application as a low cost and eco-friendly alternative for removing inorganic contaminants from both groundwater and wastewater sources. The schematic representation of the physicochemical biosorption mechanism of Water hyacinth (*Eichhornia crassipes*) powder is shown in Figure 7.

**Figure 7: Schematic representation of the physicochemical biosorption mechanism of Water hyacinth (*Eichhornia crassipes*) powder**




## 4. Conclusion

This study demonstrates that both *Chrysopogon zizanioides* (Vetiver) and *Eichhornia crassipes* (Water hyacinth) are effective, ecofriendly, and sustainable plant-based solutions for water quality restoration. Vetiver, through its extensive root network and associated rhizosphere microbial community, achieved remarkable reductions in organic pollutants with 97.5% for nitrate, 87.7% for COD, and 54.9% for BOD. The mechanisms responsible for this activity involve root released oxygen, root-based uptake of nutrients, surface area for microbial growth, and root exuded organic carbon, with bacterial genera such as Arthrobacter, Bradyrhizobium, Nocardioides, and Rhodococcus playing a crucial role in degradation as documented by researchers in 2023. Water hyacinth powder, with its abundant functional groups including hydroxyl, carboxyl, and carbonyl and crystalline structures confirmed through FTIR, XRD, and AAS analyses, demonstrated exceptional biosorption capacity, achieving up to 86.2% removal of TDS and EC and confirming chromium accumulation of approximately 103 ppm in the biomass. The adsorption mechanisms involve coordination, ion exchange, complexation, and surface adsorption, with functional groups playing a key role in metal binding as reported by researchers in 2016. The exhausted Water hyacinth biomass containing adsorbed heavy metals was safely disposed by using an eco-friendly method known as controlled landfilling, thereby preventing secondary contamination and completing the sustainable treatment cycle. While these plants can be used effectively for water treatment individually, with Vetiver for organic pollutant removal and Water hyacinth for ionic and heavy metal removal, their distinct mechanisms of action make them suitable for different contamination scenarios. The present findings support the government's vision of clean and safe water through nature based, cost effective, and decentralized solutions that can complement existing infrastructure investments under programs such as Namami Gange, Jal Jeevan Mission, AMRUT, and the National River Conservation Plan. Future research should investigate the long term stability and reusability of Water hyacinth powder through multiple adsorption desorption cycles, conduct pilot scale studies for field validation, explore the safe disposal or recovery of heavy metals accumulated in Water hyacinth biomass including pyrolysis for metal recovery or biochar production, perform detailed metagenomic analysis of Vetiver's rhizosphere microbial community and their specific contributions to pollutant degradation mechanisms, evaluate economic viability through life cycle assessment and cost benefit analysis, and examine whether specific combinations or sequences of these treatment approaches might offer synergistic benefits for particular contamination scenarios.

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