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The capability of *Phragmiteskarka* in phytoremediation for the treatment of municipal wastewater through a constructed wetland model

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Abstract

The growing utilization of constructed wetlands for sewage treatment, alongside increasingly stringent water quality regulations, underscores the need for enhanced process design tools. This paper examines how seasonal variations influence the efficiency of pollution removal in sewage treatment. In this study, Phragmiteskarka was cultivated in constructed wetlands and evaluated for its effectiveness in treating various concentrations of municipal wastewater. Samples of municipal wastewater were collected before and after treatment and analyzed for specific parameters, including pH, electrical conductivity (EC), total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), nitrate (NO_3), phosphate (PO_4), and sulfate (SO_4), using standardized methods. The objective of this investigation was to assess the treatment efficacy of Phragmiteskarka across different concentrations of municipal wastewater. The findings indicate that Phragmiteskarka achieves the highest level of pollution reduction when municipal wastewater is treated in constructed wetlands, with no observed phytotoxic effects.

Keywords: Aquatic Macrophytes, Constructed Wetland, Municipal Wastewater, *Phragmiteskarka*, Wastewater Concentrations.

Introduction

The rapid advancement of urbanization has led to significant growth in industrial and agricultural production. However, the reliance on outdated technologies has resulted in environmental degradation and resource depletion, drawing increasing attention to issues such as resource scarcity and environmental pollution, particularly water pollution. Literature indicates that many rivers worldwide are impacted to varying extents, with occurrences of red tides becoming more frequent in various marine regions[1]. In China, the primary cause of water pollution in oceans, lakes, and rivers is attributed to nutrient-rich water bodies, primarily due to the presence of untreated or inadequately treated phosphorus and nitrogen[2]. Wastewater treatment has become a significant concern in contemporary times, primarily due to the high expenses associated with equipment and chemicals. Additionally, there are instances where it is challenging to reduce pollutants, such as heavy metals or nitrogen, to acceptable levels.

Wastewater treatment has become a significant concern in contemporary times, primarily due to the high costs associated with equipment and chemicals. Additionally, there are instances where pollutants, such as heavy metals or nitrogen, cannot be reduced to acceptable levels. Water pollution poses a critical challenge for development, as it directly affects human health, limits water resources, and threatens the sustainability of alternative water sources. Over the past two to three decades, the Indian government has prioritized environmental protection. Nevertheless, as economic growth has accelerated, water pollution has emerged as a significant environmental concern. In India, a minimal proportion of municipal sewage undergoes treatment. While some large metropolitan areas have established sewage treatment facilities, smaller cities often discharge untreated sewage directly into water bodies. The establishment of effective sewage treatment systems is essential; however, it is imperative to consider the economic and social implications when selecting suitable treatment technologies for expanding urban areas in developing nations. Advanced treatment technologies, such as activated sludge systems and membrane technology, are commonly employed in developed countries for municipal wastewater treatment. However, these technologies may not be practical for India, particularly in smaller cities, due to their high construction and operational costs[1,2].

One effective and economical method for wastewater treatment that is easy to implement, requires relatively low energy consumption, and complies with effluent standards is the constructed wetland[3,4]. Constructed wetlands serve as a viable alternative to traditional wastewater treatment systems, particularly for small communities[5]. These systems utilize a combination of physical, chemical, and biological processes to accommodate varying levels of organic content[6]. Additionally, the incorporation of vegetation in the treatment process enhances the environmental sustainability of constructed wetlands. The efficiency of these systems is influenced by factors such as microbial activity, hydraulic retention time, pollutant load, temperature, and the types of vegetation used[7].

Materials and Methods

Selection of research topic: Natural treatment systems have emerged as highly effective technologies for managing various types of wastewater, garnering significant interest in recent years. These systems utilize renewable energy sources, including solar, wind, and the energy stored in biomass and soil. They encompass natural soil systems, aquatic systems, and wetlands. Among these, the pond system has gained prominence as a natural treatment method, particularly in developed nations over the past few decades, with a focus on phytoremediation or wetland systems that utilize plants for wastewater treatment.

Recent insights into the capacity of plants to decompose and purify pathogenic microorganisms, as well as to eliminate numerous contaminants, have spurred the increased use of plant-based systems and a broader scope of research in this field[8]. Wetland systems are continually gaining traction due to their multifaceted purification capabilities—encompassing physical, biological, and chemical processes—along with their cost-effectiveness, ease of operation, and high purification efficiency. In these systems, plants play a crucial role by providing oxygen for heterotrophic microorganisms in the root zone, absorbing nutrients, and enhancing the hydraulic conductivity of the substrate. As an effective secondary treatment solution, wetlands can significantly reduce various contaminants, including organic and inorganic matter, as well as a range of pathogenic microorganisms, to acceptable levels[9].

Phytoremediation represents a cutting-edge approach for the removal or recovery of nutrient excess from contaminated ecosystems. The application of aquatic plants in the phytoremediation of wastewater proves to be highly effective, as these plants can absorb and break down pollutants such as phosphates, nitrates, and metal ions from tainted water. This process enhances the quality of wastewater prior to its release into the natural environment. Additionally, phytoremediation techniques can facilitate the recovery of nutrients like phosphates and nitrates from wastewater, which can subsequently be utilized in the production of chemical fertilizers and livestock food additives. Various aquatic plants are prominent in wastewater treatment due to their availability, resilience in polluted environments, and capacity for bioaccumulation, invasive growth patterns, and potential for biomass generation. Some of these yield substantial biomass, making them viable options for bioenergy production. The biomass of plants cultivated in constructed wetlands during phytoremediation can be utilized for biogas generation through anaerobic fermentation processes[10-12]. Despite the promising attributes of these species, their full capabilities remain largely unexplored. Consequently, further research is essential to investigate the potential of these plants in the remediation of wastewater. Therefore, the present investigation was undertaken using constructed wetlands.

Constructed wetlands can function as primary treatment systems or serve as secondary or tertiary treatment options for both domestic and industrial wastewater, typically following initial treatment processes. While the application of constructed wetlands has primarily focused on domestic wastewater, research is ongoing regarding their use for industrial wastewater due to the diverse compositions of industrial effluents that require tailored treatment approaches[13]. This study aims to evaluate the effectiveness of constructed wetlands in removing various pollutants, which are generally assessed through multiple parameters in municipal wastewater. The scientific studies on the use of CWs for wastewater treatment began in the middle of the last century. The first experiments were undertaken by Kathe Seidel in Germany in the early 1950s at the Max Planck Institute in Plon[14]. In 1953, Dr. Kathe Seidel for the first time presented methods for improvement of inland waterways which suffered from over-fertilizaton, pollution from sewage and siltation by means of appropriate plant species[15]. However, at that time, views on wastewater treatment among experts were limited to physical, chemical and biological (bacterial) methods and the controlled use of macrophytes for water purification was not taken into consideration. In addition, it was believed that most macrophytes cannot grow well in polluted water and the ability of macrophytes to eliminate toxic substances in water was not recognized as well[16].

Aquatic vegetation plays a crucial ecological role. The growing use of constructed wetlands for sewage treatment, alongside increasingly stringent water quality standards, creates a strong impetus for the advancement of improved process design tools. Constructed wetlands (CWs) have emerged as a viable treatment alternative, particularly for developing nations[7,17-20]. They are characterized by low capital and operational costs, the ability to produce high-quality treated effluent with minimal energy loss, and relative ease of operation[2,21,22]. Research indicates that constructed wetlands typically achieve high removal rates for solids, BOD, COD, and pathogens, while the removal rates for nutrients such as nitrogen and phosphorus tend to be lower and more variable. Constructed wetlands are intricate systems involving biological, hydraulic, and chemical processes. However, most existing data on constructed wetland treatments has been sourced from either larger polishing wetlands or smaller constructed wetlands utilized for secondary treatment.
There is a notable deficiency in high-quality, detailed data regarding full-scale constructed wetlands for wastewater treatment, both in terms of temporal and spatial coverage. This gap has compelled CW designers to estimate wetland system parameters by aggregating performance data from various wetlands, resulting in uncertainties regarding the reliability of these parameters[23].

In recent years, global research has focused on the design, construction, and efficacy of constructed wetlands for treating various types of wastewater, including sewage, storm water, industrial effluents, agricultural runoff, acid mine drainage, and landfill leachate. China has recently taken a leading role in these investigations[24,25]. However, most studies concerning the removal of organic matter and nutrients from wastewater using constructed wetlands have been limited to short-term, pilot-scale, or laboratory experiments, with very few long-term assessments of full-scale constructed wetlands. This study aims to evaluate the treatment efficiency and overall functionality of an Angular Horizontal Subsurface Flow constructed wetland system, as well as to analyze seasonal and annual variations in the removal of pH, electrical conductivity (EC), solids, biochemical oxygen demand (BOD5), chemical oxygen demand (COD), nitrates, phosphates, and sulfates.

Numerous researchers have employed phytoremediation techniques in diverse applications. For instance[26] utilized phytoremediation to address water pollution issues in simulated constructed wetlands using *Potamogetoncrispus* and *Hydrillaverticillata*, while Witters et al.[27] applied phytoremediation for energy generation and carbon dioxide reduction on contaminated agricultural land. The current study compares the treatment efficacy of municipal wastewater with and without the presence of macrophytes to assess the potential of phytoremediation. The findings indicate that the macrophytes *Phragmiteskarka*is an effective, rapidly growing floating plant that can adapt to various aquatic environments[28,29]. Its broad leaves and fibrous root system enable it to withstand high pollution loads, making it a suitable macrophyte for municipal wastewater treatment[30,31]. Heavy metals are absorbed by plant tissues (Mishra and Tripathi, 2008) and can subsequently be recovered through drying or ashing processes. This approach not only minimizes the production of hazardous waste but also creates opportunities for recycling revenue[33].

Selection of Vegetation/Plants: The constructed wetland was populated with *Phragmiteskarka*, chosen for its availability and proven effectiveness in previous studies. Research has demonstrated that *Phragmiteskarka*ca effectively treat both domestic and industrial wastewater, particularly from the tannery and food processing sectors. Numerous studies have confirmed its success in removing parameters such as COD, BOD, TSS, TN, NH4-N, TP, and FC[34]. Consequently, *Phragmiteskarka* manually planted at a density of 25 plants per square meter. Prior to its introduction into the wastewater, the plants underwent a one-month acclimatization period using domestic wastewater to enhance their resilience against pollution loads. Throughout this acclimatization phase, the plants were monitored weekly for any signs of toxicity, including chlorosis, necrosis, and malformation, as detailed in previous research[13].

Preference for Emergent Macrophytes: Aquatic macrophytes encompass all sufficiently large plants that are visible to the naked eye. These plants possess parts that are either submerged, floating, or emerging above the water surface, either permanently or for extended periods throughout the year. This category includes not only flowering plants but also ferns, bryophytes, and macrophytic *algae*[35]. While numerous studies have explored the use of floating and submerged macrophytes for the phytoremediation of wastewater and industrial effluents, there is a notable scarcity of research focused on emergent macrophytes for similar applications. Consequently, the role of emergent vegetation in wastewater treatment remains poorly understood and frequently overlooked due to its lack of structural complexity.

Extensive scientific research has been conducted on phytoremediation, particularly examining the role of macrophytes. A significant portion of this research has concentrated on submersed macrophytes rather than emergent ones. The emphasis on submersed macrophytes is largely due to their structural complexity and the associated ecological advantages they provide[36-39]. In contrast, emergent macrophytes are often perceived as less structurally complex, as their intricate growth typically occurs above the water's surface, making them less accessible to various aquatic organisms. Numerous studies have indicated that the greater structural complexity of submersed macrophytes offers enhanced predation refuge for juvenile fish[36,40]. Furthermore, these complex macrophytes are associated with a higher abundance of invertebrates[41,42]. Given the simpler structure of emergent macrophytes, it is hypothesized that they provide a uniform habitat and fulfill similar ecological functions across various trophic levels.

Nevertheless, there is a lack of empirical data from field studies, leaving it uncertain whether all emergent macrophytes confer the same advantages to aquatic organisms. These organisms may colonize different areas or habitats and exist in varying densities. Consequently, further research is necessary to understand the role of emergent macrophytes in shaping littoral habitats.

Emergent macrophytes play several crucial roles within aquatic ecosystems. Notably, they can occur in greater densities than submersed macrophytes in shallow natural lakes and water bodies[43]. It is important to recognize that emergent vegetation can significantly influence ecosystem processes by providing predation refuge for zooplankton, which can lead to a reduction in algae and an improvement in water clarity.

Furthermore, various studies have indicated that submerged and emergent macrophytes exhibit similar levels of invertebrate abundance[44], while other research has highlighted distinct differences in the invertebrate communities associated with these two types of macrophytes[45]. Emergent macrophytes are also crucial for the recruitment dynamics of certain fish species, as they offer essential refuge habitats and access to zooplankton prey during the juvenile stage of their life cycle[46,47]. For instance, the establishment of emergent macrophytes is vital for juvenile fish habitats in turbid water bodies and reservoir systems where submerged macrophytes are challenging to cultivate[48-50]. Radomski and Goeman[51] noted a reduction in the average size and biomass of certain fish species when the coverage of emergent macrophytes was minimal. Nevertheless, there is a scarcity of information regarding the use of aquatic habitats among different species of emergent vegetation, despite their significant ecological role.

Collection of macrophytes: For this study, macrophytes were carefully selected and collected from a nala that flows between Chhatrapati Sambhajinagar and Ahilyanagar at the bridge, ensuring that their root systems remained undamaged and based on their phyto-morphological characteristics. The aquatic macrophyte samples were gathered by hand from the littoral zone and the exposed marginal areas of the sampling sites during the monsoon season, when the soil was moist, allowing for minimal root damage during collection. Only fresh, healthy plants with vibrant green leaves were harvested and kept submerged in water. The plants were then promptly transported to the laboratory, rinsed with tap water, and maintained under appropriate environmental conditions for a month to facilitate acclimatization.

Regarding the test plant: *Phragmites*, commonly referred to as reeds, play a crucial role in constructed wetlands for the treatment of wastewater. Two prominent species include *Phragmitesaustralis* and *Phragmites karka*[52]. *Phragmiteskarka* is typically found in tropical and subtropical regions, often in disturbed habitats. Generally shorter than *P. australis*, it reaches heights of approximately 2-3 meters and forms dense clusters. Its nutrient uptake capacity is comparable to that of *P. australis*, although efficiencies may vary based on local environmental conditions. While it is native to Asia and less frequently invasive than *P. australis*, it can still dominate local vegetation in certain settings. In contrast, *P. australis* has a more extensive global distribution, whereas *Phragmiteskarka*is primarily located in warmer climates.*Phragmiteskarka*, commonly referred to as Common Reed Grass, is a tall, aquatic perennial belonging to the Gramineae family. This plant is characterized by its gregarious nature, growing upright to a height of up to 4 meters, with creeping stolons that can extend as far as 20 meters. The stems, which can reach a width of 1.5 centimeters, are hollow and feature multiple nodes. The leaves measure between 20 to 60 centimeters in length and 8 to 30 millimeters in width, arranged alternately. The inflorescence, which can grow 20 to 70 centimeters long, appears on drooping panicles that are densely packed with fine branches, initially brownish in color but turning silver as they mature.

The *Phragmites* is recognized as a highly invasive species. It has the ability to spread laterally throughout the year by generating new shoots from its rhizomes. Additionally, *Phragmitesaustralis* can reproduce through seeds and stem cuttings, although the germination rate of its seeds is relatively low. This plant thrives in moist and waterlogged environments, including both freshwater and brackish areas, often found along rivers, ditches, lake shores, and ponds. It is also prevalent in abandoned mining sites and is widespread across India. In this context, efforts have been made to highlight the significance of wetlands in treating wastewater using marsh plants.

Research on the application of constructed wetlands (CWs) for wastewater treatment began in the early 1950s. The pioneering experiments were carried out by Kathe Seidel in Germany at the Limnological Station in Plon, affiliated with the Max Planck Society[53-55]. In 1953, she introduced methods to improve inland waterways suffering from over-fertilization, sewage pollution, and siltation through the use of selected macrophyte species[53]. Her early trials demonstrated that macrophytes could thrive in polluted waters and actively remove toxic substances, challenging prevailing expert opinion at the time[16]. During the mid-1950s, Seidel conducted experiments on the use of wetland plants for treating phenol-laden wastewater, and later expanded to dairy and livestock wastewaters[14,16].

Sampling of Municipal Wastewater: The sewage sample was collected from the Nala adjacent to the bridge near Nath Seeds on Paithan Road for phytoremediation experimental studies, utilizing grab sampling techniques. Plastic containers with a capacity of 20 liters each were employed for sampling in duplicate. One set was designated for experimental studies, while the other was sent to laboratories for the analysis of initial parameters, along with additional required samples from the experimental setups. Samples for intermediate and final assessments were collected from the experimental setup as needed and analyzed during the specified intervals.

Wastewater Analysis: Municipal wastewater was sourced from the sampling point at the bridge, and the samples were stored in a refrigerator at a temperature of 4°C until the experiment could be conducted. These samples were initially analyzed prior to treatment with macrophytes to establish baseline values for parameters such as pH, total nitrogen, total phosphorus, COD, BOD, TSS, TDS, and TS, using standard methods. Each sample was filtered through filter paper before analysis.

Experimental Setup: The experimental constructed wetland reactors were utilized to establish the experimental configurations. These reactors were composed of polyvinyl chloride (PVC) crates designed to support the growth of macrophyte islands. The crates, which were perforated and rectangular in shape, served as containers for the phytoremediation beds. Each crate measured 16.0 cm in height, 47.0 cm in length, and 38.0 cm in width at the top, featuring a sloping bottom measuring 40.0 cm in length and 31.0 cm in width, with a working depth of 12.0 cm to accommodate the bedding base for the macrophyte bed. These specially designed crates were employed in the current study.

For the experimental procedure, each setup had a capacity of 36 liters, filled with 32 liters of municipal wastewater. Replicates of both macrophyte species, matched in size and weight, were introduced into each setup separately for a duration of one month. A control setup was also established, consisting of a similar experimental bed without macrophytes, containing only municipal wastewater to allow for natural processes. Throughout the experiment, any effects of evapotranspiration were mitigated by the addition of distilled water as necessary[56,57].

Treatment Methodology: The current research was conducted at the Department of Environmental Science, Indian Institute of Food Science and Technology, Chhatrapati Sambhajinagar, utilizing the constructed wetland approach for the treatment of municipal wastewater with *Phragmiteskarka*. This plant, representative of emergent macrophytes, was collected and exposed to municipal wastewater at a minimum concentration of 10% for acclimatization and stabilization within a specific environment. Following this acclimatization period, the plants were transplanted into the constructed wetlands. The *Phragmiteskarka* plants were positioned in beds prepared with neutral materials conducive to the development of the root zone.

The treatment systems, designed and constructed from plastic crates, were filled with municipal wastewater, leaving a 5 cm freeboard at the top for both the macrophyte and control sets without macrophytes. *Phragmiteskarka* plants were cultivated in a natural environment, while the control set was maintained under the same conditions for comparative analysis. The *Phragmiteskarka*, which were exposed to municipal wastewater, continued to grow with the aim of facilitating nutrient absorption and pollutant degradation. The effectiveness of the treatment was assessed based on various pollution parameters. Treatment efficiency was evaluated across different parameters at multiple treatment intervals, and sewage treatment efficiencies were calculated for both constructed wetland systems: one with *Phragmiteskarka* and the other serving as a control without these plants, yet utilizing similar constructed wetland beds.

Results and Discussion

Changes in the Control Set: The control set was maintained in the same environment as the set containing *Phragmiteskarka*, which was utilized for the treatment of municipal wastewater. Various parameters were monitored, revealing reductions attributed to the natural treatment processes facilitated by microorganisms, including bacteria and fungi. The pH levels shifted from an initial value of 6.77 to 6.78 on the third day, 6.81 on the sixth day, 6.85 on the ninth day, 6.91 on the twelfth day, and 6.94 on the fifteenth day of natural treatment without macrophytes. The electrical conductivity (EC) decreased from 259 µS/cm to 256 µS/cm on the third day, 251 µS/cm on the sixth day, 242 µS/cm on the ninth day, 234 µS/cm on the twelfth day, and 231 µS/cm on the fifteenth day.

There was a slight decline in total suspended solids (TSS), total dissolved solids (TDS), and total solids (TS) concentrations. Initially, TSS was recorded at 593 mg/L, decreasing to 588 mg/L on the third day, 566 mg/L on the sixth day, 552 mg/L on the ninth day, 530 mg/L on the twelfth day, and 521 mg/L on the fifteenth day. Concurrently, TDS levels fell from 1062 mg/L to 1051 mg/L on the third day, 1042 mg/L on the sixth day, 1028 mg/L on the ninth day, 1016 mg/L on the twelfth day, and ultimately to 1003 mg/L on the fifteenth day. Finally, TS concentrations decreased from 1655 mg/L to 1639 mg/L on the third day, 1608 mg/L on the sixth day, 1580 mg/L on the ninth day, 1546 mg/L on the twelfth day, and to 1524 mg/L on the fifteenth day. All these characteristics of municipal wastewater were observed during the treatment process in the control set, which did not include macrophytes throughout the treatment period, with results detailed in Table-1.

A slight decrease in Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) was observed each day throughout the natural treatment process, which did not involve any macrophytes. Initially, BOD and COD levels were recorded at 46.72 mg/L and 136 mg/L, respectively. By the third day, these values decreased to 45.98 mg/L and 132 mg/L; on the sixth day, they further declined to 44.93 mg/L and 127 mg/L; on the ninth day, they were 44.13 mg/L and 118 mg/L; on the twelfth day, they reached 42.89 mg/L and 113 mg/L; and finally, on the fifteenth day, they were measured at 41.9 mg/L and 106 mg/L.

Similarly, nutrient levels also decreased during the wastewater treatment process that utilized natural methods without macrophytes. The nitrate concentration decreased from 28.4 mg/L to 27.3 mg/L by the third day, 23.3 mg/L by the sixth day, 22.4 mg/L by the ninth day, 21.5 mg/L by the twelfth day, and 20.6 mg/L by the fifteenth day. Phosphate and sulfate levels were reduced from 24 mg/L and 168 mg/L to 23.7 mg/L and 162 mg/L on the third day, 23.2 mg/L and 158 mg/L on the sixth day, 22.9 mg/L and 149 mg/L on the ninth day, 21.4 mg/L and 145 mg/L on the twelfth day, and 20.3 mg/L and 141 mg/L on the fifteenth day, respectively. Chloride concentrations decreased from 228 mg/L to 226 mg/L, 220 mg/L, 218 mg/L, 215 mg/L, and 213 mg/L on the third, sixth, ninth, twelfth, and fifteenth days, respectively. These findings are illustrated in Figure-1.

Pollution Reduction in Control: The control sets were positioned near the environment where the *Phragmiteskarka* was utilized for the treatment of municipal wastewater; however, the reduction observed in these control sets was minimal. The alterations and reductions in various parameters within the control sets can be attributed to the natural treatment of wastewater facilitated by the presence of microorganisms, including bacteria and fungi. On the third day, the pH level increased by 0.01 from its initial value of 6.77. This increase continued, resulting in total increments of 0.04, 0.08, 0.14, and 0.17 on the sixth, ninth, twelfth, and fifteenth days, respectively.

The electrical conductivity (EC) exhibited changes of 5 µS/cm, 8 µS/cm, 17 µS/cm, 25 µS/cm, and 28 µS/cm on the third, sixth, ninth, twelfth, and fifteenth days, respectively, starting from an initial value of 259 µS/cm.

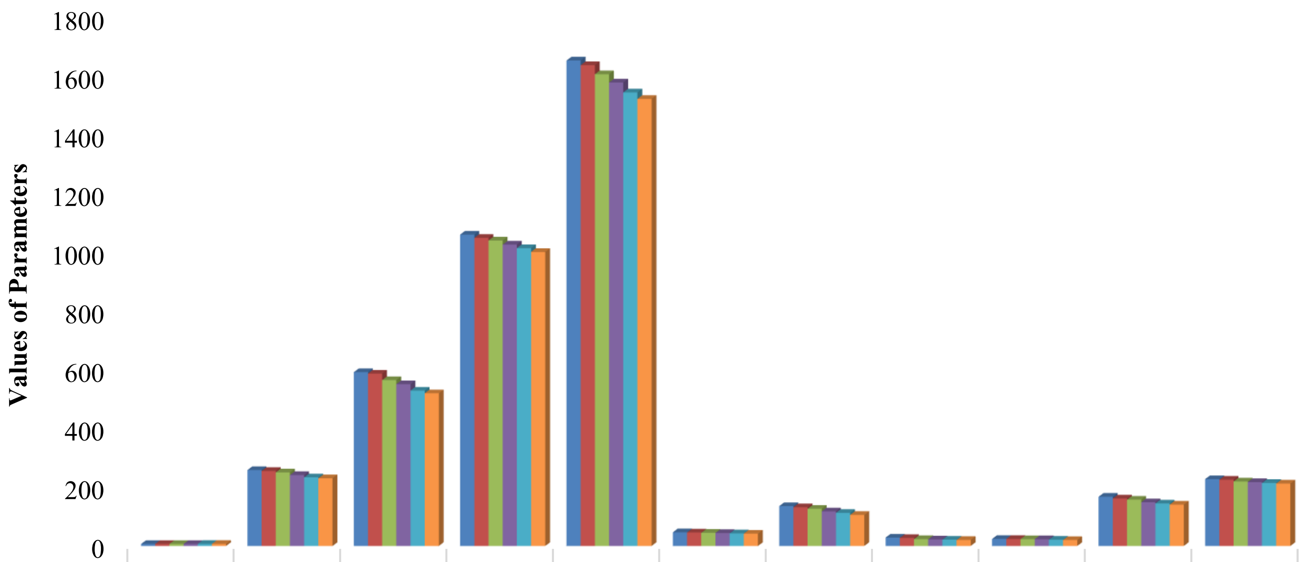
The reductions in total suspended solids (TSS), total dissolved solids (TDS), and total solids (TS) were minimal. TSS levels decreased by 5, 27, 41, 63, and 72 mg/L on the third, sixth, ninth, twelfth, and fifteenth days, respectively. Concurrently, TDS levels were reduced by 11 mg/L on the third day, 20 mg/L on the sixth day, 34 mg/L on the ninth day, 46 mg/L on the twelfth day, and 59 mg/L on the fifteenth day. Ultimately, there was a reduction in TS levels, which decreased by 16 mg/L on the third day, 47 mg/L on the sixth day, 75 mg/L on the ninth day, 109 mg/L on the twelfth day, and 131 mg/L on the fifteenth day. All observed reductions and changes in municipal wastewater during the treatment process in this control set throughout the duration of the study are summarized in Table-2.

The natural treatment process demonstrated a decrease in Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) of 0.74 mg/L and 4 mg/L on the third day, followed by reductions of 1.79 mg/L and 9 mg/L on the sixth day, 2.59 mg/L and 18 mg/L on the ninth day, 3.83 mg/L and 23 mg/L on the twelfth day, and 4.82 mg/L and 30 mg/L on the fifteenth day of treatment, respectively.

Additionally, the control sets exhibited a decline in nutrient levels, including nitrates (NO_3), phosphates (PO_4), sulfates (SO_4), and chlorides during the wastewater treatment process. Nitrate levels decreased by 1.1 mg/L on the third day, 3.1 mg/L on the sixth day, 5 mg/L on the ninth day, 5.9 mg/L on the twelfth day, and 6.8 mg/L on the fifteenth day. Phosphate and sulfate concentrations were reduced by 0.3 mg/L and 6 mg/L on the third day, 0.8 mg/L and 10 mg/L on the sixth day, 1.1 mg/L and 19 mg/L on the ninth day, 2.6 mg/L and 23 mg/L on the twelfth day, and 3.7 mg/L and 27 mg/L on the fifteenth day, respectively. Chloride levels decreased from an initial 228 mg/L by 2 mg/L, 8 mg/L, 10 mg/L, 13 mg/L, and 15 mg/L on the third, sixth, ninth, twelfth, and fifteenth days, respectively. These findings are illustrated in Figure-2.

Table-1: Attributes of municipal wastewater observed during the treatment process without the inclusion of macrophytes in the control group throughout the treatment duration.

Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
pH	6.77	6.78	6.81	6.85	6.91	6.94
EC (µS/cm)	259	256	251	242	234	231
TSS (mg/L)	593	588	566	552	530	521
TDS (mg/L)	1062	1051	1042	1028	1016	1003
TS (mg/L)	1655	1639	1608	1580	1546	1524
BOD (mg/L)	46.72	45.98	44.93	44.13	42.89	41.9
COD (mg/L)	136	132	127	118	113	106
NO_3 (mg/L)	28.4	27.3	23.3	22.4	21.5	20.6
PO_4 (mg/L)	24	23.7	23.2	22.9	21.4	20.3
SO_4 (mg/L)	168	162	158	149	145	141
Cl^- (mg/L)	228	226	220	218	215	213

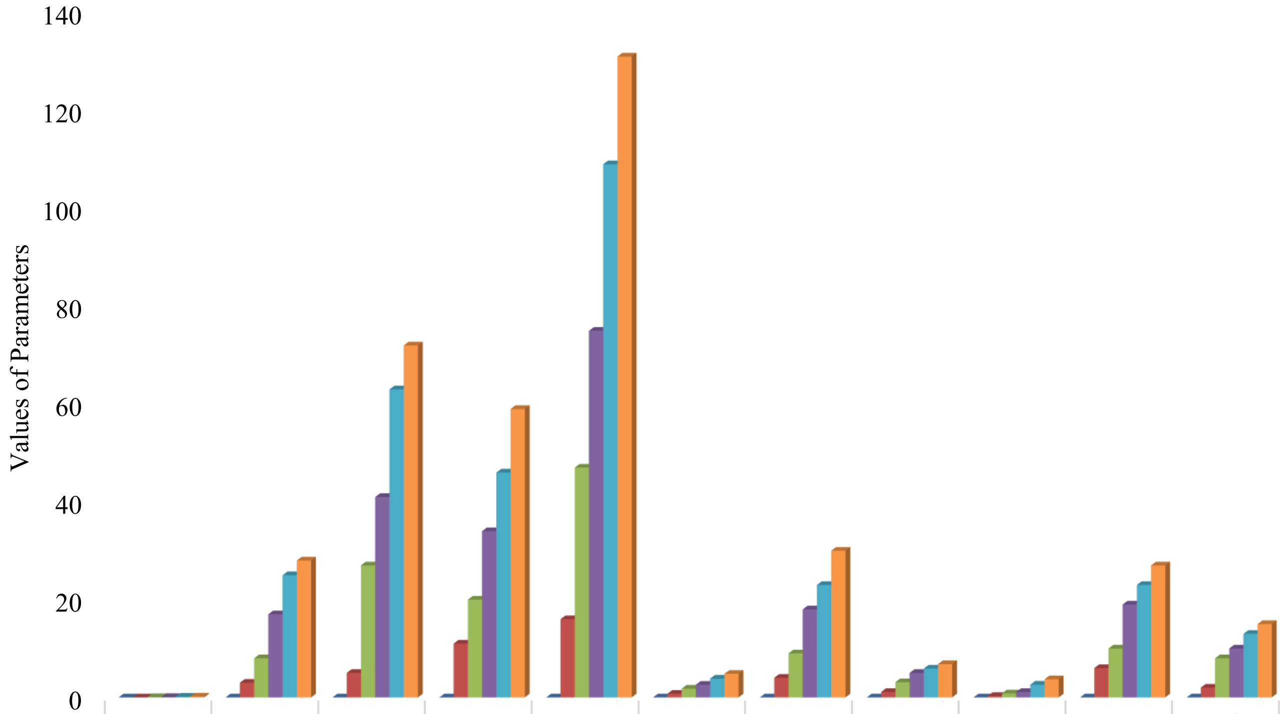


	pH	EC	TSS	TDS	TS	BOD	COD	NO3	PO4	SO4	Cl
Day 1	6.77	259	593	1062	1655	46.72	136	28.4	24	168	228
Day 3	6.78	256	588	1051	1639	45.98	132	27.3	23.7	162	226
Day 6	6.81	251	566	1042	1608	44.93	127	23.3	23.2	158	220
Day 9	6.85	242	552	1028	1580	44.13	118	22.4	22.9	149	218
Day 12	6.91	234	530	1016	1546	42.89	113	21.5	21.4	145	215
Day 15	6.94	231	521	1003	1524	41.9	106	20.6	20.3	141	213

Figure-1: Attributes of municipal wastewater throughout the treatment process when macrophytes are not utilized during the treatment duration.

Table-2: Alterations in parameters during treatment without the presence of macrophytes.

Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
pH	00	0.01	0.04	0.08	0.14	0.17
EC (µS/cm)	00	3	8	17	25	28
TSS (mg/L)	00	5	27	41	63	72
TDS (mg/L)	00	11	20	34	46	59
TS (mg/L)	00	16	47	75	109	131
BOD (mg/L)	00	0.74	1.79	2.59	3.83	4.82
COD (mg/L)	00	4	9	18	23	30
NO_3 (mg/L)	00	1.1	3.1	5	5.9	6.8
PO_4 (mg/L)	00	0.3	0.8	1.1	2.6	3.7
SO_4(mg/L)	00	6	10	19	23	27
Cl^- (mg/L)	00	2	8	10	13	15



	pH	EC	TSS	TDS	TS	BOD	COD	NO3	PO4	SO4	Cl
Day 1	0	0	0	0	0	0	0	0	0	0	0
Day 3	0.01	3	5	11	16	0.74	4	1.1	0.3	6	2
Day 6	0.04	8	27	20	47	1.79	9	3.1	0.8	10	8
Day 9	0.08	17	41	34	75	2.59	18	5	1.1	19	10
Day 12	0.14	25	63	46	109	3.83	23	5.9	2.6	23	13
Day 15	0.17	28	72	59	131	4.82	30	6.8	3.7	27	15

Figure-4: Alterations in parameters during treatment without the presence of macrophytes.

Alterations in the treatment of municipal wastewater using Phragmiteskarka: The application of *Phragmiteskarka* macrophytes in the treatment of municipal wastewater demonstrated superior efficacy compared to natural treatment methods devoid of macrophytes. The reduction in various pollution indicators was more pronounced in the treatments involving *Phragmiteskarka*. The pH levels shifted from an initial measurement of 6.77 to 6.82 on the third day, 6.95 on the sixth day, 7.02 on the ninth day, 7.12 on the twelfth day, and reached 7.24 by the fifteenth day of treatment with *Phragmiteskarka*.

The electrical conductivity (EC) decreased from 259 µS/cm to 247 µS/cm on the third day, 231 µS/cm on the sixth day, 220 µS/cm on the ninth day, 202 µS/cm on the twelfth day, and ultimately to 198 µS/cm on the fifteenth day.

There was a modest reduction in total suspended solids (TSS), total dissolved solids (TDS), and total solids (TS) concentrations. Initially, TSS levels were recorded at 593 mg/L, decreasing to 438 mg/L on the third day, 392 mg/L on the sixth day, 352 mg/L on the ninth day, 310 mg/L on the twelfth day, and 280 mg/L on the fifteenth day. Concurrently, TDS levels fell from 1062 mg/L to 921 mg/L on the third day, 812 mg/L on the sixth day, 723 mg/L on the ninth day, 624 mg/L on the twelfth day, and finally to 599 mg/L on the fifteenth day. Additionally, TS concentrations decreased from 1655 mg/L to 1359 mg/L on the third day, 1204 mg/L on the sixth day, 1075 mg/L on the ninth day, 934 mg/L on the twelfth day, and concluded at 879 mg/L on the fifteenth day. These characteristics of municipal wastewater were monitored throughout the treatment process involving macrophytes, with the results detailed in Table-3.

A significant decrease in Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) was observed daily throughout the treatment process utilizing *Phragmiteskarka*. Initially, the BOD and COD levels were recorded at 46.72 mg/L and 136 mg/L, respectively. By the third day, these values decreased to 38.8 mg/L and 102 mg/L; on the sixth day, they further declined to 30.13 mg/L and 86 mg/L; on the ninth day, they reached 25.7 mg/L and 63 mg/L; on the twelfth day, they were reduced to 23.4 mg/L and 51 mg/L; and finally, on the fifteenth day, they measured 21.9 mg/L and 42 mg/L.

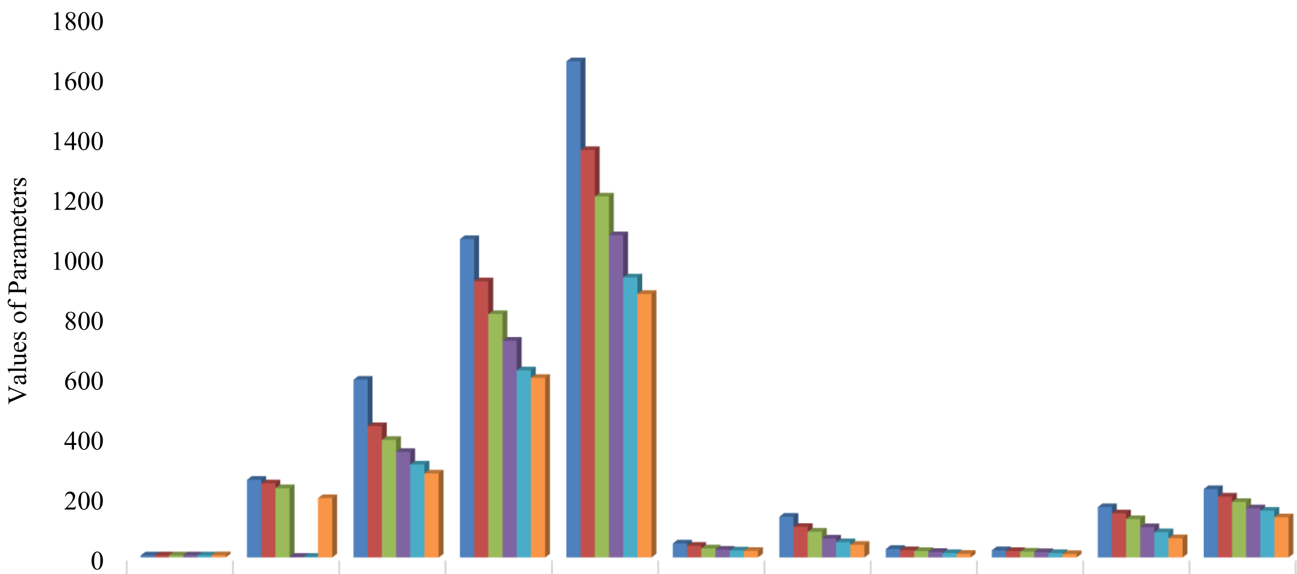
Additionally, the treatment process, which incorporated the natural capabilities of *Phragmiteskarka* macrophytes, resulted in a reduction of various nutrients in the wastewater. The nitrate concentration decreased from 28.4 mg/L to 24.2 mg/L by the third day, further dropping to 21.3 mg/L on the sixth day, 18.4 mg/L on the ninth day, 14.5 mg/L on the twelfth day, and 12.1 mg/L on the fifteenth day. Phosphate and sulfate levels were also reduced from 24 mg/L and 168 mg/L to 21.2 mg/L and 147 mg/L on the third day, 19.5 mg/L and 128 mg/L on the sixth day, 17.9 mg/L and 101 mg/L on the ninth day, 14.4 mg/L and 85 mg/L on the twelfth day, and finally to 11.3 mg/L and 64 mg/L on the fifteenth day. Chloride levels decreased from 228 mg/L to 203 mg/L, 185 mg/L, 164 mg/L, 156 mg/L, and 134 mg/L on the third, sixth, ninth, twelfth, and fifteenth days, respectively. These findings are illustrated in Figure-3.

Pollution Mitigation in Macrophyte Systems: The control sets were positioned next to the environment where the *Phragmiteskarka* was utilized for the treatment of municipal wastewater; however, the reduction observed in these control sets was minimal. The alterations and reductions in various parameters within the control sets can be attributed to the natural treatment of wastewater facilitated by the presence of microorganisms, including bacteria and fungi. The pH levels shifted from an initial value of 6.77, changing by 0.05 on the third day, 0.18 on the sixth day, 0.25 on the ninth day, 0.35 on the twelfth day, and by 0.47 on the fifteenth day during the wastewater treatment with *Phragmiteskarka* macrophytes. The electrical conductivity (EC) changed from 259 µS/cm, increasing by 12 on the third day, 28 on the sixth day, 39 on the ninth day, 57 on the twelfth day, and by 61 on the fifteenth day.

The observed reductions in total suspended solids (TSS), total dissolved solids (TDS), and total solids (TS) indicate that TSS levels decreased by 155, 201, 241, 283, and 313 mg/L on the third, sixth, ninth, twelfth, and fifteenth days, respectively. Concurrently, TDS levels were reduced by 141 mg/L on the third day, 250 mg/L on the sixth day, 339 mg/L on the ninth day, 438 mg/L on the twelfth day, and by 463 mg/L on the fifteenth day. The reductions in TSS and TDS consequently led to a decrease in TS levels, which diminished by 296 mg/L on the third day, 451 mg/L on the sixth day, 580 mg/L on the ninth day, 721 mg/L on the twelfth day, and by 776 mg/L on the fifteenth day. All these reductions and changes in municipal wastewater were documented throughout the treatment process in this control set, with results detailed in Table-2.

Table-3: Attributes of municipal wastewater throughout the treatment process involving *Phragmiteskarka* during the designated treatment period.

Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
pH	6.77	6.82	6.95	7.02	7.12	7.24
EC (µS/cm)	259	247	231	2.20	2.02	198
TSS (mg/L)	593	438	392	352	310	280
TDS (mg/L)	1062	921	812	723	624	599
TS (mg/L)	1655	1359	1204	1075	934	879
BOD (mg/L)	46.72	38.8	30.13	25.7	23.4	21.9
COD (mg/L)	136	102	86	63	51	42
NO_3 (mg/L)	28.4	24.2	21.3	18.4	14.5	12.1
PO_4 (mg/L)	24	21.2	19.5	17.9	14.4	11.3
SO_4 (mg/L)	168	147	128	101	84	64
Cl^- (mg/L)	228	203	185	164	156	134

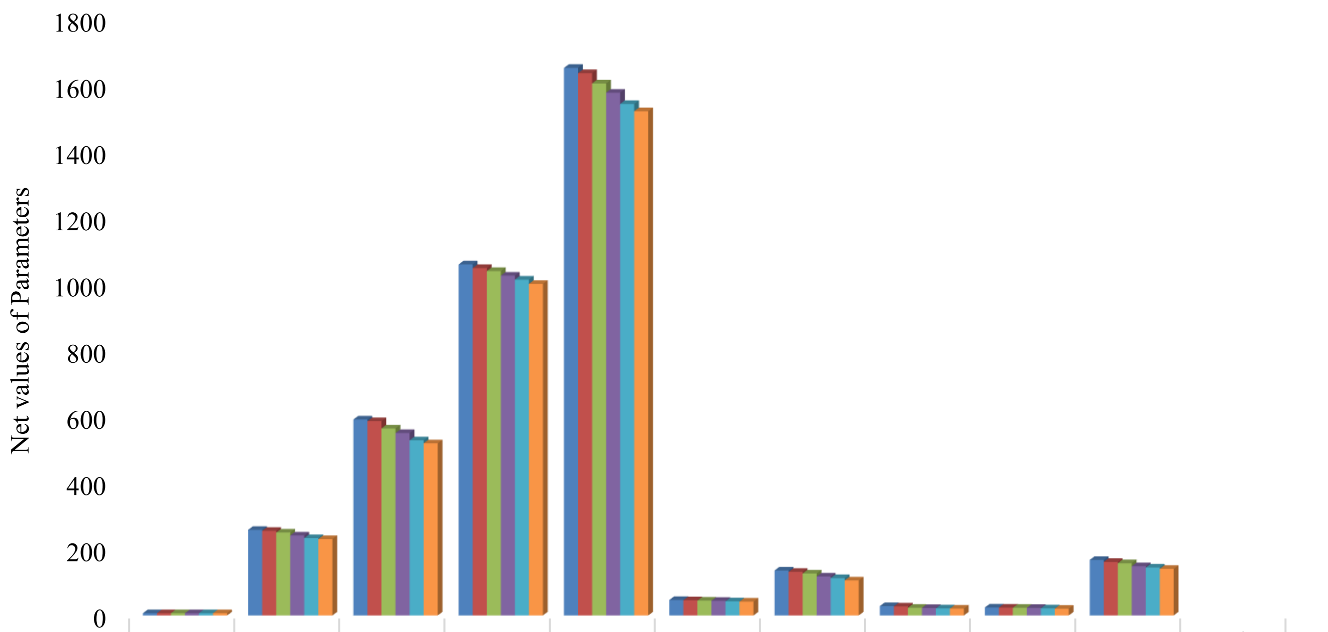


	pH	EC	TSS	TDS	TS	BOD	COD	NO3	PO4	SO4	Cl
Day 1	6.77	259	593	1062	1655	46.72	136	28.4	24	168	228
Day 3	6.82	247	438	921	1359	38.8	102	24.2	21.2	147	203
Day 6	6.95	231	392	812	1204	30.13	86	21.3	19.5	128	185
Day 9	7.02	2.2	352	723	1075	25.7	63	18.4	17.9	101	164
Day 12	7.12	2.02	310	624	934	23.4	51	14.5	14.4	84	156
Day 15	7.24	198	280	599	879	21.9	42	12.1	11.3	64	134

Figure-3: Attributes of municipal wastewater throughout the treatment process utilizing *Phragmiteskarka* during the designated treatment period.

Table-4: Net alterations in the characteristics of municipal wastewater throughout the treatment period using *Phragmiteskarka*

Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
pH change	6.77	6.78	6.81	6.85	6.91	6.94
EC (µS/cm)	259	256	251	242	234	231
TSS (mg/L)	593	588	566	552	530	521
TDS (mg/L)	1062	1051	1042	1028	1016	1003
TS (mg/L)	1655	1639	1608	1580	1546	1524
BOD (mg/L)	46.72	45.98	44.93	44.13	42.89	41.9
COD (mg/L)	136	132	127	118	113	106
NO_3 (mg/L)	28.4	27.3	23.3	22.4	21.5	20.6
PO_4 (mg/L)	24	23.7	23.2	22.9	21.4	20.3
SO_4 (mg/L)	168	162	158	149	145	141
Cl^- (mg/L)						



	pH change	EC	TSS	TDS	TS	BOD	COD	NO3	PO4	SO4	Cl
Day 1	6.77	259	593	1062	1655	46.72	136	28.4	24	168	
Day 3	6.78	256	588	1051	1639	45.98	132	27.3	23.7	162	
Day 6	6.81	251	566	1042	1608	44.93	127	23.3	23.2	158	
Day 9	6.85	242	552	1028	1580	44.13	118	22.4	22.9	149	
Day 12	6.91	234	530	1016	1546	42.89	113	21.5	21.4	145	
Day 15	6.94	231	521	1003	1524	41.9	106	20.6	20.3	141	

Figure-4: Net alterations in the characteristics of municipal wastewater throughout the treatment period using *Phragmiteskarka*.

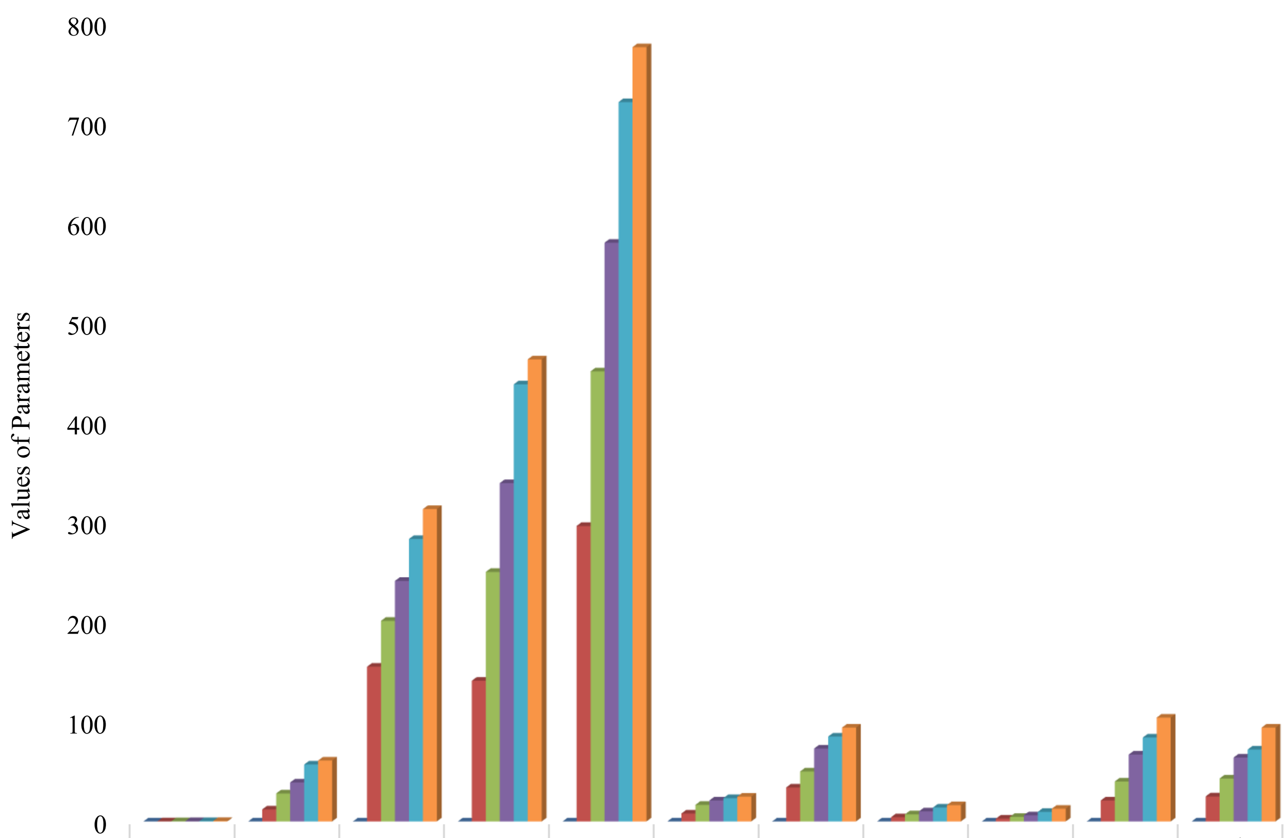
Table-5: Alterations in parameters during treatment with *Phragmiteskarka* macrophytes.

Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
pH	00	0.05	0.18	0.25	0.35	0.47
EC (µS/cm)	00	12	28	39	57	61
TSS (mg/L)	00	155	201	241	283	313
TDS (mg/L)	00	141	250	339	438	463
TS (mg/L)	00	296	451	580	721	776
BOD (mg/L)	00	7.92	16.59	21.02	23.32	24.82
COD (mg/L)	00	34	50	73	85	94
NO_3 (mg/L)	00	4.2	7.1	10	13.9	16.3
PO_4 (mg/L)	00	2.8	4.5	6.1	9.6	12.7
SO_4 (mg/L)	00	21	40	67	84	104
Cl^- (mg/L)	00	25	43	64	72	94

The natural treatment process demonstrated a decrease in Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) of 7.92 mg/L and 34 mg/L on the third day, followed by reductions of 16.59 mg/L and 50 mg/L on the sixth day, 21.02 mg/L and 73 mg/L on the ninth day, 23.32 mg/L and 85 mg/L on the twelfth day, and 24.82 mg/L and 94 mg/L on the fifteenth day of treatment, respectively.

Additionally, the nutrient levels, including nitrate (NO_3), phosphate (PO_4), sulfate (SO_4), and chlorides, were also diminished in the control sets throughout the wastewater treatment process. Nitrate levels decreased by 4.2 mg/L on the third day, 7.1 mg/L on the sixth day, 10 mg/L on the ninth day, 13.9 mg/L on the twelfth day, and 16.3 mg/L on the fifteenth day. Phosphate and sulfate levels were reduced by 2.8 mg/L and 21 mg/L on the third day, 4.5 mg/L and 40 mg/L on the sixth day, 6.1 mg/L and 67 mg/L on the ninth day, 9.6 mg/L and 84 mg/L on the twelfth day, and 12.7 mg/L and 104 mg/L, respectively. Chloride levels decreased from 228 mg/L by 25 mg/L, 43 mg/L, 64 mg/L, 72 mg/L, and 94 mg/L on the third, sixth, ninth, twelfth, and fifteenth days, respectively. These findings are illustrated in Figure-5.

In the treatment of municipal wastewater, a natural degradation process was observed, akin to that in the control groups. The improvement in the treatment efficacy can be attributed to the incorporation of *Phragmiteskarka*. To accurately assess the reduction in pollutants, it is essential to subtract the values recorded in the control groups. In summary, the net decrease in pollution parameters of municipal wastewater, after accounting for the values from the control groups, reflects the true reduction in pollution achieved through the use of *Phragmiteskarka* in constructed wetlands. The findings are presented in Table 6 and illustrated in Figure-6.

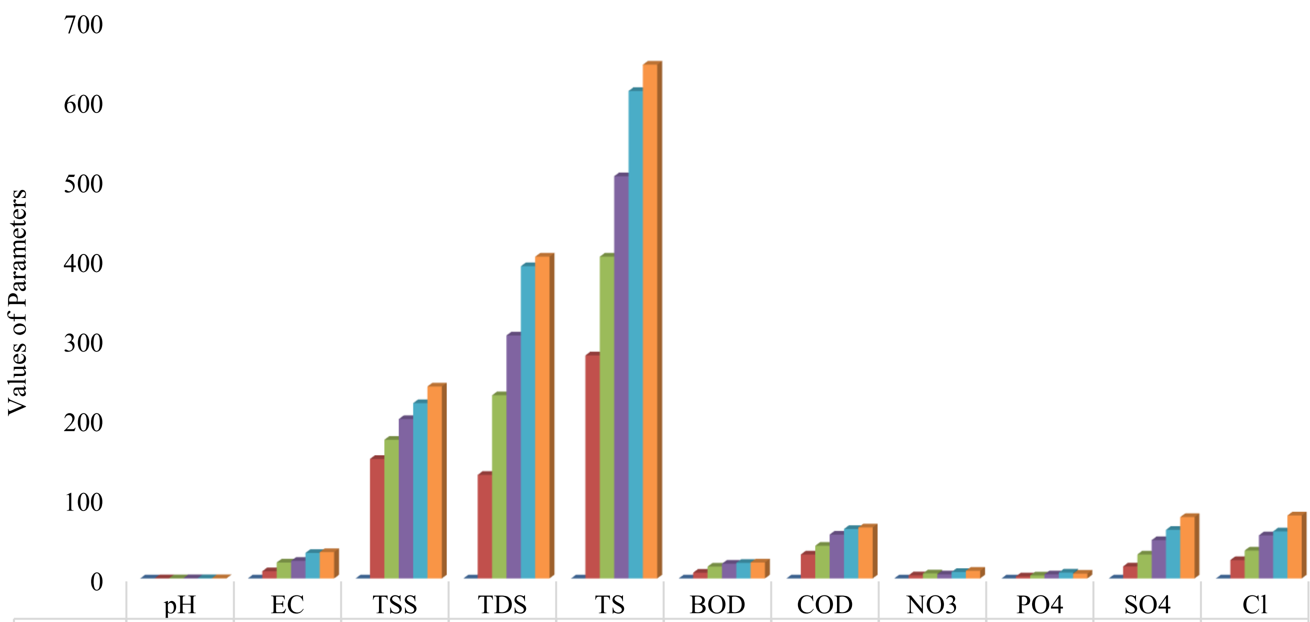


	pH	EC	TSS	TDS	TS	BOD	COD	NO3	PO4	SO4	Cl
Day 1	0	0	0	0	0	0	0	0	0	0	0
Day 3	0.05	12	155	141	296	7.92	34	4.2	2.8	21	25
Day 6	0.18	28	201	250	451	16.59	50	7.1	4.5	40	43
Day 9	0.25	39	241	339	580	21.02	73	10	6.1	67	64
Day 12	0.35	57	283	438	721	23.32	85	13.9	9.6	84	72
Day 15	0.47	61	313	463	776	24.82	94	16.3	12.7	104	94

Figure-5: Alterations in parameters during treatment with *Phragmiteskarka* macrophytes.

Table-6: Overall change in parameters resulting from the treatment with *Phragmiteskarka.*

Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
pH	00	0.04	0.14	0.17	0.21	0.30
EC (µS/cm)	00	9	20	22	32	33
TSS (mg/L)	00	150	174	200	220	241
TDS (mg/L)	00	130	230	305	392	404
TS (mg/L)	00	280	404	505	612	645
BOD (mg/L)	00	7.18	14.8	18.43	19.49	20
COD (mg/L)	00	30	41	55	62	64
NO_3 (mg/L)	00	3.9	6.3	5	8	9.5
PO_4 (mg/L)	00	2.5	3.7	5	7.3	5.9
SO_4 (mg/L)	00	15	30	48	61	77
Cl^- (mg/L)	00	23	35	54	59	79



	pH	EC	TSS	TDS	TS	BOD	COD	NO3	PO4	SO4	Cl
Day 1	0	0	0	0	0	0	0	0	0	0	0
Day 3	0.04	9	150	130	280	7.18	30	3.9	2.5	15	23
Day 6	0.14	20	174	230	404	14.8	41	6.3	3.7	30	35
Day 9	0.17	22	200	305	505	18.43	55	5	5	48	54
Day 12	0.21	32	220	392	612	19.49	62	8	7.3	61	59
Day 15	0.3	33	241	404	645	20	64	9.5	5.9	77	79

Figure-6: Overall change in parameters resulting from the treatment with *Phragmiteskarka.*

Parameter-wise Comparison: Variation in pH Levels: In wastewater treatment, it is essential to optimize biological processes to guarantee effective pollutant removal and maintain microbial activity. At the outset, the pH levels in both the control groups and those incorporating *Phragmiteskarka* within the constructed wetlands for municipal wastewater treatment were the similar. Nevertheless, the control groups demonstrated a more gradual rise in pH values in comparison to the groups with *Phragmiteskarka*. Over the entire treatment duration, the rate of pH increase in the groups containing the macrophyte remained consistently elevated. The variations in pH throughout the treatment phases for both sets are detailed in Table-7 and illustrated graphically in Figure-7.

Variation in Electrical Conductivity (EC): Electrical conductivity plays a crucial role in wastewater management, as it indicates the concentration of dissolved substances, including total dissolved solids (TDS), chemicals, and minerals present in the water. A higher level of impurities correlates with increased conductivity. It is important to note that even minimal levels of contaminants can significantly alter the electrical conductivity of wastewater.The electrical conductivity consistently increased in both the control groups and those containing macrophytes within the constructed wetlands (Table-8). Notably, the rise in EC was more pronounced in the groups treated with *Phragmiteskarka* compared to those without macrophytes. The fluctuations in EC throughout the entire duration of municipal wastewater treatment in both the control groups and those with *Phragmiteskarka* are illustrated in Figure-8.

Table-7: Variation in pH Levels during the Treatment of Municipal Wastewater.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
pH in Control		6.77	6.78	6.81	6.85	6.91	6.94
pH in P karka		6.77	6.82	6.95	7.02	7.12	7.24
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

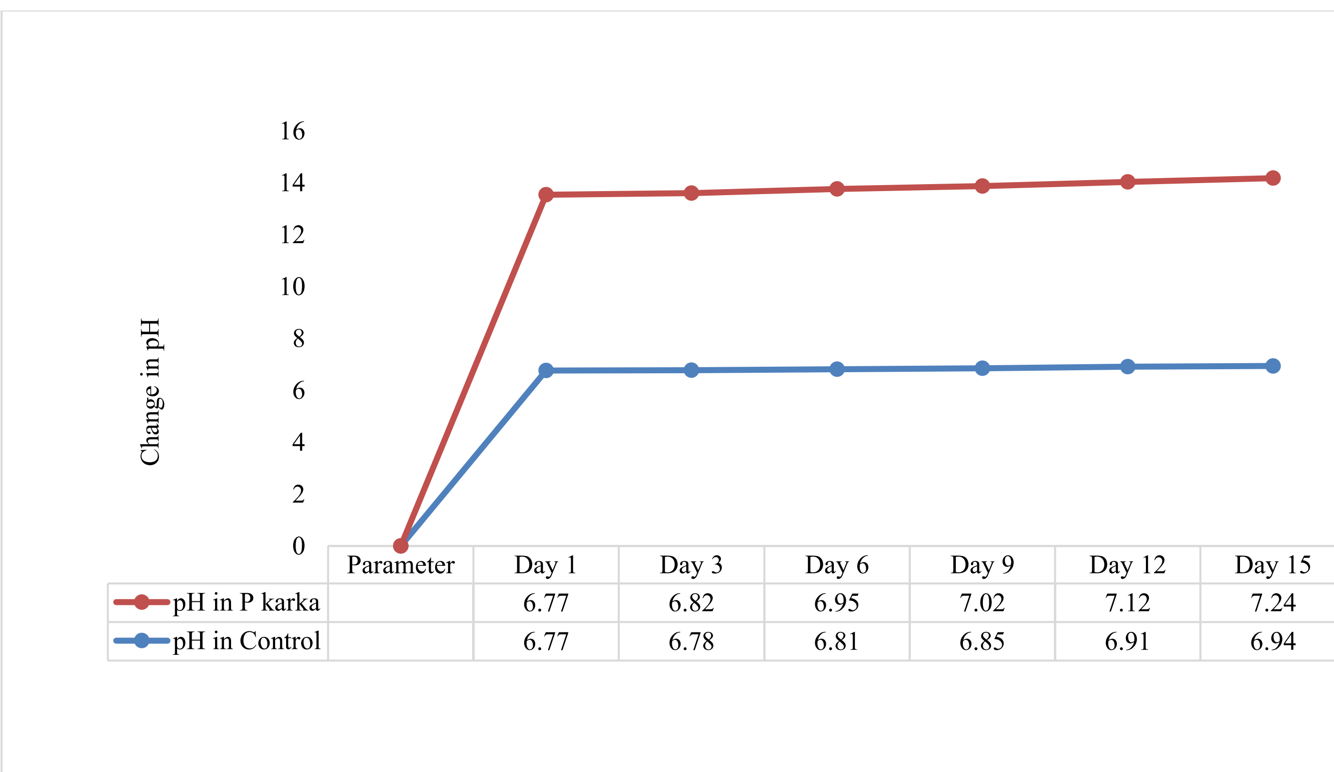


Figure-7: Variation in pH Levels throughout the Treatment of Municipal Wastewater.

Reduction in Total Suspended Solids (TSS): Various sizes of organic particles and inorganic impurities can play a significant role in elevating the concentration of suspended solids. The majority of suspended solids consist of inorganic materials. TSS is a crucial indicator of water quality in wastewater treatment processes and for assessing environmental health. Wastewater is often laden with significant amounts of suspended organic and inorganic substances that need to be eliminated through methods such as screening, filtration, or settling/flotation before being released into the environment. The total suspended solids (TSS) in municipal wastewater treated with *Phragmiteskarka* exhibited a consistent decrease, in contrast to the slower reduction observed in the control groups that did not utilize this plant. Both treatment sets were conducted under identical environmental conditions and operational parameters. Comparative data illustrating the TSS reduction in both treatment groups is provided in Table 9 and visually represented in Figure-9.

Table-8: Variation in Electrical Conductivity (EC) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
EC in Control		259	256	251	242	234	231
EC in P karka		259	247	231	2.20	2.02	198
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

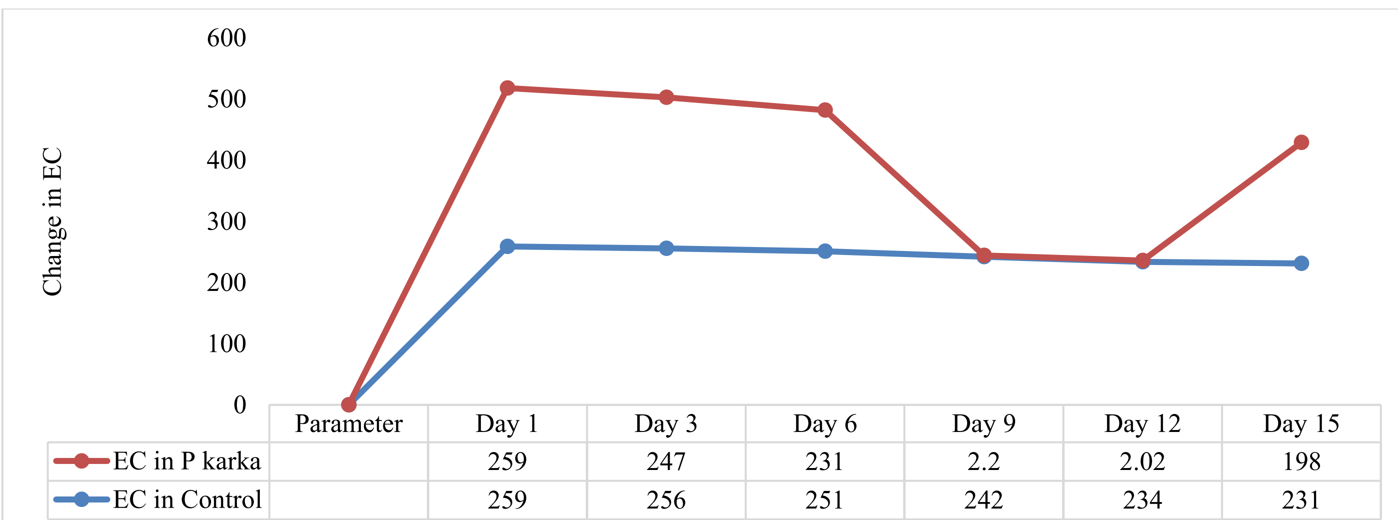


Figure-8: Variation in Electrical Conductivity (EC) during the treatment of municipal water in both the control group and the group with Phragmiteskarka macrophytes.

Table-9: Variation in total suspended solids (TSS) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
TSS in Control		593	588	566	552	530	521
TSS in P karka		593	438	392	352	310	280
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

Decrease in Total Dissolved Solids (TDS): The term "total dissolved solids" (TDS) refers to particles with a diameter greater than approximately 2 µm present in the water column. Particles smaller than 2 µm are classified as soluble in water and are referred to as "dissolved solids." The majority of suspended solids consist of inorganic materials, although algae and bacteria can also contribute to the overall concentration of total dissolved solids. These solid particles encompass a range of drifting and floating objects in water, including sand, silt, sediments, algae, and plankton. Additionally, the concentration of TDS can be further increased by organic particles derived from the decomposition of animal and plant matter.

There was a significant reduction in Total Dissolved Solids (TDS) in both control groups without macrophytes and in those containing Phragmiteskarka macrophytes throughout the treatment period. The decline in TDS levels was notably greater in the treatment groups that included macrophytes compared to those without. The findings regarding TDS reduction in both groups are summarized in Table 10 and illustrated in Figure-10.

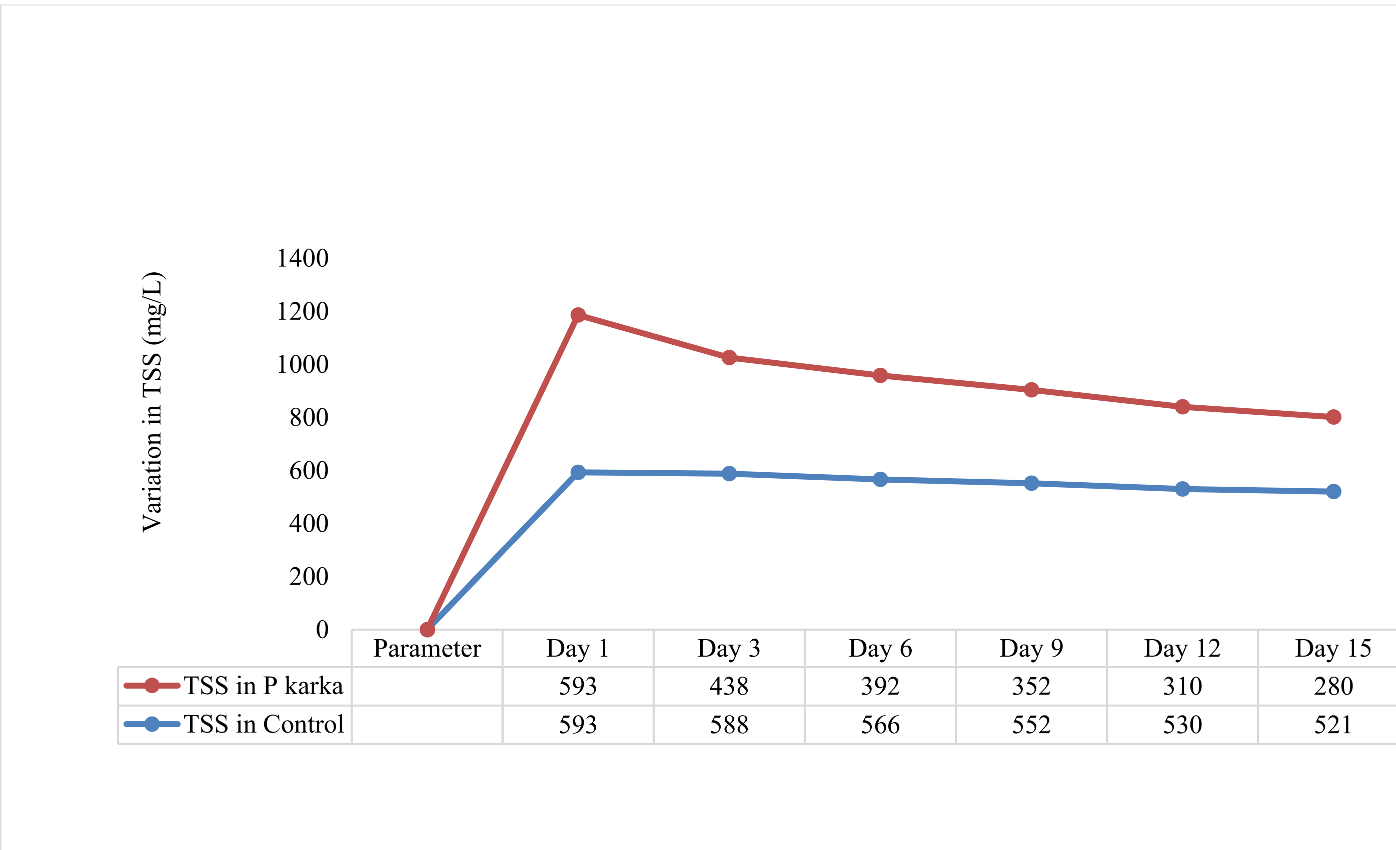


Figure-9: Variation in total suspended solids (TSS) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Table-10: Changes in total dissolved solids (TDS) during the treatment of municipal water in both control groups and those with Phragmiteskarka macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
TDS in Control		1062	1051	1042	1028	1016	1003
TDS in P karka		1062	921	812	723	624	599
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

Decrease in Total Solids (TS): Total solids in water comprise both dissolved solids and suspended or settleable solids. In the context of stream water and wastewater, dissolved solids include various ions and particles such as calcium, chlorides, nitrate, phosphorus, iron, sulfur, and others.

Elevated levels of total solids can render the water unappealing and may negatively impact individuals who are not accustomed to such water quality. Additionally, both excessively high and low concentrations of total solids can hinder the effectiveness of wastewater treatment facilities and disrupt industrial processes that rely on raw water.

The presence of total solids in water influences water clarity. Increased solid concentrations reduce light penetration in the water, which can impede photosynthesis in aquatic vegetation. Furthermore, water with higher total solids tends to warm more quickly and retain heat, potentially harming aquatic organisms that thrive in cooler environments.

Total solids originate from various sources, including industrial effluents, sewage, fertilizers, runoff from roads, and soil erosion. In the present research work, the treatment of municipal wastewater in both the control groups, which lacked macrophytes, and the groups containing *Phragmiteskarka* in constructed wetlands led to a reduction in total solids in both experimental conditions. However, the rate of TS reduction was significantly greater in the groups with *Phragmiteskarka* compared to the control groups. The findings regarding TS reductions in these groups are detailed in Table 11, and the corresponding values are illustrated in Figure-11.

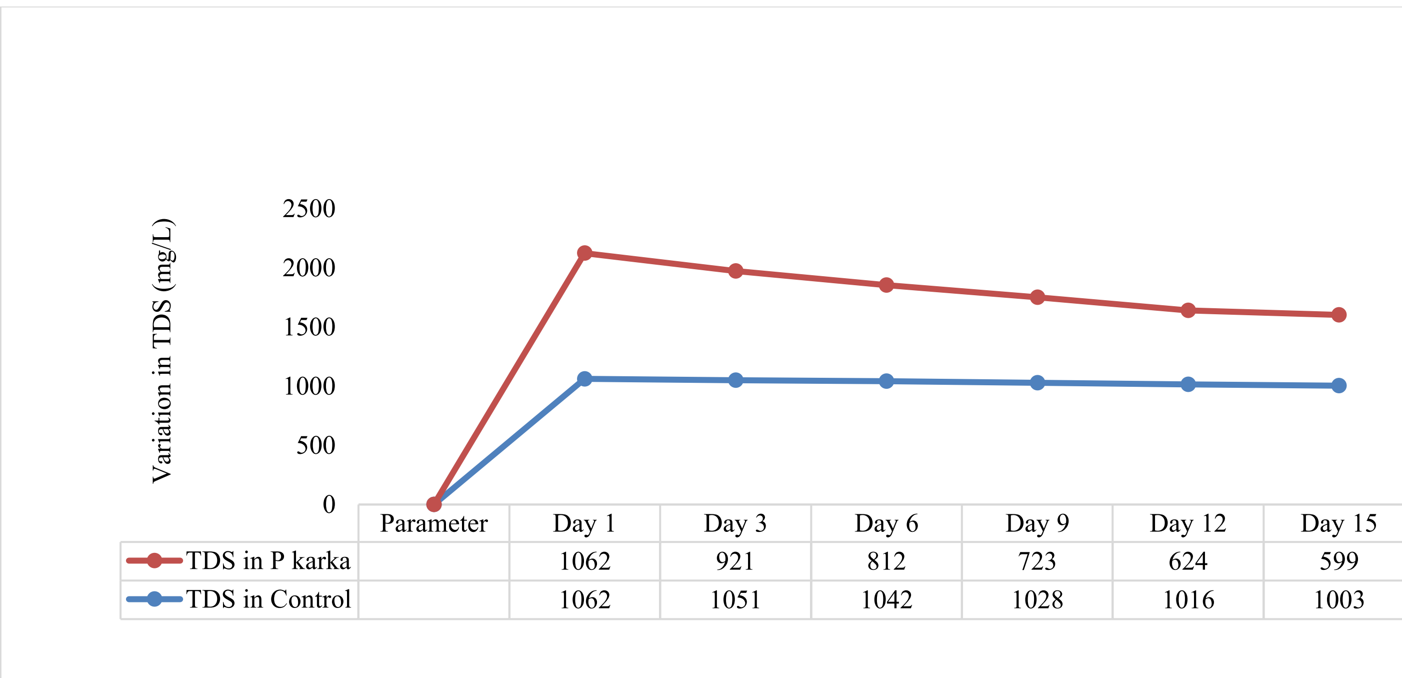


Figure-10: Variation in total dissolved solids (TDS) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Table-11: Decrease in total solids (TS) during the treatment of municipal wastewater in both control groups and groups with *Phragmiteskarka* macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
TS in Control		1655	1639	1608	1580	1546	1524
TS in P karka		1655	1359	1204	1075	934	879
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

Reduction in BOD: Biological/Biochemical Oxygen Demand (BOD) serves as a crucial indicator in wastewater treatment operations, evaluating the efficacy of the treatment process. Elevated BOD levels suggest inadequate treatment, necessitating modifications or enhancements to the treatment approach. Conversely, low BOD levels indicate effective treatment, demonstrating that organic pollutants have been successfully eliminated. Biochemical Oxygen Demand (BOD) serves as a crucial indicator of the pollution level in wastewater. In this study, reductions in BOD were noted in both the control groups and those containing macrophytes. However, the decrease in BOD was significantly lower in the control groups compared to the reductions observed in the treatment groups with Phragmiteskarka. The findings regarding BOD reduction from this investigation are summarized in Table 12 and illustrated graphically in Figure-12.

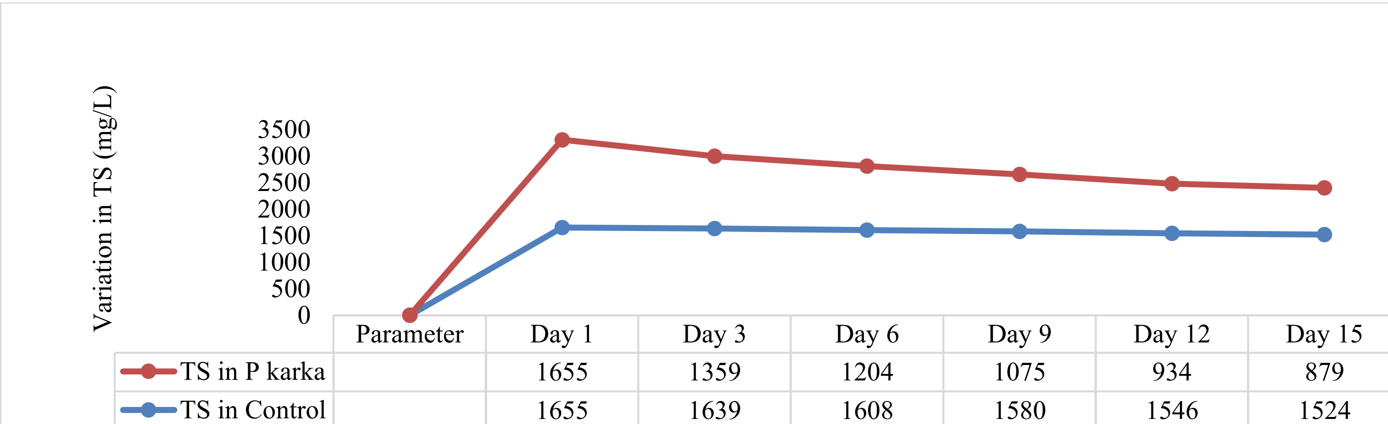


Figure-11: Variation in total solids (TS) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Table-12: Changes in Biochemical Oxygen Demand (BOD) during the treatment of municipal water in both control groups and those with *Phragmiteskarka* macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
BOD in Control		46.72	45.98	44.93	44.13	42.89	41.9
BOD in P karka		46.72	38.8	30.13	25.7	23.4	21.9
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

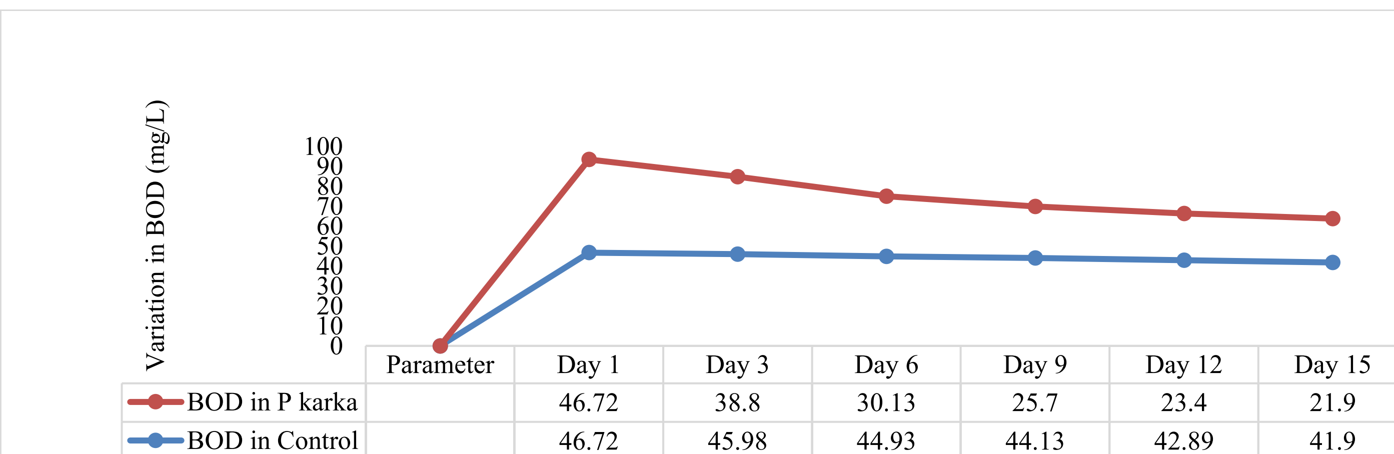


Figure-12: Variation in Biochemical Oxygen Demand (BOD) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Reduction in COD: COD is the most widely used alternative to BOD for determining the concentration of organic matter in wastewater samples. The chemical oxygen demand (COD) test quantifies the total organic content in terms of oxygen by oxidizing both biodegradable and non-biodegradable organic materials present in the wastewater. It serves as an indicator of reducing substances in the water, including organic compounds, nitrites, sulfides, and ferrous salts, with organic matter being the most prevalent. This measurement is essential for evaluating the potential environmental impact of wastewater. Elevated COD levels are often associated with organic pollutants such as food waste, fats, oils, and greases, which are typically found in both industrial and municipal wastewater. Reducing COD is vital for preserving healthy aquatic ecosystems and ensuring compliance with environmental regulations.

Chemical Oxygen Demand (COD) is commonly utilized as a key indicator in wastewater treatment processes. This study examined the reduction of COD in municipal wastewater within constructed wetlands, comparing systems that included *Phragmiteskarka* to those that did not incorporate any macrophytes. The findings revealed that the COD reduction in the systems lacking macrophytes was minimal, whereas a significantly greater reduction was noted in the systems that utilized *Phragmiteskarka*. The comprehensive results from this investigation are detailed in Table 13 and illustrated in Figure-13.

Table-13: Reductions in Chemical Oxygen Demand (COD) during the treatment of municipal wastewater in both control systems and those with *Phragmiteskarka* macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
COD in Control		136	132	127	118	113	106
COD in P karka		136	102	86	63	51	42
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

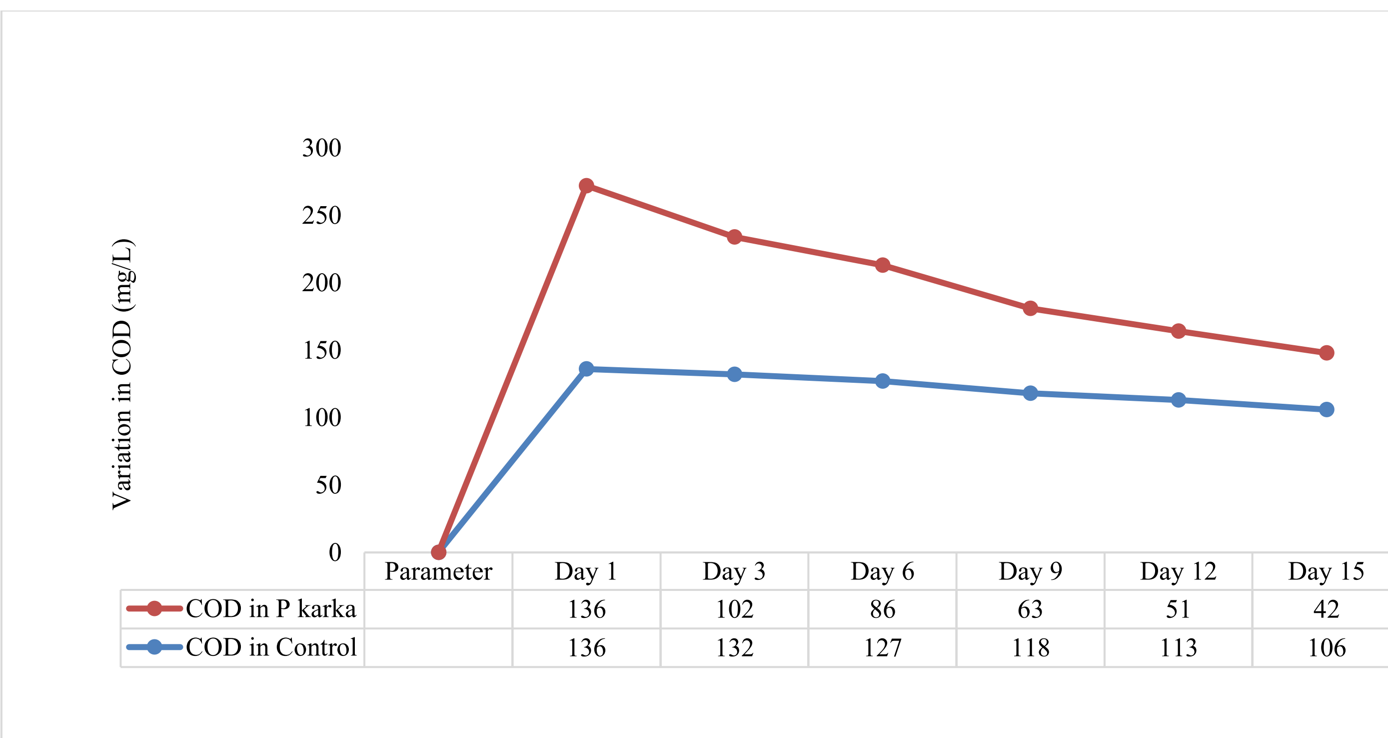


Figure-13: Variation in Chemical Oxygen Demand (COD) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Nitrate (NO_3) Reductions: Nitrate pollution in water bodies and wastewater is a global issue, presenting significant challenges from both technical and scientific perspectives. The presence of nitrates in water or wastewater leads to critical problems, including the depletion of aquifers and the eutrophication of rivers and other aquatic environments. Nitrates originate from both natural processes and human activities, particularly due to the uncontrolled discharge of treated or untreated domestic and industrial wastewater[58,59]. Consequently, numerous studies have been conducted to explore methods for removing nitrates from wastewater, aiming to achieve acceptable concentrations in treated water before it is released into the environment. This investigation can be regarded as part of this ongoing research effort.

Nitrates are essential for the growth of all living organisms. This study examined the reduction of nitrates in municipal wastewater utilizing *Phragmiteskarka*, comparing the results with control groups that did not include any macrophytes, implemented through constructed wetlands. The control groups exhibited only minimal reductions in nitrates, while the treatment groups with *Phragmiteskarka* demonstrated significant and notable reductions. A summary of the findings is presented in Table-14, with graphical representation provided in Figure-14.

Table-14: Reductions in Nitrate (NO_3) Levels during the Treatment of Municipal Water in Both Control Groups and Groups with *Phragmiteskarka* Macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
NO_3 in Control		28.4	27.3	23.3	22.4	21.5	20.6
NO_3 in P karka		136	102	86	63	51	42
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

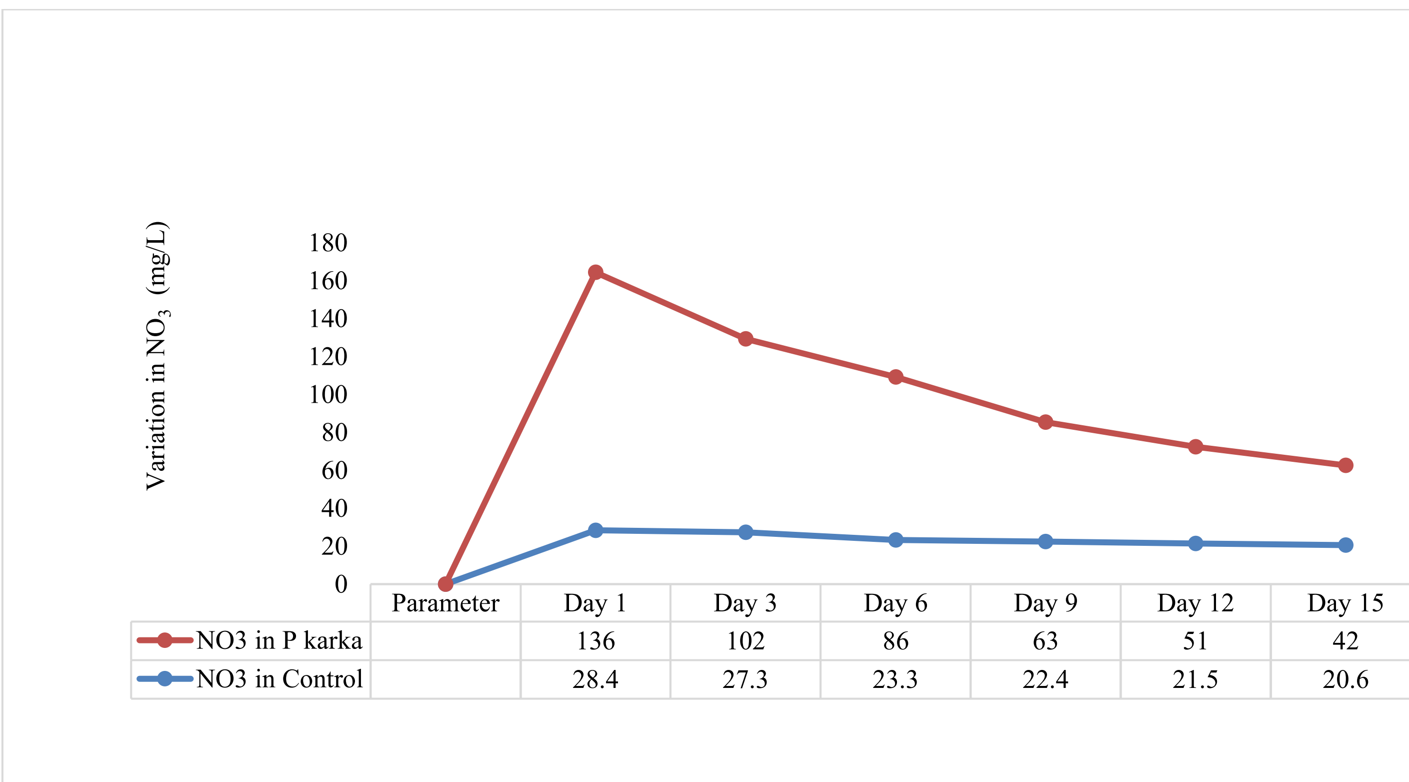


Figure-14: Variation in Nitrates (NO_3) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Reduction of Phosphates: Phosphates present in water bodies and wastewater can lead to significant issues, disrupting the fragile equilibrium of aquatic flora and fauna. Typically, phosphate pollution stems from human activities such as the disposal of fertilizers, runoff from agricultural and urban areas, and the release of industrial and household sewage, including effluents from overloaded septic systems. In natural ecosystems, phosphorus is recognized as a limiting nutrient for plant development, meaning that plant growth is constrained until adequate phosphorus is accessible for absorption. Municipal wastewater often contains elevated levels of phosphate, which can enhance both growth and the effectiveness of phytoremediation processes in treating wastewater[60]. Constructed wetlands present a promising solution to many challenges related to wastewater management. These macrophytes-based systems operate autonomously, utilizing natural processes to extract phosphates from wastewater and surrounding water sources, all while preserving the integrity of the environment and fostering a more diverse ecological landscape.

Phosphates are commonly found in municipal wastewater in significant quantities. It is essential to eliminate these phosphates from the wastewater prior to its discharge into aquatic environments, as their presence can result in eutrophication. The current study observed a reduction in phosphates. The findings revealed that the rate of phosphate reduction in natural treatment conditions, without the presence of macrophytes, is considerably slow. In contrast, the reduction rate is significantly higher in the treatments that included *Phragmiteskarka* macrophytes. These macrophytes absorb and utilize phosphates for their growth, leading to a decrease in phosphate levels in the wastewater.

The data from this investigation demonstrate that the phosphate reduction rate was more pronounced in the treatment groups containing *Phragmiteskarka* compared to the control groups. The results from both treatment conditions are detailed in Table 15 and illustrated graphically in Figure-15.

Table-15: Variation in Phosphates (PO_4) during the treatment of municipal water in both control groups and groups with *Phragmiteskarka* macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
PO_4 in Control		24	23.7	23.2	22.9	21.4	20.3
PO_4 in P karka		24	21.2	19.5	17.9	14.4	11.3
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

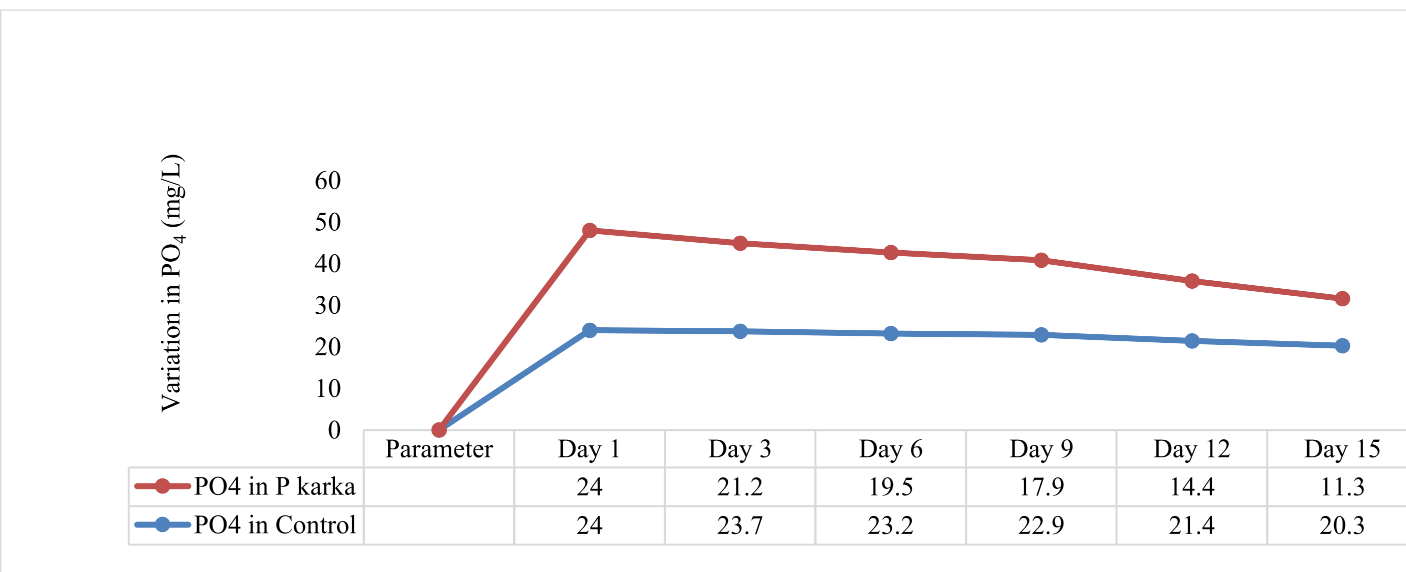


Figure-15: Variation in Phosphates (PO_4) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Reduction in Sulfates: Sulfur is frequently found in wastewater, particularly within the sludge, and it is present in both organic and inorganic forms[61]. Elevated sulfate levels can lead to salinization[62], which poses a threat to aquatic life that can only tolerate specific salinity ranges[63]. This phenomenon can disrupt aquatic ecosystems and result in potentially detrimental consequences. Consequently, the removal of sulfate has been the focus of extensive research globally[64]. Various technologies have been employed for sulfate treatment in water and wastewater, with biological methods being prominent[65-67], including phytoremediation, which is the subject of the current study. It is important to note that sulfate can act as a nutrient for certain bacteria, thereby promoting microbial growth in processes such as the root zone in phytoremediation.

Chlorides in wastewater arise from various sources, with household activities such as cooking and the use of water softeners playing a significant role in increasing chloride concentrations. Water softeners utilize sodium chloride to regenerate ion-exchange resins, which leads to higher chloride levels in the discharged water. Additionally, many household cleaning products contain chloride compounds that are released into wastewater after use. Elevated chloride levels in water or wastewater can pose risks to aquatic life. To tackle the challenge of chloride in wastewater, innovative and effective treatment methods, such as phytoremediation, are being explored in current research. Due to chloride being a conservative ion, conventional biological treatment methods, including activated sludge and trickling filters, are typically ineffective. There are several advanced and emerging techniques for chloride removal, one of which is constructed wetlands. These engineered systems replicate the natural filtration capabilities of wetlands. While constructed wetlands may not be highly effective for chloride removal on their own, they can be integrated into a comprehensive treatment strategy that incorporates additional methods.

In the context of wastewater treatment, sulfates and chlorides are significant components, with sulfates typically being a prevalent and generally non-toxic element. Conversely, while chlorides are essential for certain aquatic environments, elevated concentrations can adversely affect water quality by increasing conductivity and corrosivity. Sulfate contributes to total dissolved solids (TDS) and can react with cations such as sodium, potassium, and magnesium to form various salts. Naturally occurring sulfates can be found in concentrations ranging from a few to several hundred milligrams per liter. The current studies indicate that the reduction of sulfates in wastewater treatments utilizing constructed wetlands was more pronounced in systems containing *Phragmiteskarka* macrophytes compared to control systems devoid of macrophytes. The findings from this investigation are compiled in Table 16 and illustrated in Figure-16.

Table-16: Variation in sulfates (SO_4) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
SO_4 in Control		168	162	158	149	145	141
SO_4 in P karka		168	147	128	101	84	64
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

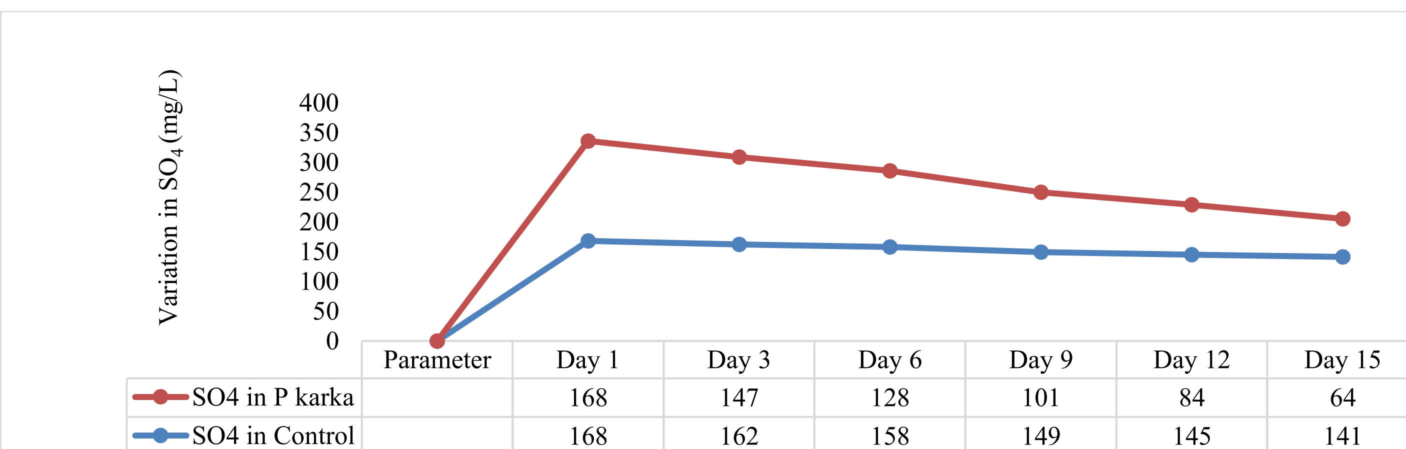


Figure-16: Variation in Sulfates (SO_4) during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Reduction in Chlorides: Chloride is identified as a pollutant for several reasons. While it is essential for the health of aquatic ecosystems, high concentrations of chloride can lead to harmful consequences. Increased levels of chloride can interfere with the reproductive success of freshwater species and plants, raise mortality rates among various organisms, and modify the essential traits of the surrounding ecosystem. Furthermore, when chloride permeates the water table, it can hinder plant respiration and negatively affect the quality of drinking water.

In the current study, the concentration of chlorides decreased gradually in control groups subjected to natural treatment of wastewater, while the treatment groups utilizing macrophytes exhibited a more significant rate of chloride reduction. The findings of this investigation are summarized in Table 17 and illustrated in Figure-17.

Overall Plant Growth: Aquatic plants, known as macrophytes, are vital in the phytoremediation of sewage due to their inherent capacity to absorb, decompose, and stabilize pollutants. Through the process of phytoremediation, these plants can metabolically transform organic contaminants within their tissues, converting harmful substances into less toxic variants. Additionally, macrophytes create habitats and provide nourishment for a variety of microorganisms that assist in further degrading pollutants. In the context of this study focusing on *Phragmiteskarka*, macrophytes are indispensable for sewage phytoremediation, enhancing wastewater treatment and promoting healthier ecosystems. Their proficiency in nutrient absorption and contaminant breakdown renders them essential components of sustainable wastewater treatment systems.

The *Phragmiteskarka* specimens exhibited robust growth in the present studies in municipal wastewater treatments, displaying no evident signs of toxicity or nutrient deficiency. The plants developed fresh green foliage. Observations indicated that during the establishment phase, new growth primarily emerged from rhizomes or rootstocks, while older shoots typically experienced dieback within the initial days of growth.

Table-17: Variation in Chlorides (Cl^-) during the treatment of municipal water in both control groups and those with *Phragmiteskarka* macrophytes.

Set	Parameter	Day 1	Day 3	Day 6	Day 9	Day 12	Day 15
Cl^- in Control		228	226	220	218	215	213
Cl^- in P karka		228	203	185	164	156	134
Change in control		00	0.01	0.04	0.08	0.14	0.17
Change in P karka		00	0.05	0.18	0.25	0.35	0.47
Net change in P karka		00	0.04	0.14	0.17	0.21	0.30

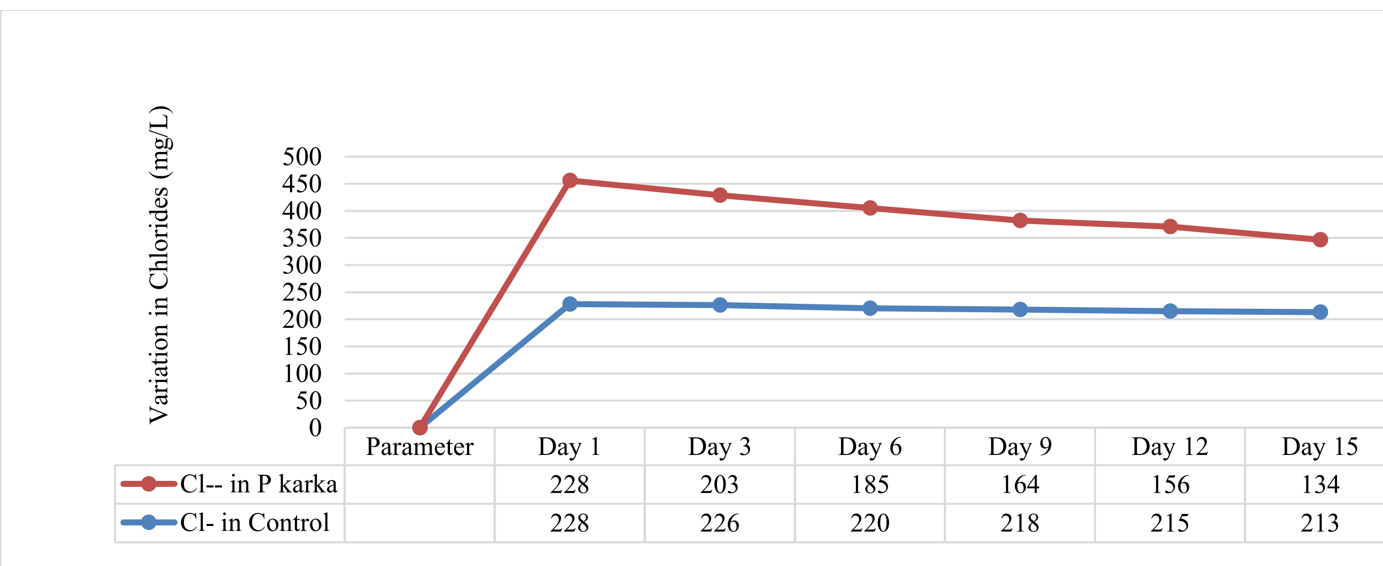


Figure-17: Variation in Chlorides during the treatment of municipal water in both the control sets and the sets with *Phragmiteskarka* macrophytes.

Nutrient Uptake by *Phragmiteskarka*: Municipal wastewater is characterized by substantial concentrations of nutrients such as nitrogen, phosphorus, and sulfate, as indicated by the current research. Macrophytes play a crucial role in nutrient absorption, particularly nitrogen and phosphorus, from wastewater, thereby mitigating issues like eutrophication. In this study focused on municipal wastewater treatment using constructed wetlands, *Phragmiteskarka* effectively absorbed these nutrients through phytoremediation. The plants exhibited a rapid nutrient removal rate during the initial treatment phases, which gradually decreased in subsequent periods when compared to control groups. Nutrient uptake rates were systematically tracked in both the macrophytes-included and control sets, revealing significant differences that underscore the essential function of *Phragmiteskarka*. The variations in nitrogen removal associated with plant biomass may also be partially due to the indirect promotion of nitrification, facilitated by oxygen release in the root zone, which results in gaseous losses through de-nitrification[56,57].

Sewage Treatment Performance: The present study on municipal wastewater treatment highlighted the effectiveness of *Phragmiteskarka* within the constructed wetland, achieving notable reductions in various pollution indicators, including TDS, TSS, BOD, COD, and several nutrients. The system that included *Phragmiteskarka* demonstrated superior pollutant removal efficiency compared to the control group that did not contain macrophytes.

Conclusion

The wastewater that has been treated and processed with *Phragmiteskarka* in constructed wetlands is found to be suitable for various reuse applications. Significant reductions were noted in the average removal efficiencies for several parameters, such as total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nutrients like nitrates, phosphates, sulfates, and chlorides. Furthermore, the pH and electrical conductivity (EC) levels met the standards set by the Bureau of Indian Standards (BIS) for land disposal, discharge into flowing water, and connection to public sewer systems. As a result, the treated wastewater is considered appropriate for a range of uses, including irrigation, including gardening, aquaculture, cleaning, and other secondary applications.

Scope for future study: This treatment method presents significant advantages for managing domestic wastewater compared to conventional techniques such as physical, biological, chemical, and sludge treatment methods. It does not require electrical equipment or chemicals, instead utilizing naturally available materials like gravel, sand, charcoal, and sawdust in the treatment process.

Limitations: There are some major limitations for the widespread applicability and common public acceptance. Further research is needed to overcome the following limitations. i. Phytoremediation is not a universal solution; it has specific limitations that should be considered when selecting the appropriate method for contaminant removal. ii. Time-Intensive: This process is not rapid. It can take several years for plants to effectively lower pollutant concentrations, particularly for contaminants that are deeply entrenched in the soil. iii. Depth Constraints: The reach of plant roots is limited, making it challenging to remediate contaminants that are located at significant depths. iv. Climatic Constraints: The effectiveness of phytoremediation is influenced by climatic conditions. Certain plant species utilized in this method may not flourish in all geographical areas, which restricts its applicability in some regions. In India, there are approximately 400 plant species suitable for phytoremediation, but their effectiveness depends on their compatibility with the local environment and the specific pollutants involved. v. Potential Impact on Wildlife: There is a concern that animals may ingest contaminated plants, leading to potential harm. This risk must be managed carefully, especially in areas with abundant wildlife.

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