Treatment Efficiency of Integrated Constructed Wetland for Domestic Wastewater

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Received: 09-12-2022, Received in Revised form: 24-05-2024, Accepted: 11-06-2024, Published: 30-06-2024

Abstract

Constructed wetlands (CWs) are considered one of the most efficient solutions for treating wastewater and reusing water resources. The present study aimed to monitor the performance of an integrated constructed wetland (ICW) located at NUST, H-12 campus, Islamabad. It has a sedimentation tank for pre-treatment, eight ponds planted with different vegetation (Typha latifolia, Pistia stratiotes, and Centella asiatica), and a FILTER (filtration and irrigated cropping for land treatment and effluent reuse) technology. The objectives of the present study were divided into the analysis of the physicochemical parameters, microbial analysis, and comparison with the past studies on the same ICW. The samples for physicochemical and microbial analysis were collected from four points, i.e., the inlet, sedimentation tank, pond 8, and collection tank. The results indicated that average temperature, pH, and DO range between 23.95-24.20, 6.95-7.20, and 2.25-3.10, respectively. Whereas other parameters showed the removal efficiency as follows: EC 10%, turbidity 73.99%, TSS 79.16%, TDS 32.60%, TS 47.22%, COD 69.01%, NO3-N 52.76%, NO2-N 50.53%, TKN 63.50%, and PO_4^{3-} 41.24%. Gram-negative bacteria with dominating microbial species such as Salmonella, Shigella, and E. coli were found to have a removal rate of up to 95%. The findings indicate that ICW is effective at removing pathogenic microorganisms, organic contaminants, nutrients, and maintaining temperature and pH changes in the water. Moreover, the comparison with past studies showed that the performance of ICW has been maintained over the years.

Keywords: Nutrient removal, Integrated constructed wetland, Physicochemical parameters, Microbial parameter, Phytoremediation, Microbial degradation

Introduction

Rapid urbanization and industrialization adversely affect the environment globally. One of the major problems that cause environmental pollution and degradation is inappropriate wastewater management. Water pollution contaminates drinking water, rivers, lakes, and oceans around the globe. According to estimates from the World Health Organization, 780 million people lack access to potable water, and almost 2.5 billion people lack even the most basic sanitation [1]. Over 40% of the world's population suffers from water scarcity, and the percentage of people who drink treated versus untreated water is expected to rise according to the United Nations [2]. Increased population and improper waste dumping degrade and put stress on the quantity and quality of water bodies. The availability of water in Pakistan was recorded as 5,000 m^3 in 1951 and eventually decreased to 1038 m^3 in 2010, which is very close to the internationally accepted water scarcity level i.e., 1000 m^3. Globally, Pakistan is considered the third most water-stressed country due to yearly per capita water availability of 1017 m^3 [3]. Pakistan is an agrarian nation where the majority of the economy relies on water for crop growth. Currently, just 20% of the nation's population has access to safe drinking water. Twenty-odd percent of the population does not have accessibility to clean water and must make do with tainted water from many sources, including fertilizers, industrial effluents, etc. Water recovery and recycling is therefore the only remaining alternative in light of wastewater management and water sustainability to address the concerns of future water shortages. [4]

One of the alternatives to combat water scarcity and maintain water quality is the development of wastewater treatment systems [5]. Wastewater treatment not only helps in limiting the contaminated water intrusion into water reservoirs, but water requirement may be decreased in various sectors including agriculture, i.e., by reuse of treated water for horticulture. Various natural or conventional systems and ecologically engineered treatment systems and are used for wastewater treatment depending upon their treatment efficiency, effectiveness, climate, topography, variations in season and climate, energy sources, land availability, and capital cost [6].

The majority of nations have effectively controlled water pollution through the deployment of conventional centralized sewage treatment facilities. Activated sludge processing, membrane bioreactors, and membrane separation are a few examples of wastewater treatment technologies that are somewhat expensive and may not be suitable for widespread use in rural areas. Moreover, they prove to be inadequate and restricted in the face of increasingly strict water and wastewater treatment regulations. Therefore, it is crucial to use affordable and effective decentralized alternative treatment technologies for wastewater, particularly in developing nations. Compared to traditional methods, decentralized wastewater treatment systems (DWWTS) are more efficient [7]. Septic tanks, facultative and anaerobic pond systems, and constructed wetlands are some examples of the various forms and configurations of DWWTS. [8]

Among various decentralized treatment systems, constructed wetlands (CWs) are considered as an efficient wastewater treatment technique. Constructed wetland is considered as a treatment system that utilizes natural processes including vegetation of wetlands, media/substrate, and associate microbes, thus enabling the reduction of energy consumption [9, 10]. Constructed wetlands have demonstrated vast potential for domestic and municipal wastewater treatment in rural areas, communities, and developing countries [11, 12].

When compared to conventional wastewater treatment techniques, CWs offer the following benefits: a low construction cost, easy operation, convenient maintenance, and a favorable purifying impact. Not only does it clean wastewater and improve the surrounding environment, but it also has some ecological and financial advantages [13].One of the demerits of constructed wetlands is they may require more area. Despite being more effective, MBR systems are costly and energy-intensive. Whereas, activated sludge processes fall in between in terms of moderate cost, handling adds to the operational complexity of activated sludge systems. Although constructed wetlands need more space than other technologies like Sequential Batch Reactor (SBR), Up-flow Anaerobic Baffled Reactor (UASB), Trickling Filter, Moving Bed Biofilm Reactor (MBBR), and Activated Sludge Process (ASP). In comparison to other technologies, the operating and maintenance costs of constructed wetlands are likewise extremely low, ranging from 1% to 2% of the capital cost. The constructed wetland is energy-efficient [14]. In contrast to mechanical wastewater treatment (i.e., activated sludge system), that costs approximately US $50 per person, subsurface constructed wetlands for the treatment of wastewater in Africa are estimated to cost about US $5 per person [15].

As a developing country Pakistan cannot afford to use traditional wastewater treatment techniques because of the cost factor. Pakistan's land availability and climate make it suitable to use constructed wetland as treatment technology at the fringes of its towns and cities. CW can lower irrigation and power requirements in all areas, from tiny towns to peri-urban areas [4].

The current study was conducted on NUST integrated constructed wetland to evaluate its efficiency in treating wastewater coming from institutes and residential areas of university premises.

The main objectives of this research were a) to measure the percentage removal efficiency of physicochemical and microbial parameters and b) to compare the performance of the constructed wetland with the previous studies conducted on the same integrated constructed wetland to evaluate whether its effectiveness is maintained.

Materials and Methods

Description of integrated constructed wetland (ICW)

The study site was an integrated constructed wetland located at the National University of Science and Technology (NUST), Sector H-12, Islamabad, Pakistan at the following global coordinates. Latitude: 33°38'31.1"N Longitude: 73°00'13.7"E. The United Nations Educational and Cultural Organization (UNESCO) funded the integrated constructed wetland. It was inaugurated on 13th November 2014 by the Minister of Science and Technology. In 2022 the total population of NUST is around 6000 and it covers an area of 707 acres. The total number of students residing in hostels is approximately 3456. The approximate number of residences, flats, and houses for faculty and staff is 238. The total volume of wastewater generated at NUST by different schools, institutes, hostels, and residential areas is about 200,000 US gallons/day. Of which 60-65% of wastewater enters an integrated constructed wetland. CWs installed at NUST may treat around 0.1 million gallons of water per day. The flow into ICW is maintained at 70000 US gallons per day at the inlet. The layout of the wetland system consists of a sedimentation tank, 8 ponds planted with different species of plants, and FILTER technology that further treats wastewater from the 8th pond, and water is then stored in the collection tank. About 70000 US gallons of water per day are being treated and used for horticulture purposes in NUST. The current number of trees in NUST is about 18000. The salient features of the project are shown in **Table I** [6]. As indicated in **Figure 1**, residential wastewater after primary treatment from the sedimentation tank moves through eight HSSF-CW ponds connected in series from pond 1 to pond 8 before entering into FILTER technology. The ICW's treated water is utilized for horticulture, and excess water is discharged into a nearby stream. The substratum used to fill the reed beds in the HSSF-CW is made up of PET (polyethylene terephthalate) sheets and fine and coarse gravel. FILTER-technology composition is as follows: a top layer of soil, followed by sand, gravel, and a layer of pipes protected by a geotextile membrane. The macrophytes for ICW were selected considering the following factors i.e., tolerance, root structure, and nutrient removal efficiency. In this study, the treatment system was planted with *Typha latifolia*, *Pistia stratiotes*, *Centella asiatica*, and *Typha angustifolia*. *Typha latifolia* was planted in pond 1. Whereas ponds 2, 3, 4, and 6 were planted with *Centella asiatica*, and ponds 5 and 7 were planted with *Pistia stratiotes*. In pond 8 aerators were attached. *Typha angustifolia* is planted in FILTER technology [6].

Table I

Topographical characteristics of integrated constructed wetland (ICW)

Location	NUST, H-12 Islamabad
Latitude, Longitude	33.6417767, 73.0035925
Climate	Subtropical
Area of ICW	3065.80 m^2 (0.76 Acre)
Size of HSSF-CW	36.75 m x 30.4 m
Size of FILTER-technology	51.8 m x 36.5 m
Capacity	283.90 m^3 /day
HRT	3.7 days

Table II

Structural specifications of integrated constructed wetland (ICW)

Source of Table I and Table II: Note: From "Performance Efficiency of a Large-Scale Integrated Constructed Wetland: Designed for Domestic Wastewater Treatment" by Naseer et al., 2021, *Journal of Environmental Treatment Techniques*, 9(3), p. 630 (https://dormaj.org/index.php/jett) (https://doi.org/10.47277/JETT/9(3)635). CC

Descriptions		Substrates	HRT (hours)	Width× Length× Depth	Plantations	Other Information
	Sedimentation Tank	-	3-4	12'× 32'× 6'	-	Sludge recovered to be used as fertilizer
HSSF-CW	Pond 1	Fine and Coarse Gravel	6.87	20'× 50'× 7'	*Typha latifolia*	Approximately 15 plants per m^2 are cultivated
	Pond 2		10.30	20'× 50'× 7'	*Centella asiatica*	Approximately 20 plants per m^2 are cultivated
	Pond 3	Soil, Sand, and Gravel	9.16	20'× 50'× 7'	*Centella asiatica*	Approximately 20 plants per m^2 are cultivated
	Pond 4		11.44	20'× 50'× 7'	*Centella asiatica*	Approximately 20 plants per m^2 are cultivated
	Pond 5	Fine and Coarse Gravel	14.88	20'× 50'× 7'	*Pistia stratiotes*	Approx 10 plants per m^2 are cultivated
	Pond 6		10.07	20'× 50'× 7'	*Centella asiatica*	Approximately 20 plants per m^2 are cultivated
	Pond 7		9.16	20'× 50'× 7'	*Pistia stratiotes*	Approx 10 plants per m^2 are cultivated
	Pond 8		5.61	20'× 50'× 7'	Aeration pond	Aerators are installed to boost up oxygen level in the system
FILTER Technology		Soil, Sand, and Gravel	11.44	20'× 50'× 7'	*Typha angustifolia*	Approximately 10 plants per m^2 are cultivated
Collection Tank		-	-	14'× 14'	-	Final treated water ready to be used for horticultural purposes

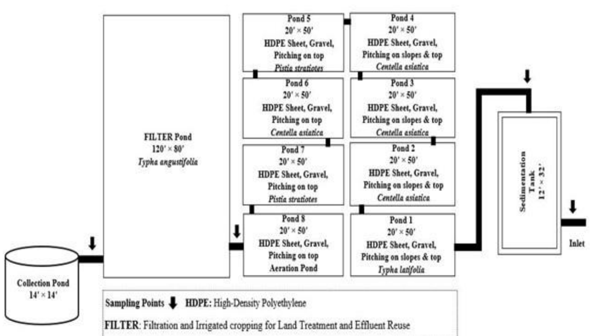


Figure 1. Schematic diagram of integrated constructed wetland

Sample Collection and Analysis

Physicochemical Analysis

Sampling of integrated constructed wetland was performed twice a month (March 2021). During each visit, wastewater samples were collected in autoclaved glass bottles from the outlet of four points i.e., inlet, sedimentation tank, pond 8, and FILTER-technology. These points represent different treatment stages: first stage inlet, where wastewater enters; second stage, after the sedimentation tank (pre-treatment stage); third stage, after passing through 8 ponds; showing the removal efficiency of the ponds and finally collection tank, where the treated water is collected for horticultural purposes at NUST. HANNA HI 83141 was used to carry out the onsite analysis of pH and temperature. EC and DO were determined by WTW Cond-3210 and HANNA oxy-check HI 9147 respectively. Then collected samples were directly transferred to the Environmental Microbiology Laboratory for the remaining parameter's analysis i.e., TKN, Nitrate, Nitrite, Phosphate, COD, Turbidity, TSS, TDS, and TS using the standard methods [16].

Microbial Analysis

Water samples from the four stages i.e. outlets of i.e., inlet, sedimentation tank, pond 8, and FILTER-technology of constructed wetlands were analyzed to determine the removal efficiency of gram-negative bacteria by spread plate technique according to standard protocol [16] by using MacConkey Agar. The measuring unit was CFU/ml. the following formula has been used to calculate the removal efficiency:

Removal efficiency (%) = (Input-Output)/Input x 100

Results and Discussions

The temperature of the current study ranged between 23.95-24.20ºC as shown in Figure 2. The temperature in ICW is influenced by different factors such as vegetation, change in season, time of day, and total dissolved solids content in wastewater. Microbial degradation and plant mechanism activity are aided by a moderate temperature [17, 18, 19]. However, as temperature drops, the rate of degradation lowers [20, 21]. Temperature also affects sedimentation and sorption processes in the wetland. The ideal temperatures for plant and bacterial growths are between 20 °C and 30 °C [15]. The solubility and toxicity of chemicals are affected by pH, which is a key parameter in the biodegradation of organic compounds [22]. Figure 3 shows that mostly pH recorded ranged between 6.95-7.20, in ICW which is suitable for a variety of microbes [23, 24].

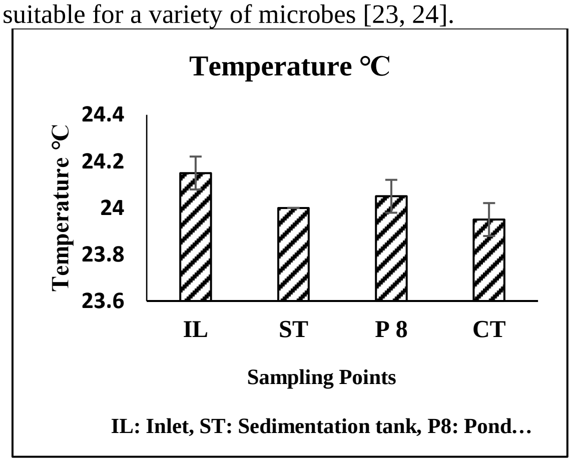
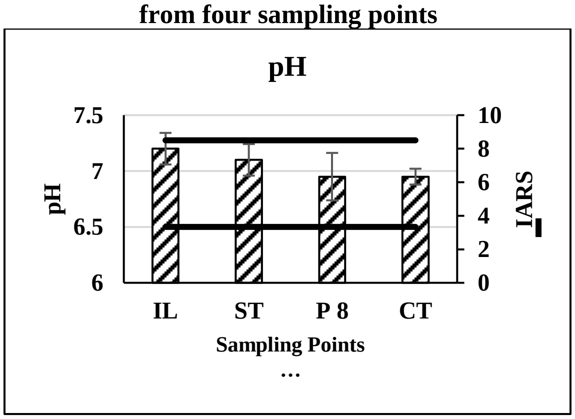


Figure 2. Effluent concentration of temperature from four sampling points



*IARS= International Agricultural Reuse Standards (Non-fodder crops)

Figure 3. Effluent concentration of pH from four sampling points

The presence of positive and negative ions, total dissolved solids (TDS), and diatomic nitrates in wastewater are all factors that influence electrical conductivity (EC). Figure 4 depicts that as the concentration of charged ions falls, the conductivity level lowers, it might be explained by a drop in concentration of TDS and NO_3-N conversion into the diatomic molecular nitrogen (N_2) [25]. Water's turbidity is a reflection of its organic, inorganic, suspended, and colloidal constituents, all of which have an impact on water's clarity [26, 27]. Figure 5 shows that the minimum value for turbidity was observed in the collection tank. The turbidity removal efficiency of ICW observed was 73.99 %. Water turbidity in wetlands is removed via processes such as sedimentation and filtration, which is supported by plant roots. This process minimizes the spaces between gravels by creating a dense filter medium that removes suspended particles [28].

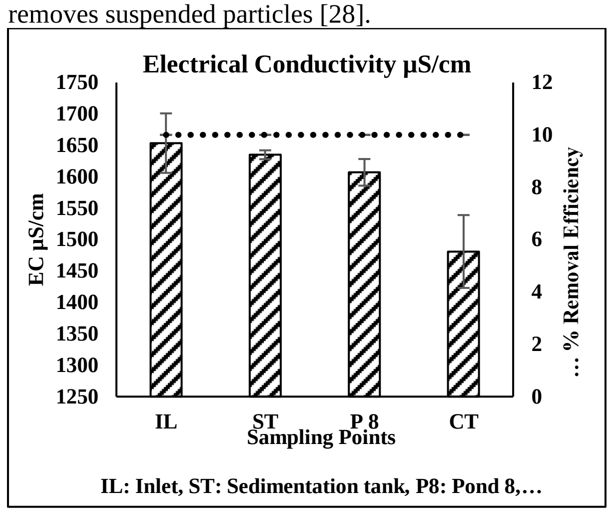


Figure 4. Effluent concentration and removal efficiency of electrical conductivity from four sampling points

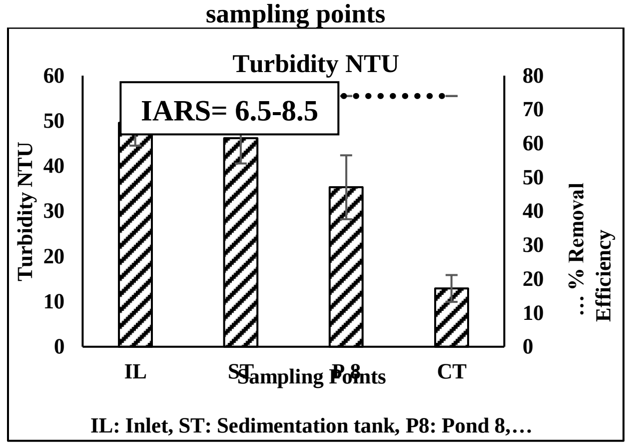


Figure 5. Effluent concentration and removal efficiency of turbidity from four sampling points.

TSS refers to solids that remain suspended in the air, and it opposes matter settling. Wetland vegetation slows the flow of water through various ponds, causing the majority of suspended solids to settle out of the water column which results in the lowest concentration at the collection tank (effluent) [29]. Removal efficiency of the TSS of the ICW was 79.16% (Figure 6). The low concentration of dissolved particles shown in Figure 7 in the collection tank (outlet) might be due to less deposition of solids when the water speed slows down during its flow through different ponds. Additionally, it may be due to the existence of ICW plants that uptake dissolved solids [30]. In addition to helping to lower water velocity, vegetation facilitates the removal of particles by offering a place for microbial adhesion and filtering in the structure of roots [31, 32]. The average removal efficiency of TS is 47.22% (Figure 8).

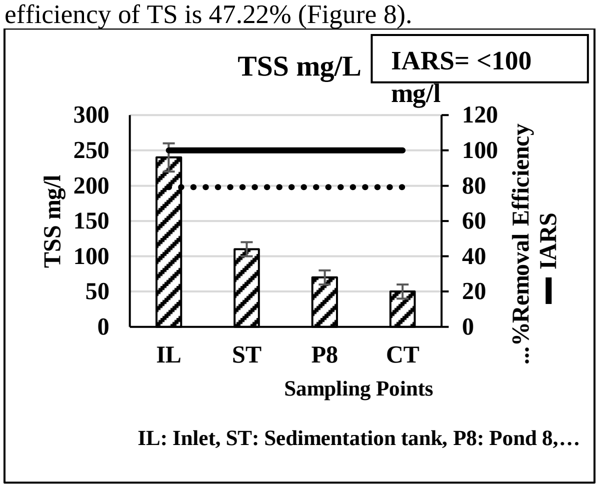


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Figure 6. Effluent concentration and removal efficiency of total suspended solids from four sampling points

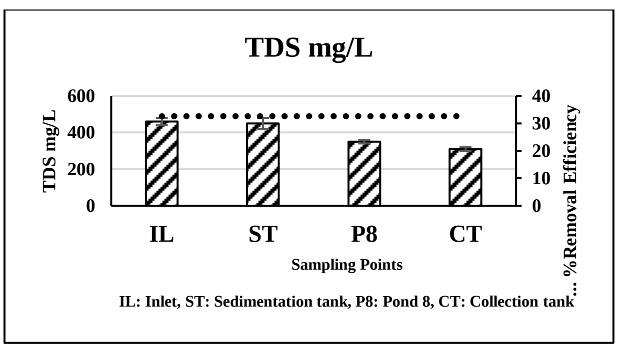


Figure 7. Effluent concentration and removal efficiency of total dissolved solids from four sampling points

The measurement of chemical oxygen demand (COD) is essential for identifying organic contamination in water, and it is used as a national standard in many countries to assess aqueous organic contamination. Low COD is caused by wetlands vegetation, decomposing microorganisms, and water temperature. The low COD concentration at discharge could be ascribed to bacteria in the wetland responsible for biodegrading the organic matter and particle organic matter uptake by the wetland plants [33]. The COD removal efficiency of ICW was 69.01 % (Figure 9). One important indicator of the biological and physical processes occurring in wastewater bodies is dissolved oxygen. In Figure 10, dissolved oxygen was in the range of 2.25-3.10. The low values of DO might be the result of degradation of organic matters by ICW microbes [26]. A study showed that the rhizosphere of plants in CW serves as an attachment place for aerobic microbes that use DO to break down organic material [34].

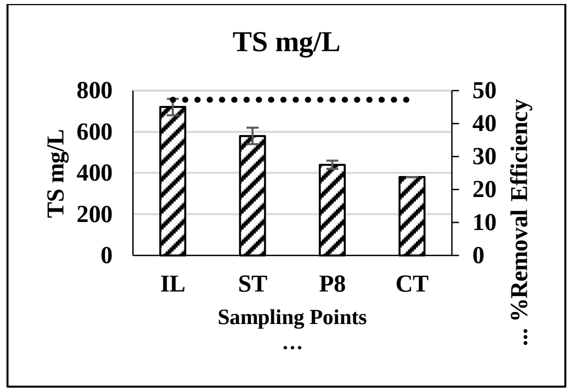
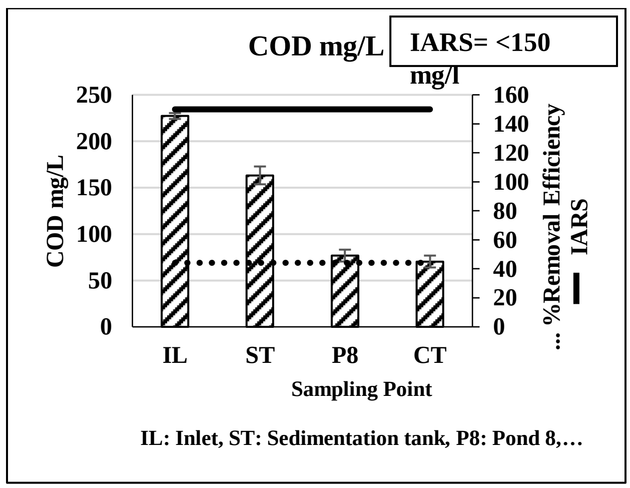


Figure 8. Effluent concentration and removal efficiency of total solids from four sampling points.



*IARS= International Agricultural Reuse Standards (Non-fodder crops)

Figure 9. Effluent concentration and removal efficiency of chemical oxygen demand from four sampling points

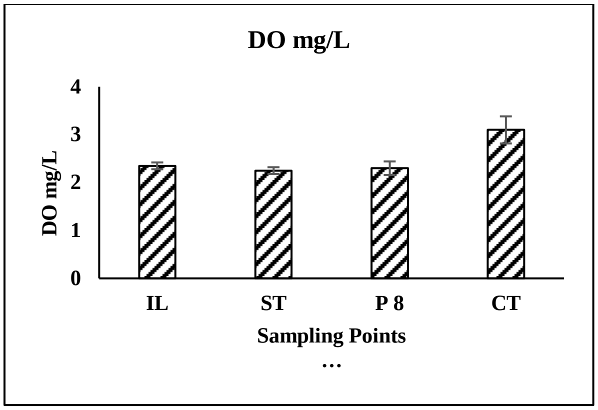


Figure 10. Effluent concentration of dissolved oxygen from four sampling points

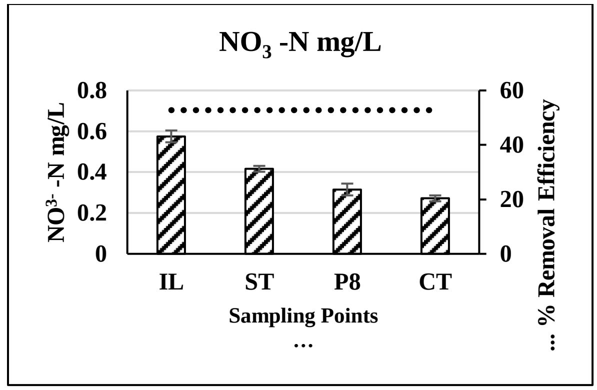


Figure 11. Effluent concentration and removal efficiency of nitrate nitrogen from four sampling points

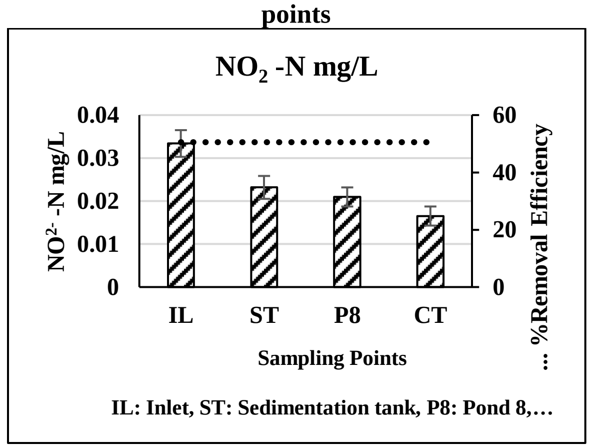


Figure 12- Effluent concentration and removal efficiency of nitrite nitrogen from four sampling points

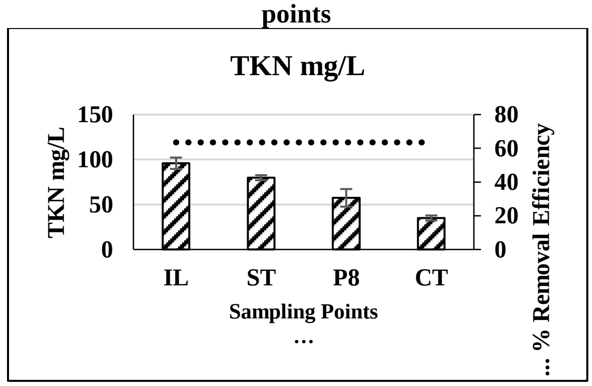


Figure 13- Effluent concentration and removal efficiency of total Kjeldahl nitrogen from four sampling points

The two main pollutants in wastewater are nitrate and nitrate, and both can be dangerous in excess because they can cause eutrophication [31]. The presence of facultative bacteria in ICW increase nitrate production. Low concentrations of nitrate-nitrogen observed at the ICW outlet may be due to denitrification, in which nitrate conversion to diatomic molecular nitrogen occurs. Moreover, it may be due to nitrate deposition at the ICW bottom in sediments, and plant absorption [35]. The nitrate-nitrogen removal efficiency of ICW was 52.76 % (Figure 11). Figure 12 illustrates a downward trend, with the lowest value of nitrite-nitrogen occurring in the collection tank due to constant conversion to nitrate-nitrogen [36]. The nitrite-nitrogen removal efficiency of ICW observed was 50.53 %. The removal efficiencies of nitrate-nitrogen and nitrite-nitrogen are probably because of the vegetation in ICW. In addition to taking up nitrate and nitrite from soil water that they use for their own growth, plants also offer a lot of surface area for microorganisms to grow and build biofilms, which release a lot of oxygen around the roots. Consequently, there was an increase in the dissolved oxygen concentration, making it more available for nitrification. This also meant that there would be a higher amount of organic matter that is needed for denitrification. As a result, the processes of nitrification and denitrification happen simultaneously [32, 37].

The amount of organic and ammonia nitrogen present determines how much of a pond's total nitrogen content (TKN) is present at any given time. The conversion of organic nitrogen into ammonium ions produces an increase in TKN concentration in wastewater influent. The consistent decreasing trend in values of different ponds and minimum concentration detected in the collection pond's final effluent could be due to the different substrates and the presence of aerobic or anaerobic conditions [38]. TKN removal efficiency of ICW was 63.50 % (Figure 12).

Adsorption and plant absorption contributes to the little removal of the phosphate-phosphorous while microbial breakdown accounts for major phosphate removal. Phosphate removal demonstrates a steady reduction at each sampling location, with the lowest concentration found at the collection tank due to the uptake of phosphate by plant or its deposition in the sediments and adsorption [39]. The removal efficiency of PO4-³- P in ICW was 41.24 % (Figure 14).

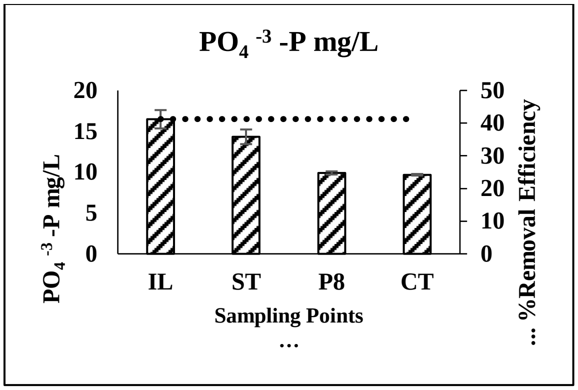


Figure 14. Effluent concentration and removal efficiency of phosphate phosphorus from four sampling points

Gram-negative bacteria are pathogenic microorganisms and are responsible for various diseases. The heterotrophic plate count of water samples was analyzed and results showed bacterial load ranging from 8.6 x10^6 in the inlet to 4.2 x10^4 in the outlet. *E. coli*, *Salmonella,* and *Shigella* were the most prevalent microbial species, and removal efficiency of gram-negative bacteria was observed to be up to 95% (Figure 15). The physical (such as filtration, sedimentation), biological (such as predation, biolytic processes, antibiosis, natural die-off), and chemical (such as oxidation, UV radiation from sunlight, plant biocides exposure, organic matter and biofilm adsorption) factors are all accountable for the pathogenic microorganisms in wetland environments. The elimination of pathogenic microbes in constructed wetlands is the consequence of a complex interaction among these variables [40].

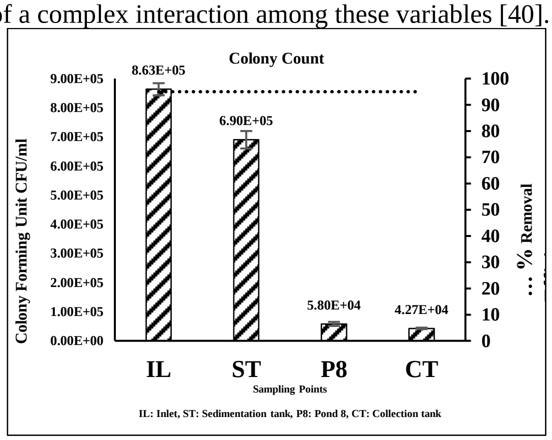


Figure 15. Effluent concentration and microbial removal efficiency from four sampling points

Comparison of percentage removal efficiency of physicochemical and microbial parameters with past studies

The overall percentage removal efficiency of ICW is reported in Table III. When compared with the past study conducted by Naseer et al., 2021 [6] where different parameters including Electrical conductivity (EC), nitrate-nitrogen (NO_3-N), Nitrite-nitrogen (NO_2-N), Total Kjeldahl Nitrogen (TKN), Phosphate phosphorous ((PO_4^{3-}) were measured for the same ICW. The removal efficiency of the mentioned parameters was recorded as 8, 77, 47, 55, and 56% respectively. These results are quite in line with the current study. This shows the performance of the ICW has been maintained over the years.

Constructed wetlands are efficient in removing microorganisms from wastewater. By comparing the current study with the previous study conducted by Andleeb et al., 2018 [41], results showed a consistent decrease in total coliform (TC) from the inlet to the sedimentation tank. The removal efficiency of total coliform was recorded as 88.9%. Another study conducted by Abeerah Shahid in 2015 [42] revealed the removal efficiency of 98.61% for total coliform and 94.29% for fecal coliforms. The present study was specifically targeted to analyze the removal efficiency of the gram-negative bacteria. Microbial analysis results indicate that constructed wetlands are capable of removing total coliforms as well as other gram-negative bacteria.

These results showed that an integrated constructed wetland system (ICW) performed well and has considerable potential for the removal of pollutants from wastewater.

Table III

Percentage removal efficiency of integrated constructed wetland (ICW)

Parameters	Sampling Points			System Removal Efficiencies (%)
	Sedimentation Tank (%)	Pond 8 (%)	Collection Tank (%)	
EC	1.11	1.71	7.84	10
Turbidity	6.95	23.51	63.45	73.99
TSS	54.16	36.36	28.57	79.16
TDS	2.17	22.22	11.42	32.60
TS	19.44	24.13	13.63	47.22
COD	28.16	52.94	8.33	69.01
NO_3 -N	27.63	24.30	13.76	52.76
NO_2 -N	30.58	9.57	21.18	50.53
TKN	16.78	28.07	39.02	63.50
PO_4^{3-}-P	13.03	30.87	2.26	41.24

Table IV
p-values (P (T<=t) two tail) of physicochemical parameters of ICW

Parameters	pH	EC µS/cm	Turbidity NTU	TSS mg/L	TDS mg/L	TS mg/L	COD mg/L	DO mg/L	NO_3^- -N mg/L	NO_2^- -N mg/L	TKN mg/L	PO_4^{3-} -P mg/L
P – values	0.12	0.25	0.02	0.09	0.04	0.07	0.03	0.20	0.09	0.03	0.09	0.09

Statistical analysis

To perform a statistical analysis and find the significant difference between untreated and treated water, the t-test (paired two sample for means) was used. Microsoft Excel 365 was used to perform the t-test: paired at the 0.05 significant level (at the 95% confidence level). The t-Test: paired results showed that 'p' values of Turbidity 0.02, TDS, 0.04, COD 0.03, and NO_2-N 0.03 are less than 0.05. Additionally, t critical one-tail values were also smaller than t stat values that means the results are statistically significant. Whereas the 'p' values of pH, EC, TSS, TS, DO, NO_3-N, TKN, and PO_4^{3-} -P are greater than 0.05 indicating the insignificant difference between treated and untreated water.

Conclusions

Integrated constructed wetlands (ICWs) for wastewater treatment are becoming an emerging environmentally friendly technology worldwide for removing contaminants from wastewater and reusing it for agricultural/horticultural purposes. In the present study despite quite high influent concentrations of organic matter and nutrients for instance >200 mg/L COD and >80 mg/L TKN the effluent concentrations were very low with removal efficiency accounting for 69.01% and 63.50% respectively. Microbial analysis indicate 95% removal efficiency for pathogenic gram-negative bacteria. From this study, it may be concluded that ICWs are efficient in terms of removing nutrients, incoming dissolved and suspended materials, pathogenic micro-organisms, and regulating pH, and temperature of the water. However, it is recommended to monitor the effect of treated wastewater after irrigation on soil structure and its microbiota. Further, the usage of alternative plants to increase the performance efficiency of integrated constructed wetland may also be explored. It is also recommended that plant biomass must be treated or properly dumped to decrease the spread of contaminants, in the environment.

Acknowledgments

The authors gratefully acknowledge the support from the Postgraduate Office, National University of Sciences and Technology, Islamabad, Pakistan for providing research funds to undertake the said research. Suggestions from colleagues from the Environmental Microbiology Research Group, Institute of Environmental Sciences and Engineering, SCEE, NUST are also appreciated.

Competing interests

None.

Authors' contribution

All authors of this study have a complete contribution to data collection, data analysis, and manuscript writing.

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