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Performance of a Horizontal Subsurface Flow Constructed Wetland in Treating Aquaculture Wastewater

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ABSTRACT

The escalating demand for water and the increasing pollution of natural water bodies necessitate innovative solutions for wastewater treatment and reuse. This study investigated the potential of a horizontal subsurface flow (HSSF) constructed wetland to treat aquaculture wastewater for reuse. The system, planted with Taro (*Colocasia esculenta*) and sugarcane (*Saccharum officinarum* L.), received effluent from a recirculating aquaculture system (RAS) producing African Catfish (*Clarias gariepinus*). The study assessed the impact of varying hydraulic retention times (1–3 days) and flow rates (11–108 L/min) on water quality parameters, including dissolved oxygen, electrical conductivity, salinity, total dissolved solids, temperature, and pH. Results showed significant increase in dissolved oxygen (4.25–5.52 mg/L), while electrical conductivity (491–677 µS/cm), salinity (0.23–0.32 ppt), and total dissolved solids (237–332 mg/L) decreased considerably. Temperature (29.28–31.07 °C) and pH (7.57–7.59) remained stable and within acceptable ranges for reuse in African Catfish production. However, retention time and flow rate did not significantly affect treatment efficiency within the tested parameters. Further research is recommended to explore the impact of longer retention times, wider flow rate ranges, different plant species and substrate types, and microbial community analysis to optimize the system's performance and promote sustainable aquaculture practices.

Keywords: constructed wetland, aquaculture effluent, water quality, hydraulic retention time, flow rate.

INTRODUCTION

The treatment of wastewater effluent stands as a critical component in the preservation of environmental integrity and human health. However, conventional strategies employed for this purpose have often been laden with challenges, including exorbitant costs, the demand for constant and specialized operator presence, and inefficiencies when implemented on a smaller scale [EPA, 2021]. A constructed wetland, on the other hand, is a sanitation technology that utilizes natural removal mechanisms provided by plant vegetation, soil, and associated microbial populations [Kadlec and Wallace, 2008]. There are three main types of constructed wetlands namely, horizontal subsurface, free water surface and vertical flow constructed wetlands [Vymazal et al., 2021; Wu et al., 2015]. These systems mimic the natural purification processes of wetland ecosystems which collectively work to improve water quality by reducing pollutants, organic matter and nutrient levels as the water passes through the wetland. These processes include; physical filtration, biological degradation, adsorption and precipitation, nutrient uptake and microbial action [Choudhary and Kumar, 2011; Jokerst et al., 2012; Kurniawan et al., 2021].

From domestic wastewater channeled into the streets, to industrial wastewater like the end result of the illegal mining colloquially referred to in Ghana as "Galamsey". Whether medical waste from Korle Bu dumped in the Korle Lagoon, or the vast amounts of wastewaters from agricultural activities, there exists excessive pollution of the environment and its ecosystems [Asare, 2022; WHO, 2017]. The world produces a massive 380 trillion liters of wastewater annually, emphasizing the critical necessity for sustainable water management on a global scale [Qadir et al., 2020]. This is a substantial problem and factors such as population expansion, urban development, rising water scarcity, and the impacts of climate variability have necessitated the use of wastewater as a dependable source of water and nutrients for reuse purposes such as agriculture or other non-potable uses [Chen and Wong, 2016]. With local aquaculture production currently meeting less than a fifth of Ghana's fish demand, there is a clear opportunity to significantly increase aquaculture's contribution to bridging the existing supply gap [Amponsah et al., 2021; Ansah, 2014]. Generally, aquaculture industries heavily rely on water consumption and generate substantial volumes of effluent [Kurniawan et al., 2021; Frimpong et al., 2017]. Best management practices (BMPs) encompass a wide range of techniques and strategies aimed at minimizing the environmental impact of aquaculture operations while optimizing production efficiency and profitability [FAO, 2022]. Ensuring the sustainability of aquaculture relies heavily on implementing BMPs that involve the treatment and reuse of wastewater, or its responsible disposal in an environmentally-friendly manner [Crab et al., 2007; Ansah et al., 2014; Schneider, 2010; Zhang et al., 2011].

Constructed wetlands have been used to treat both centralized and on-site wastewater with design specifications altered according to the types of wastewaters, and the prospective use of the treated water. For example, primary treatments such as sedimentation and flotation are recommended when there is a large number of suspended solids or insoluble organic matter so as not to encourage clogging of the distribution network [Zhang et al., 2023; EPA, 2021]. Some Ghanaian researchers like Dwumfour-Asare [2019] have conducted studies on the potential of CWs to treat domestic wastewater and others like Osei et al. [2019] have demonstrated same with faecal sludge among other wastewater sources. These are significant strides but unfortunately zero work has been done on the potential of using constructed wetlands as an avenue to bolster the growing aquaculture industries by promoting waste recovery and increasing productivity. According to studies conducted by Merino-Solís et al. [2015] and Minakshi et al. [2022], the treatment potential of constructed wetlands is affected by various parameters such as hydraulic loading rate (HLR), mass loading rate (MLR), flowrate and hydraulic retention time (HRT), among others. While some research has examined the individual effects of flow rate and retention time on constructed wetland performance [Saeed and Sun, 2012; Wu et al., 2015], few studies have explicitly investigated the interactive effects of these parameters, as this current research aims to do [Kadlec and Wallace, 2008]. Understanding how flow rate and retention time interact is crucial for optimizing wetland design and operation, as their combined influence can significantly impact treatment efficiency [García et al., 2010]. This knowledge gap is particularly relevant for achieving Sustainable Development Goal (SDG) 6.3, which calls for halving the proportion of untreated wastewater and increasing safe reuse globally [United Nations, 2015]. By providing insights into the optimal combination of flow rate and retention time, this study can inform policymakers, practitioners, and stakeholders, facilitating the wider adoption of constructed wetlands as a sustainable wastewater treatment solution. By assessing these factors, multifunctional CWs can be effectively designed and operated to address water treatment challenges, promote water reuse, and support sustainable aquaculture practices.

Study objectives

The main aim of this research was to study the treatment efficiency of a horizontal sub-surface flow (HSSF) constructed wetland for treatment of aquaculture wastewater. Specifically, the study sought to:

- to assess the impact of hydraulic retention time and flow rate on the overall water quality parameters (e.g., dissolved oxygen, pH, temperature, total dissolved solids) in the treated effluent;
- to determine the optimal combination of HRT and flow rate that results in the best effluent water quality suitable for reuse in aquaculture.

MATERIALS AND METHODS

Study area

The study was conducted at a pilot-scale horizontal subsurface flow (HSSF) constructed wetland located on the research fields of the CSIR-Crops Research Institute, Fumesua Campus, in the Ashanti region of Ghana. Agroecological information on the study area is shown in Table 1.

Description of the multifunctional constructed wetland

The constructed wetland (Figure 1), covering a total area of approximately 58.63 m^2, consists of two 5.5 2.7 m rectangular filter beds, lined with an impermeable liner and filled with rounded river gravel substrate (16–52 mm diameter) to a depth of 1.2 m. The constructed wetland was set at a slope of 0.5% to allow water flow by natural gravity. The wetland was planted with Taro (Colocasia esculenta) and sugarcane (*Saccharum officinarum* L.) to enhance the treatment process. Research suggests that both taro and sugarcane show promise in phytoremediation. Taro has been found to effectively remove nitrogen and phosphorus from wastewater [Chen et al., 2019] and accumulate heavy metals [Rahman et al., 2011]. Sugarcane has demonstrated effectiveness in removing organic matter and nutrients from domestic wastewater [Wang et al., 2018] and treating textile industry effluent [Ganga et al., 2014].

This constructed wetland design utilizes two filter beds (labelled (c) and (e) in Figure 1) arranged horizontally in a subsurface flow configuration to carry out wastewater treatment using a combination of physical, biological, and chemical processes. The wastewater from the RAS pond (labelled (a) in Figure 1) first enters the system through an inlet by gravity, and then passes through two intermediate bulk container (IBC) tote tanks that act as sedimentation tanks for initial pre-treatment of the effluent (labelled (b) in Figure 1). These tanks allow heavier materials to settle and reduce the organic load, which helps prevent the gravel media in the filter beds from getting clogged. The water that has been treated beforehand is directed through a network of PVC pipelines located within the filter beds. The flow rate of the water is carefully controlled by adjusting the valve on the sedimentation tank accordingly. The water then moves horizontally across the gravel media, promoting the growth of beneficial microorganisms. The treated water is

Table 1. Agro-ecological characteristics of the study site

Characteristics	Location (6” 41’ N, 1” 28’ W)
Agro-ecological zone	Humid forest
Soil type	Ferric Acrisol; Asuasi series upper topsoil consisted of 5 cm greyish brown sandy loam topsoil of dark brown gritty clay loam.
Temperature (Min–Max)	21–31 °C
Major season	March – mid-August
Minor season	September – November: peak in October
Total annual rainfall (mm)	1027–1322 averaging 1184 mm/yr.

Note: Adapted from Danquah et al. [2022].

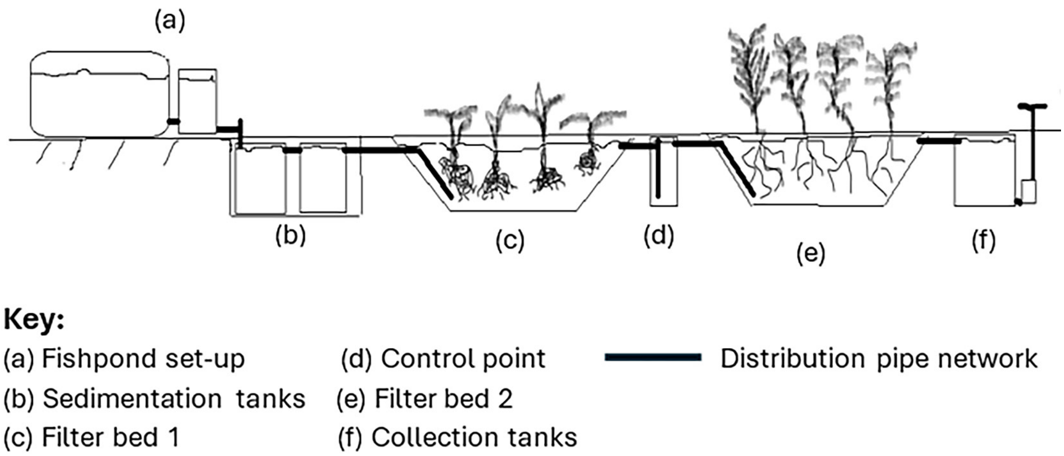

Figure 1. Schematic configuration of the HSSF multifunctional constructed wetland

collected and stored in a water tank (f) at the end of the process. The stored treated water is either pumped back into the fishpond or utilized to irrigate vegetable fields nearby.

Wastewater source and characteristics

Effluent from two 4.2-meter diameter recirculating aquaculture systems (RAS) producing African Catfish (*Clarias gariepinus*) was utilized for this study. Each tank was initially stocked with 1000 pieces of catfish (10 ± 2 g), and the fish were fed a commercial pelleted diet twice daily. The RAS setup utilizes mechanical filtration to eliminate uneaten feed, faecal matter, algae, dust, and debris from the pond water. This filtered waste is then stored as effluent before being disposed of. This effluent, while potentially beneficial for plant growth due to elevated concentrations of nitrogen, phosphorus, and other compounds, can significantly impair pond water quality if not properly managed. The high levels of nutrients can lead to eutrophication and result in oxygen depletion, increased organic matter, and potential toxin release, which can be detrimental to fish [Smith et al., 1999]. Table 2 shows the quality characteristics of the untreated fishpond effluent.

Experimental setup and data collection

Five hundred (500) liters-per-pond was fed into the wetland system at a specified flowrate (FR) and retained in the system with corresponding hydraulic retention times (HRT). Effluent flow rates from the mechanical filter exits of both fish tanks were manipulated at three levels: quarter open (11.4 L/min), half open (47 L/min), and fully open (108 L/min). Retention times were set at 24, 48, and 72 hours. Water quality data were collected at three specific sampling locations within the treatment system: the inlet of filter bed 1 (FB1), the control tank (CT), and the collection point (CP) depicted in Figure 1 as point (c), (d) and (f), respectively. This sampling strategy aimed to capture spatial variations in water quality along the treatment process. The Hanna multiparameter water quality meter (model HI98194) was utilized to measure various parameters, including pH, salinity, dissolved oxygen (DO), total dissolved solids (TDS), electrical conductivity (EC), and temperature.

Table 2. Quality characteristics of untreated fishpond effluent

Parameter	Value
Dissolved oxygen (DO)	1.34 ± 0.12 mg/l
Electrical conductivity (EC)	823 ± 49.21 μS/cm
Salinity	0.44 ± 0.02 ppt
Total dissolved solids	959 ± 38.24 mg/l
Temperature	31.52 ± 1.06 °C
pH	6.83 ± 1.12

Experimental design and analysis

A split plot design with three replicates was employed, wherein the wetland system was divided into three distinct sampling locations representing blocks. Within each block, the three replicate units were randomly assigned different combinations of retention time and flow rate treatments. Water quality parameters were assessed at each location as required at 9:00 am daily. Upon achieving hydraulic equilibrium, an extensive two-month study involving eighty-one treatments was explored to assess their impact on the water quality of the effluent and its suitability for reuse in aquaculture. Data were analyzed in GenStat Version 11.1 [VSN International, 2011] using a two-way ANOVA to assess the effects of retention time (1 day, 2 days, and 3 days) and flow rates (11 L/min, 47 L/min, and 108 L/min) on treated effluent water quality parameters. Significant differences between treatment means were determined using the least significant difference (LSD) at $p < 0.05$.

RESULTS AND DISCUSSION

Effect of retention time and flow rate on water quality parameters

Figures 2–7 depict the overall effects of retention time (1, 2 and 3 days i.e. 1D, 2D and 3D, respectively) and flow rates (11 l/min, 47 l/min and 108 l/min) on selected water quality parameters (dissolved oxygen, electrical conductivity, salinity, total dissolved solids, temperature and pH) in a multifunctional constructed wetland (MfCW).

Based on the findings in Figure 2, it was observed that the levels of dissolved oxygen (DO) generally increased as the retention time increased. This is likely because longer retention times allow for more time for oxygen to be

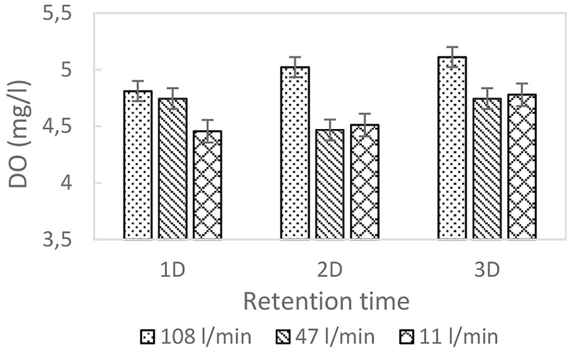

Figure 2. Effect of retention time and flow rate on dissolved oxygen (DO)

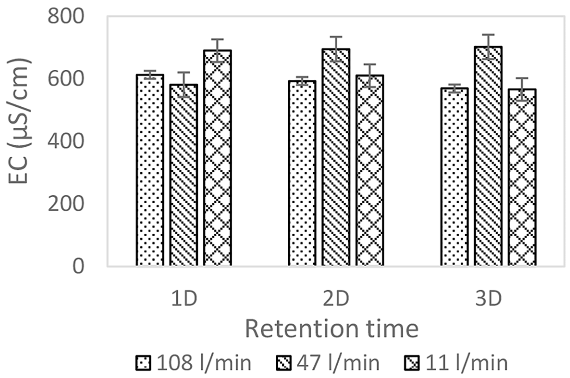

Figure 3. Effect of retention time and flow rate on electrical conductivity (EC)

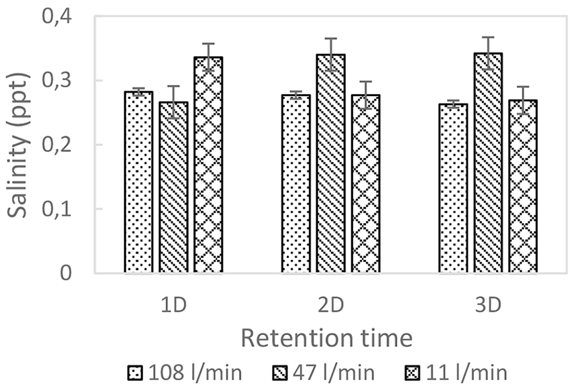

Figure 4. Effect of retention time and flow rate

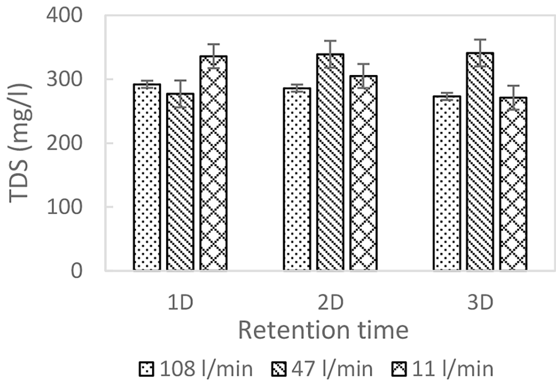

Figure 5. Effect of retention time and flow rate

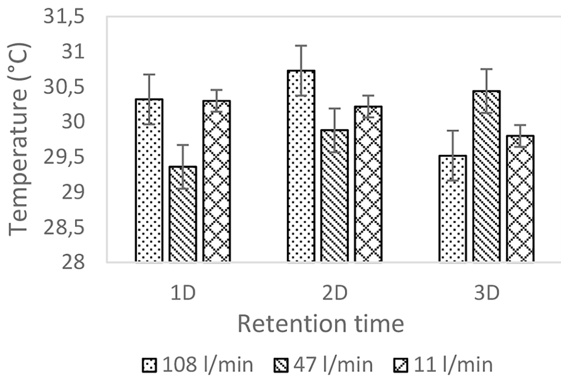

Figure 6. Effect of retention time and flow rate on temperature

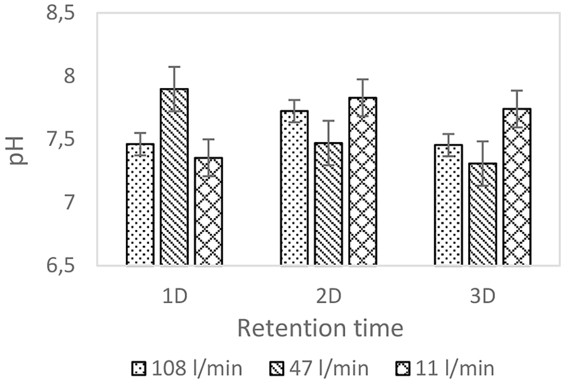

Figure 7. Effect of retention time and flow rate on pH

transferred from the atmosphere to the water. Similarly, DO levels increased with increasing flow rate. The reason for this is likely due to the increased turbulence and mixing that occurs at higher flow rates [Nivala et al., 2013]. This turbulence enhances the transfer of oxygen from the atmosphere into the water, leading to higher dissolved oxygen levels [Ahmadi et al., 2018; Lu et al., 2021]. The graph in Figure 3 shows that the EC of the water in the constructed wetland decreases as the retention time increases. This is because the longer the water is in the wetland, the more time it has to come into contact with the plants and substrate, which can remove pollutants from the water. Figure 3 also shows that the electrical conductivity of the water increases as the flow rate increases. This is because the higher the flow rate, the less time the water has to come into contact with the plants and substrates. This results in less time for the removal of ions that contribute to electrical conductivity [De La Mora-Orozco et al., 2018]. From the graph in Figure 4, as retention time increases from 1 day (1D) to 3 days (3D), the salinity tends to decrease slightly. This suggests that longer contact time between the water and the wetland environment allows for better salt removal. This could be due to various mechanisms like plant uptake, microbial activity, or adsorption onto wetland substrates. In contrast, within each retention time period, varying the flow rate seems to have a minor effect on salinity. The three flow rates (108 l/min, 47 l/min, 11 l/min) show relatively similar salinity levels at each retention time point. This implies that, in this particular wetland setup, the flow rate might not be the primary factor influencing salinity removal.

Figure 5 depicts the effect of retention time flow rate on total dissolved solids (TDS) in water under treatment within the constructed wetland. At a retention time of one day, the TDS levels are relatively high, ranging between 280–300 mg/L across the different flow rates. This indicates that a shorter retention time might not be sufficient for the wetland to effectively remove dissolved solids from the water. Increasing the retention time to two days shows a slight decrease in TDS concentration. The levels are still relatively high, but the decrease suggests that a longer retention time allows for improved removal of dissolved solids. The highest retention time of three days further reduces the TDS concentration, indicating that the wetland becomes more efficient at removing dissolved solids as the water spends more time within the system. On the other hand, the flow rates (108 L/min, 47 L/min, 11 L/min) do not seem to have a significant impact on TDS removal within each retention time period. This suggests that in this specific wetland setup, the flow rate might not be the primary factor influencing the removal of dissolved solids.

The graph in Figure 6 presents the results of the effect of retention time and flow rate on the water temperature of the constructed wetland. As retention time increases from 1 day (1D) to 3 days (3D), there seems to be a slight increase in water temperature. This could be attributed to longer exposure to solar radiation and ambient air temperature. However, the differences are not substantial and are not statistically significant. Additionally, within each retention time period, there's minor variation in temperature across the different flow rates, suggesting that retention time has a more significant impact on temperature than flow rate. Similarly, the flow rates (108 l/min, 47 l/min, 11 l/min) do not appear to significantly influence water temperature. The temperature fluctuations across flow rates are relatively small and are not statistically significant.

The graph in Figure 7 illustrates the relationship between water pH, retention time, and flow rate within a constructed wetland system. There appears to be no significant change in pH levels as the retention time increases from 1 day (1D) to 3 days (3D). This suggests that retention time might not be the primary factor influencing pH changes in this particular wetland. Similarly, the different flow rates (108 l/min, 47 l/min, 11 l/min) also do not seem to have a substantial impact on pH levels within each retention period. The pH fluctuations across flow rates are relatively small and are not statistically significant. Table 3 presents the results of a study investigating the effects of retention time and flow rate on various water quality parameters at different stages within a constructed wetland. The stages include the collection tank, control tank, and filter bed 1. The water quality parameters assessed are dissolved oxygen (DO), electrical conductivity (EC), salinity, total dissolved solids (TDS), temperature, and pH.

Under the treatment stage in Table 3, DO levels increased significantly ($p \leq 0.05$) from the filter bed 1 (4.25 mg/L) to the collection tank (5.52 mg/L). This suggests that the biological processes within the wetland, particularly in the filter bed, consume oxygen, likely due to increased microbial activity involved in pollutant removal. DO values at the end of the treatment process (collection tank) were above the desirable range of > 5 mg/L. Similarly, EC, salinity and TDS showed a significantly decreasing trend from the filter bed 1 to the collection tank (677–491 µS/cm, 0.32–0.23 ppt and 332–237 mg/l, respectively). This is likely due to the plant's absorption of these substances within the constructed wetland. The concentrations of these substances (particularly TDS and salinity) in the water decrease as the water progresses through the treatment phases, suggesting that the wetland is effective in their removal.

Generally, water temperature (29.28–31.07 °C) and pH (7.57–7.59) values remain relatively stable across the treatment stages, and both are within the desirable ranges. The significantly higher temperature (31.07 °C) seen in the control tank was likely because its lid was exposed to the sun, which raised the temperature of the water flowing through that stage. From the results in Table 3, the wetland system did not significantly influence the water pH,

Table 3. Effect of treatment stage (collection tank, control tank and filter bed 1), retention time and flow rate on water quality parameters in a multifunctional constructed wetland

Factor	Water Quality Parameter					
	Dissolved oxygen (mg/l)	Electrical conductivity (µS/cm)	Salinity (ppt)	Total dissolved Solids (mg/l)	Temperature (°C)	pH
	Treatment stage					
Collection tank	5.52[a*]	491 [b]	0.23 [b]	237 [b]	29.28 [b]	7.57
Control tank	4.44 [b]	706 [a]	0.33 [a]	337 [a]	31.07 [a]	7.59
Filter bed 1	4.25 [b]	677 [a]	0.32 [a]	332 [a]	29.84 [b]	7.58
LSD (p ≤ 0.05)	0.33	90.9	0.06	52	0.73	ns
Retention time (d)						
1	4.67	628	0.29	301	29.99	7.57
2	4.67	633	0.30	310	30.27	7.67
3	4.88	613	0.29	295	29.92	7.5
LSD (p ≤ 0.05)	ns	ns	ns	ns	ns	ns
Flow rate (l/min)						
108	4.98 [a]	592	0.27	283	30.19	7.55
47	4.65 [b]	659	0.32	319	29.89	7.56
11	4.58 [b]	622	0.29	304	30.1	7.64
LSD (p ≤ 0.05)	0.16	ns	ns	ns	ns	ns
Desirable range**	≥ 5	50–1500	< 1	50–400	22–35	6.5–9.0

Note: * Values followed by the same letter in the same column are not significantly different at 5%, ** [Akinyemi, 1988; Water Resources Commission, 2003; Boyd and Tucker, 2014].

irrespective of the treatment stage. Overall, the DO, electrical conductivity (EC), salinity, TDS, temperature and pH values were within the desirable range, irrespective of the treatment stage. This suggests that the multifunctional constructed wetland is effective in the treatment of the fishpond effluent. In contrast, retention time (1–3 days) does not appear to have a significant ($p \leq 0.05$) impact on any of the water quality parameters. This implies that the duration water spends in the wetland within this tested range does not substantially affect the treatment efficiency for these parameters.

The flow rate has a minor effect on DO, with the highest flow rate (108 l/min) resulting in slightly higher DO levels compared to lower flow rates. This could be attributed to increased aeration at higher flow rates. However, the flow rate did not significantly influence the other water quality parameters (i.e. EC, salinity, TDS, temperature, and pH).

CONCLUSIONS

The constructed wetland system effectively improved several key water quality parameters of the fishpond effluent. DO levels increased significantly throughout the treatment process, reaching levels suitable for aquaculture reuse. EC, salinity, and TDS decreased considerably, indicating the wetland's capacity to remove these substances. Temperature and pH remained relatively stable and within desirable ranges, demonstrating the system's ability to maintain suitable conditions for aquatic life. However, the study found that retention time (1–3 days) and flow rate (11–108 l/min) did not significantly influence the treatment efficiency within the tested ranges. This suggests that the wetland's performance might be more dependent on other factors, such as plant species, substrate composition, or microbial community.

Based on the results, further research is recommended to investigate the effects of longer retention times (e.g., 5–7 days) to assess if extended contact time leads to further improvements in water quality, particularly for TDS removal. Additionally, experiments with a wider range of flow rates, including lower values, should be conducted to determine if there is an optimal flow rate for maximizing treatment efficiency. To identify optimal combinations for specific water quality goals, the impact of different plant species and substrate types on the wetland's performance should be assessed. To understand how environmental conditions shape CW treatment efficiency, the influence of specific agro-ecological factors, such as soil properties, evapotranspiration rates, and climatic conditions on constructed wetland treatment efficiency could be explored. Finally, analysis of the microbial community within the wetland is necessary to understand its role in pollutant removal and identify potential strategies for enhancing microbial activity.

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