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Performance Evaluation of Subsurface Vertical Flow Constructed Wetlands to treat and reuse Institutional Wastewater in arid regions (KSA)

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ABSTRACT

Constructed wetlands (CWs) are engineered systems that mimic natural wetlands to treat wastewater. They offer several advantages over conventional wastewater treatment plants, such as low cost, low energy consumption, easy operation and maintenance, and environmental benefits. However, CWs face some challenges in arid regions, such as water scarcity, high evaporation rates, salinity stress, and land availability. In this paper, the design, performance, and evaluation of a subsurface vertical flow constructed wetland (SVFCW) system to treat and reuse institutional wastewater in the Kingdom of Saudi Arabia (KSA). The SVFCW system consists of three treatment stages, each stage (30 cm diameter and 30 cm depth) is filled with the same media layers, bottom layer consists of gravels of 8 cm depth, middle layer is filled with aggregates 8 cm depth, and the top layer is mixture of aggregates and sand of particle size with 8 cm depth and a wetland bed planted with umbrella plants (Cyperus Involucratus, Cyperaceae). The influent and effluent quality of the SVFCW system were monitored for 28 days and assessed its removal efficiency for various parameters, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), ammonia nitrogen (NH3-N), Ortho-Phosphate (Ortho-P), and total phosphorus (TP). The average removal efficiencies BOD, COD, TSS, NH3-N, Ortho-P and TP after the three stages were 76%, 70%, 93%, 83%, 61% and 64%, respectively. Stage 1 achieved a higher removal efficiencies for all pollutants than stage 2, and the efficiency did not change significantly from stage 2 to stage 3. The effluent concentrations are within the MEWA irrigation standards, allowing the treated wastewater to be used for restricted irrigation.

Keywords*:-Constructed wetland,*

INTRODUCTION

Subsurface vertical flow constructed wetlands (SVFCWs) are a promising technology for wastewater treatment and reuse, especially in arid regions where water scarcity is a major challenge. SVFCWs use natural processes to remove pollutants from wastewater, such as filtration, adsorption, and biodegradation. SVFCWs also have several advantages over conventional wastewater treatment systems, such as low energy consumption, low maintenance costs, and high aesthetic value. However, the performance and feasibility of SVFCWs in arid regions are still not well understood and require further investigation.

Institutional wastewater refers to the wastewater generated from public facilities such as schools, hospitals, mosques, and government offices. Institutional wastewater has some distinctive characteristics compared to domestic or industrial wastewater, such as lower

organic load, higher nutrient content, lower flow variability, and higher potential for reuse.

This paper aims to evaluate the effectiveness of SVFCWs to treat and reuse institutional wastewater in the Kingdom of Saudi Arabia (KSA), where water demand is expected to increase significantly in the coming years. The paper will review the existing literature on SVFCWs [1-4], present the design and operation of a pilot-scale SVFCW system installed at a university campus in KSA [5], and analyze the quality of the treated wastewater for potential reuse applications [6-8]. The paper will also discuss the challenges and opportunities of implementing SVFCWs in arid regions [9-11] and provide recommendations for future research and practice [12-14].

The removal efficiency of SVFCWs in removing total coliform and fecal coliform depends on several factors, such as the design and operation of the system, the quality and quantity of the influent wastewater, the environmental conditions, and the characteristics of the microbial community. In arid regions, where water scarcity and high temperatures are common, SVFCWs may face some challenges in achieving high removal efficiency. For example, low hydraulic loading rates may reduce the contact time between wastewater and media, high evapotranspiration rates may cause water loss and clogging, and high temperatures may favor the growth of thermotolerant bacteria.

However, some studies have reported that SVFCWs can achieve satisfactory removal efficiency of total coliform and fecal coliform in arid regions, if properly designed and operated. For instance, a study in Oman found that a SVFCW system achieved an average removal efficiency of 99.9% for total coliform and 99.8% for fecal coliform over a period of two years [15]. Another study in Jordan reported that a SVFCW system achieved an average removal efficiency of 99.7% for total coliform and 99.6% for fecal coliform over a period of one year [16]. These results suggest that SVFCWs can be an effective and sustainable option for wastewater treatment in arid regions, provided that they are adapted to the local climatic and hydrological conditions.

The removal efficiency of COD and BOD in SVFCWs depends on several factors, such as the type of plants, the filter media, the hydraulic retention time (HRT), the hydraulic loading rate (HLR) and the season. According to various studies, VSSF CW can achieve high removal efficiency of COD and BOD, ranging from 45% to 88.8% for COD and from 74.96% to 95.34% for BOD [17]. The plants, such as Typha latifolia and Phragmites australis, can enhance the treatment performance by providing oxygen and nutrients to the microbial biomass in the filter media [18]. The filter media, such as zeolite, gravel and sand, can provide physical and chemical adsorption of pollutants [19]. The HRT and HLR can affect the contact time and the flow rate of the wastewater in the SVFCWs, which can influence the removal efficiency of COD and BOD. Generally, longer HRT and lower HLR can result in higher removal efficiency [20]. The season can also affect the removal efficiency of COD and BOD, as different temperatures and rainfall can alter the biological and chemical processes in the SVFCWs [21]. According to a review by Albalawneh et al. [22], the average removal efficiency of SVFCWs for BOD ranged from 64% to 98%, while for COD it ranged from 55% to 97%. These values are comparable to or higher than those reported for other types of constructed wetlands, such as horizontal subsurface flow or surface flow systems. The high removal efficiency of SVFCWs in arid regions can be attributed to several factors, such as the high temperature, which enhances microbial activity and organic degradation; the high oxygen

transfer rate, which facilitates aerobic processes; and the presence of plants, which provide oxygen, nutrients and organic substrates for microbial growth.

SVFCWs are very effective at removing nutrients from wastewater, including nitrogen and phosphorus. Nitrogen is removed through a process called nitrification-denitrification. Nitrification is a process in which ammonia is converted to nitrate by bacteria. Denitrification is a process in which nitrate is converted to nitrogen gas by bacteria. Phosphorus is removed through a process called adsorption. Adsorption is a process in which phosphorus is attached to the surface of the media particles.

SVFCWs have been shown to be very effective at removing nutrients from wastewater from a variety of sources, including municipal wastewater, agricultural runoff, and industrial wastewater. SVFCWs are also relatively inexpensive to construct and operate.

A number of studies have been conducted on the removal of nutrients in SVFCWs. A study by Kadlec and Wallace [1] found that SVFCWs were able to remove 70-90% of the nitrogen and phosphorus from municipal wastewater. A study by Vymazal [2] found that SVFCWs were able to remove 80-90% of the nitrogen and phosphorus from agricultural runoff. A study by Wang et al. (2011) found that SVFCWs were able to remove 70-80% of the nitrogen and phosphorus from industrial wastewater.

These studies demonstrate that SVFCWs are a very effective method for removing nutrients from wastewater. SVFCWs are also relatively inexpensive to construct and operate, making them a viable option for a variety of wastewater treatment applications.

In this paper, the design, performance, and evaluation of a subsurface vertical flow constructed wetland system to treat and reuse institutional wastewater in the Kingdom of Saudi Arabia. The influent and effluent quality of the SVFCWs system were monitored for 28 days and assessed its removal efficiency for various parameters, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), ammonia nitrogen (NH3-N), Ortho-Phosphate (Ortho-P), and total phosphorus (TP).

METHODS

Source of sewage

The raw sewage effluent in this study was supplied from the King Saud University wastewater treatment plant in Riyadh, Saudi Arabia.

Construction of the SVFCW

A pilot-scale constructed wetland was built on the rooftop of the College of Engineering at King Saud University in Riyadh, Saudi Arabia. The system consists of a 60-liter tank with a tap to control the flow of raw wastewater from the KSU Wastewater Treatment Plant. The wastewater flows by gravity to three stages connected in series, each filled with media and plants. The outflow from the previous stage is the inflow to the next stage, and so on, until the water reaches the third and final stage, where the treated wastewater flows out.

The three stages of the constructed wetland system are all vertical subsurface flow, meaning that the wastewater flows beneath the surface of the media in all three stages (Figure 1).

The SVFCW system consists of three treatment stages (30 cm diameter and 30 cm depth), each stage is filled with the same media layers, bottom layer consists of gravels (2-3 cm) of 8 cm depth, middle layer is filled with aggregates (1-2 cm) 8 cm depth, and the top layer is mixture of aggregates and sand of particle size (1 mm to 2 mm) with (4:1) ratio (aggregates: sand) with 8 cm depth.

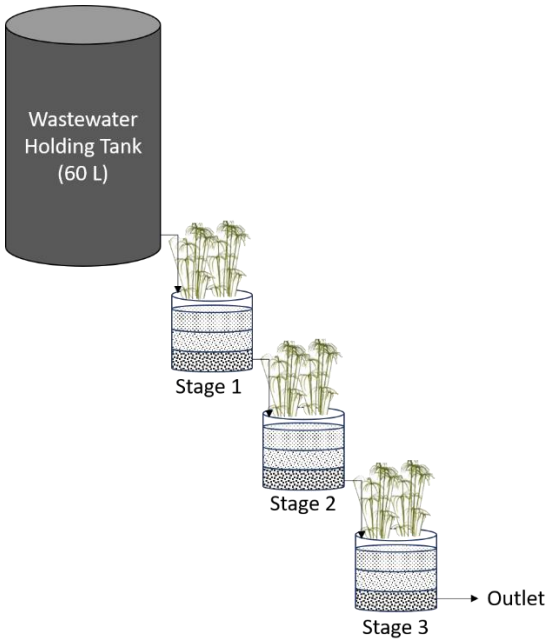


Fig.1:-*The 3-stage pilot-scale constructed wetland.*

Initiation of the wetlands

SVFCW bed planted with umbrella plants (Cyperus Involucratus, Cyperaceae). Umbrella plants are grass-like plants that are commonly planted in constructed wetlands because they are effective at removing pollutants from wastewater. The plants were then allowed to grow for three weeks and were watered with 50% potable water and 50% wastewater. After three weeks, the system was operated continuously for 28 days. New raw influent was added to the system after 10 days, while the system was kept running. This allowed the plants and the media to have enough time to treat the wastewater before it was discharged from the system.

Calculations

The result of different operational conditions on wetland performance was evaluated on the basis of percent removal, mass removal rate, areal elimination rate constant and volumetric removal rate constant.

The removal efficiency was calculated as follows:

Removal efficiency (%) = $(C_{in} – C_{out})/C_{in}$ x 100

where

C_{in} = inflow concentrations (mg/L)

C_{out} = outflow concentrations (mg/L)

The mass removal rate (r, in g/m2/d) was calculated as follows:

$r = q (C_{in} – C_{out})$

where

q = hydraulic loading rate (m/d)

Methods of analyses

Thirty (30) samples are collected in 500 ml plastic bottles from the outlet the three consecutive treatment stages every two days during the experiment. Sampling is performed at around 10 a.m. and the tests are done immediately following the collection of samples. TSS, COD, BOD, Total Coliform (TC), Fecal Coliform (FC) Ammonia Nitrogen, and Total

Phosphorous (orthophosphate and polyphosphate) are tested throughout the period of the experiment (28 days of operation) to examine the quality of the water before and after treatment. Maximum temperature of the atmosphere during the study is (38±4) ^{o}C while the temperature of the wastewater is (24±2) ^{o}C.

After samples are successfully collected from each stage every two days. The samples are then taken to the lab for analysis of the required parameters. The testing methodology is done according to the standard methods [23].

RESULTS AND DISCUSSION

Total Suspended Solids

The primary mechanism for removing suspended solids in the Vertical Flow Subsurface Constructed Wetland (VFSCW) is through filtration and sedimentation. However, bacterial growth aids in the removal of non-settling particulates that are colloidal and supra colloidal in nature. This process results in some of these particles settling while others undergo microbial decay. Additional particles are adsorbed onto other solids present in the constructed wetland such as the wetland bottom, plants, and gravel [24].

The concentration of Total Suspended Solids (TSS) in the influent is significantly reduced from 113±23 mg/L to 8±2 mg/L after passing through the third stage. As the number of stages increase, the TSS concentration decrease (Table 1).

As depicted in Figure 2 (horizontal dotted line), the TSS concentrations are within category (C) of the irrigation standards set by the Ministry of Environment, Water and Agriculture [25]. These standards, which allow a maximum TSS concentration of 40 mg/L, permit the use of treated wastewater for irrigating non-food crops such as industrial plants, energy crops, flowers, trees, and grains.

The VFSCW wetland demonstrates its effectiveness in TSS removal due to its relatively low velocity and high surface area. This provides ample opportunities for TSS separations through gravity sedimentation (discrete and flocculent), straining and physical capture, and adsorption on biomass film attached to gravel and root systems. The plant roots also contribute to the removal of suspended solids [26].

Average TSS removal efficiency (percentage) is increased throughout the treatment stages from being 82% in the first stage up to 94% in the third stage as shown in **Error! Reference source not found.**. The overall TSS concentration is noticeably reduced by 94% after leaving the constructed wetland. Average removal efficiency of TSS in the end product of VFSCW is in accordance with several researches [27, 28, 29, 30, 31].

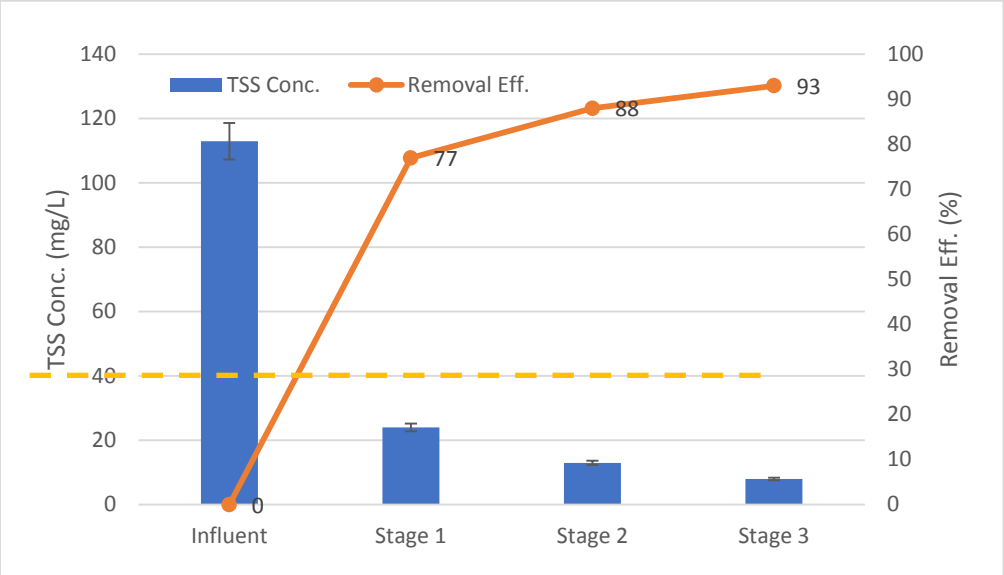


Fig.2:- *TSS concentrations and removal efficiencies for the 3 stages.*

Table 1:-*Average concentrations, removal efficiencies and mass removal rates.*

Stage	Average Concentration + SD (mg/L)	Removal Efficiency (%)	r ($g/m^2/d$)
Total Suspended Solids			
Influent	113 ± 23	-	
Stage 1	24 ± 3	79	5.34
Stage 2	13 ± 4	46	0.66
Stage 3	8 ± 2	38	0.30
Biochemical Oxygen Demand			
Influent	45 ± 5	-	
Stage 1	15 ± 3	67	1.80
Stage 2	12 ± 2	20	0.18
Stage 3	11 ± 1.5	8	0.06
Chemical Oxygen Demand			
Influent	91 ± 4	-	
Stage 1	40 ± 5	56	3.06
Stage 2	31 ± 4	23	0.54
Stage 3	27 ± 6	13	0.24
Ammonia-Nitrogen			
Influent	22 ± 5	-	
Stage 1	10 ± 3	55	0.72
Stage 2	6 ± 0.1	40	0.24
Stage 3	4 ± 0.2	33	0.12
Ortho-Phosphate			
Influent	15.2 ± 1	-	
Stage 1	10.45 ± 2	31	0.29
Stage 2	8.3 ± 1	21	0.13

Stage 3	6.2 ± 1	25	0.13
Total Phosphorus			
Influent	22 ± 1	-	
Stage 1	15 ± 1	32	0.42
Stage 2	11 ± 0.5	27	0.24
Stage 3	8 ± 0.5	27	0.18

Organic Matter

`The experiment period lasted for 28 days, during which we analyzed samples from the influent and the three treatment stages to measure the COD concentration. Figure 3 shows that the COD concentration of the treated wastewater dropped from 91±4 mg/L to 8±2 mg/L after the 3rd stage on day 28. According to the MMRA irrigation standards, the COD concentration for all days met the unrestricted irrigation standards (50 mg/L), which allowed us to use the treated wastewater for irrigating any crops (including raw food crops) with any irrigation methods.

Built wetlands have a strong ability to purify organic matter (Yu shuili, 2011). They have a high rate of removal to COD where most of the processing systems can achieve 90%. Research was done on constructed wetlands to purify municipal sewage showed that at low water concentration, the constructed wetlands COD removal is up to 80% (WEN yue, 2007). COD removal is significantly correlated with several numbers of microorganisms, this indicates that the removal of organic matter is mainly the action of microorganisms (Qin and Chen, 2016). Average COD removal efficiency (percentage) decreased throughout the treatment stages during the experiment from 56% for stage 1 to 70% for stage 3. Average removal efficiency of COD in the end product of VFSCW is in accordance with several researches [28, 29, 30, 31, 32].

Influent BOD concentration is reduced from 45±5 mg/L down to 11±1.5 mg/L. BOD concentrations of treated wastewater clearly decrease more with time and it is expected to happen due to microorganisms acclimatizing with time and improving the removal of organic matter in wastewater and consequently the overall BOD reduction. Based on Ministry of Environment, Water and Agriculture [25] irrigation standards, BOD concentrations for all days are within category (C) for MEWA irrigation standards (40 mg/L) (Figure 4).

According to Pillai and Nair [28], constructed wetlands are effective in removing organic matter from wastewater. They can achieve up to 90% BOD removal, which is a measure of the biodegradable organic content. Several studies have shown that constructed wetlands can reduce the BOD concentration of municipal sewage by 95% at low water levels [33]. Gikas and Tsihrintzis [31] found that the BOD removal was closely related to the microbial activity in the wetlands, suggesting that the organic matter degradation was mainly due to the microorganisms. In this study, the VSFCW system reduced the BOD concentration of the effluent by 76%, which is consistent with the results of previous research [30, 33, 34, 35].

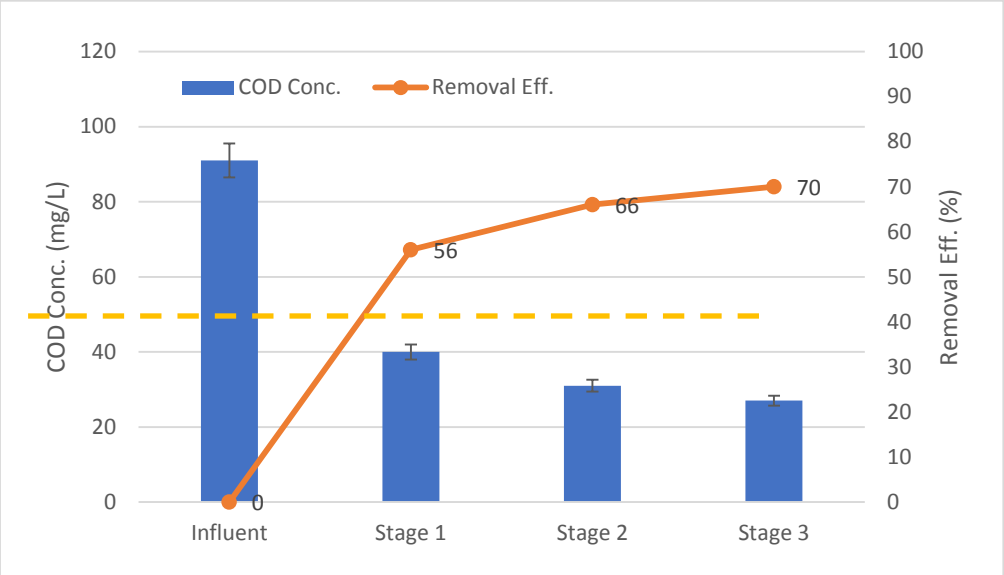


Fig.3:-*COD concentrations and removal efficiencies for the three stages.*

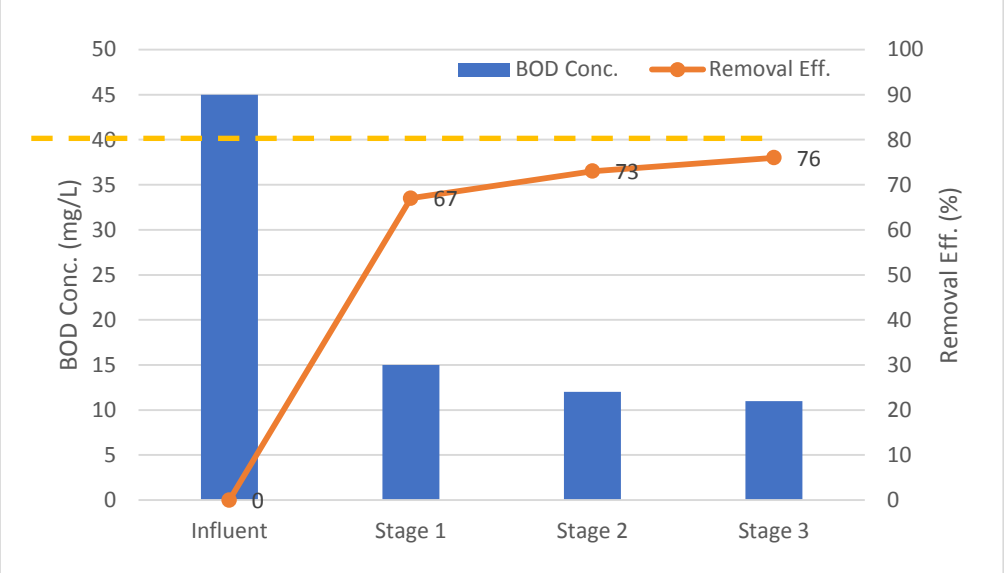


Fig.4:- *BOD concentrations and removal efficiencies for the three stages.*

Ammonium-Nitrogen

The concentration of NH3-N in treated wastewater typically diminishes over time due to the growth and activity of microorganisms, which enhances the removal of NH3-N. The concentration of NH3-N dropped from 22 mg/L to 4 mg/L, which is within the MEWA [25] irrigation standards (5 mg/L), allowing the treated wastewater to be used for restricted irrigation. Nitrogen removal involves a series of processes that act on various types of wastewater wetlands, including ammonia volatilization, ammonification, nitrification, nitrate ammonification, denitrification, fixation, plant and microbial uptake, ammonia adsorption, organic nitrogen burial, and ANAMMOX [2]. In vegetated wetlands, macrophytes are crucial for efficient nitrate removal [26], with different plant species playing unique roles in nitrogen transformations [37]. The average NH3-N removal efficiency increases across the treatment stages, starting at 54% in the initial stage and reaching up to 83% by the third stage. This efficiency aligns with findings from various studies [29, 30, 38, 39, 40].

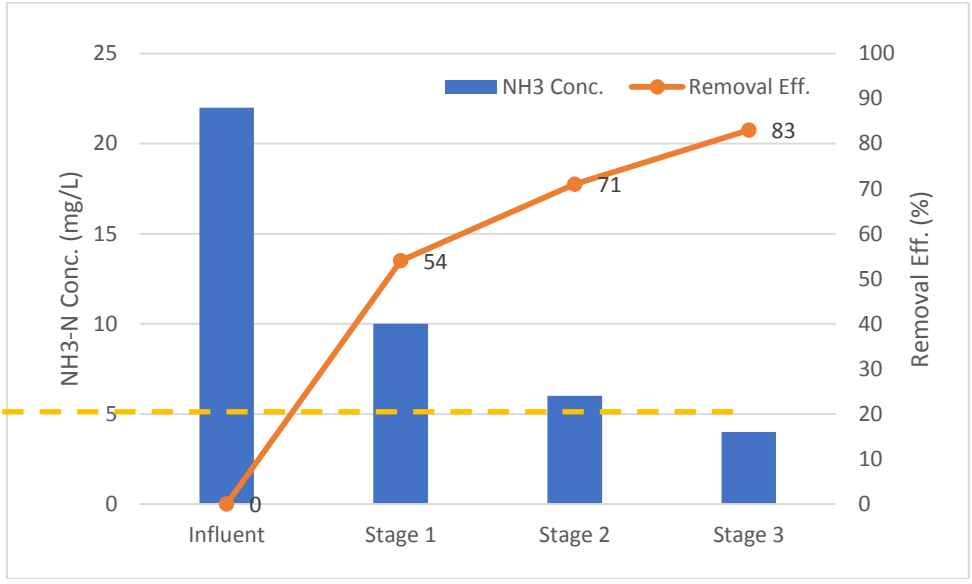


Fig.5:-*NH3-N concentrations and removal efficiencies for the three stages.*

Phosphorous

All out phosphorous (TP) gauges every one of the types of phosphorous in the examples (orthophosphate and polyphosphate).TP concentration is reduced from 22 mg/L to 13.8 mg/L after being treated in the 3rd stage. TP concentration for the effluent of the third stage of VFSCW is less than MEWA standards for wastewater discharge to sewer networks and STPs (15 mg/L) [25]. Physical/chemical and biological processes are the main ways that phosphorus is transformed in wastewater wetlands [26].

Several studies have shown that phosphorus removal in constructed wetlands occurs mostly through plant uptake, microbial accumulation, and matrix adsorption and precipitation [41]. Other research has also identified other mechanisms of phosphorus removal, such as matrix adsorption and precipitation in constructed wetland system. Plant uptake of organic phosphorus is less significant, but plant uptake of inorganic phosphorus is more important, especially for large plants like reeds that require inorganic phosphorus for their long-term growth [33].

The efficiency of Total Phosphorus (TP) removal progressively improves across the treatment stages, starting at 9% in the initial stage and reaching up to 46% by the third stage. Phosphorus removal in wastewater wetlands is typically not as effective as nitrogen removal. This is attributed to the lack of a direct metabolic pathway in wetlands for phosphorus removal. Instead, wetlands employ a combination of physical, chemical, and biological methods to decrease phosphorus levels [42]. The final TP removal efficiency in Vertical Flow Subsurface Constructed Wetlands (VFSCW) aligns with findings from various studies [30, 40, 43, 44, 45]

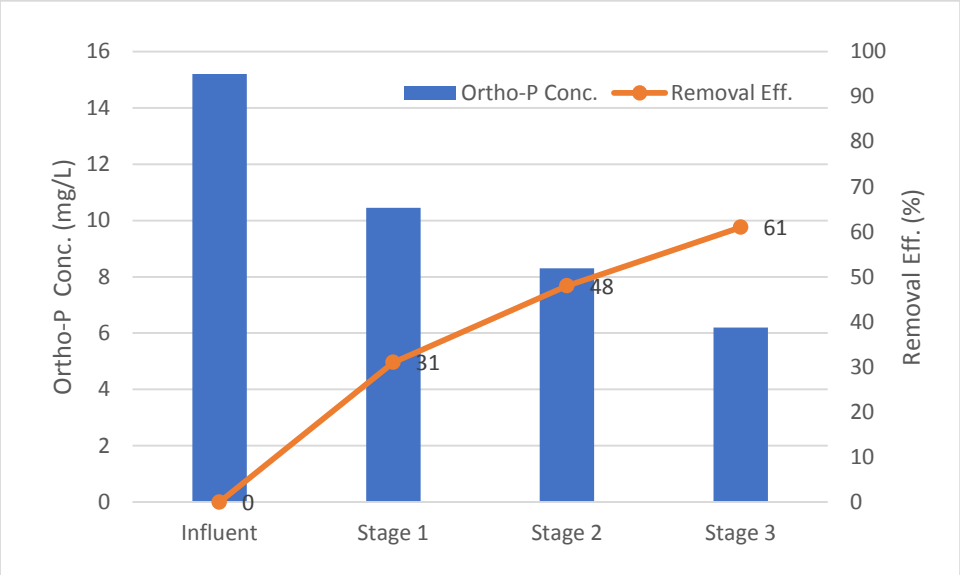


Fig.6:-*Ortho-P concentrations and removal efficiencies for the three stages.*

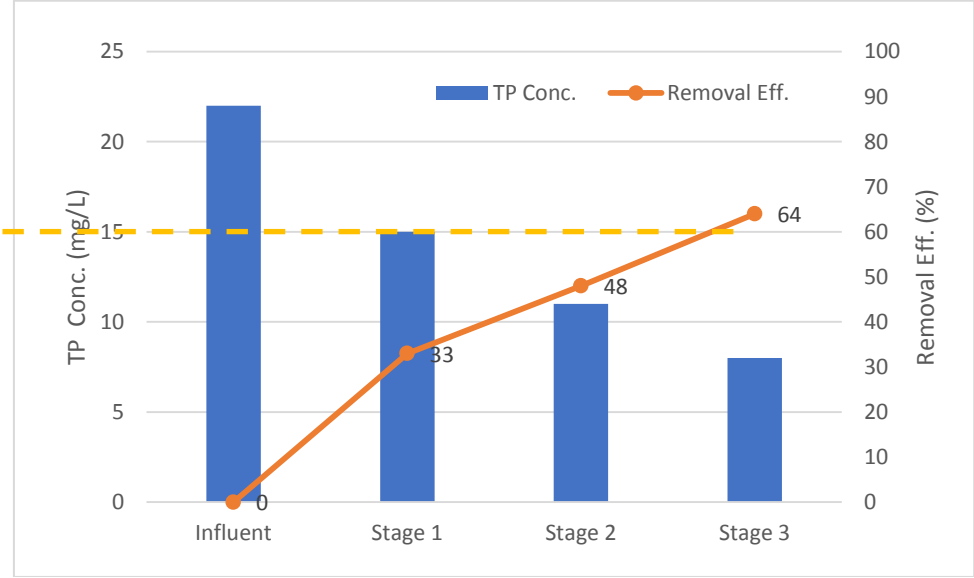


Fig.7:-*TP concentrations and removal efficiencies for the three stages.*

Contribution of Stages in Removal

Table 1 shows that among the three stages of the wetland, the three stages significantly ($P < 0.05$) affected the removal of TSS. The average percent removal of TSS (79%) for stage 1 was approximately 1.7 times that removed by stage 2 (46%) and it did not noticeably decrease from stage 2 to stage 3. The mass removal rate of the TSS in stage 1 (5.4 g/m2/d) was 8 times greater than that of stages 2 and 3. The results of the removal efficiency and mass removal rate for the TSS showed that stage 1 is more effective than stages 2 and 3.

Stage 1 of the wastewater treatment process is the most effective at removing BOD, with an average removal efficiency of 67%. This is 3.3 times greater than the removal efficiency of stage 2 (20%), and it does not noticeably decrease from stage 2 to stage 3. The mass removal rate of BOD in stage 1 is also significantly higher than in stages 2 and 3, at 1.8 g/m2/d. This is 10 times greater than the mass removal rate of stages 2 and 3, respectively. Overall, the

results of the removal efficiency and mass removal rate for BOD show that stage 1 is more effective than stages 2 and 3.

The first stage of treating wastewater has the highest COD removal, with an average of 56% efficiency. This is more than double the efficiency of the second stage (23%), and it stays almost the same from the second to the third stage. The amount of COD removed per unit area and time in the first stage is also much higher than in the other stages, at 3.06 g/m2/d. This is 5.6 times and 2.25 times higher than the amount removed in the second and third stages, respectively. Therefore, the COD removal efficiency and amount data indicate that the first stage is more effective than the other stages.

Stage 1 achieved a higher NH3-N removal efficiency (55%) than stage 2 (40%), and the efficiency did not change significantly from stage 2 to stage 3. The NH3-N mass removal rate in stage 1 (0.7 g/m2/d) was three times higher than in stages 2 and 3. The NH3-N removal efficiency and mass removal rate also indicated that stage 1 performed better than stages 2 and 3.

The TP removal efficiency is highest in the first stage of wastewater treatment, with an average value of 32%. This is 1.2 times higher than the second stage, which has an average efficiency of 27%. The efficiency does not change much from the second to the third stage. The first stage also removes more TP per unit area and time, with a value of 0.42 g/m2/d. This is 1.75 times and 1.33 times higher than the second and third stages, respectively. These results show that the first stage performs better than the other stages in removing TP.

The mass elimination rates of TSS, COD, BOD, NH3-N, TP in the present study were less to those reported by Zhao et al. [46] using the VSSFCW with alum sludge media and Dan et al. [47] using the HSSF and the VSSFCW with mixture media of gravel, coconut and sand. This can be due to the low strength of wastewater.

The percentage of each stage's contribution to the total removal of various pollutants in the system is shown in Fig. 7. The first stage had the largest contribution to the total removal for all the pollutants measured. However, the second and third stages also played a significant role depending on the pollutant. For example, the second and third stages contributed 47.2% and 50% of the total Orhto-P and TP removal, respectively, while they only contributed 15.2%, 20.3%, 11.8%, and 33.3% for TP and P, respectively.

The removal patterns of BOD, COD and TSS were similar in the first stages, indicating the effect of SS removal on organics removal. However, the removal patterns differed, especially for NH3-N, Orhto-P and TP, in the second and third stages.

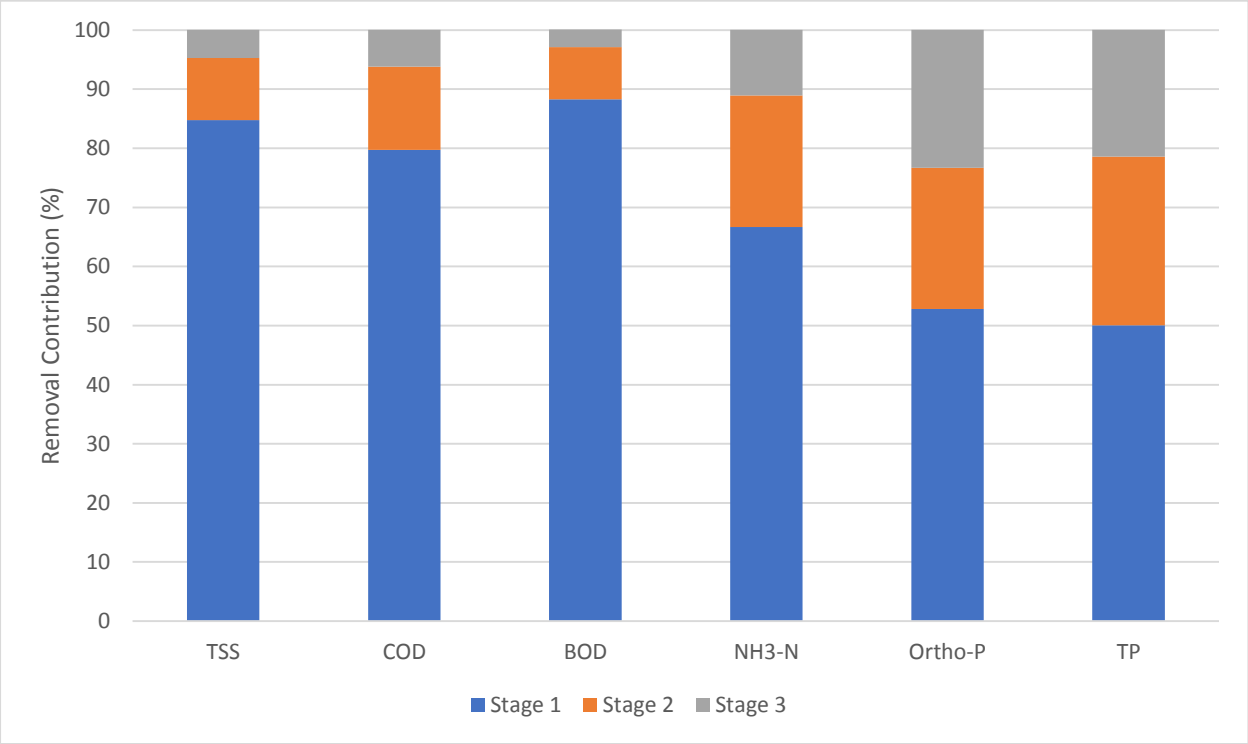


Fig.7:-*The relative contribution of each stage (in percentage terms) to the overall removal achieved in the system for the different pollutants.*

CONCLUSIONS

A pilot-scale system was used to test the performance of VFSCWs as a low-cost wastewater treatment option that can improve the removal of pollutants. The system also provided a way to reuse institutional wastewater for irrigation in KSA. The results showed that the system was effective at removing different types of pollutants from the wastewater. The average influent concentrations (in mg/L) were 113 ± 23 for TSS, 45 ± 5 for BOD, 91 ± 4 for COD, 22 ± 5 for NH3-N, 15.2 ± 1 for Ortho-P and 22 ± 1 for TP. The average removal efficiencies were 90% for TSS, 76% for BOD, 70% for COD, 83% for NH3-N, 61% for Ortho-P and 64% for TP. The system performed better in stage 1 than in stage 2 and stage 3, but the differences were not significant. The effluent concentrations met the MEWA irrigation standards, which means that the treated wastewater can be used for restricted irrigation. The system is expected to improve over time as the vegetation and microbial population grow and stabilize.

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