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Innovative Vertical Constructed Wetland for Rural Domestic Wastewater Treatment

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Abstract

The vertical constructed wetland was implemented at Karary University which is located in the city of Omdurman Sudan. The system was built inside a faculty of engineering for the university in June 2021.

A three-stage of constructed wetlands system (vertical) subsurface system joined on series was investigated in this study for treating domestic wastewater. Plastic barrels with a height of 70cm and a diameter of 55 cm were placed above each other's on steel stands with different elevations to achieve flow by gravity without pumping and it is received by storage barrels. In the three stages wastewater flow from the storage barrels to the first stage up to the third stage which is the final stage in the experiment. The system was evaluated under different operational parameters such as hydraulic retention time (HRT) as 24, 12, and 6 hours, respectively. The system was cultivated with Jatropha plant, and the period of the experimental study was three months from June to August. All stages of the system were filled with some media which was three layers from bottom medium gravels then fine gravel and sand layer in the top and the total depth of 70cm.

Many experiments were done during the operational study to check the concentrations and evaluation of the pollution removal efficiency of this system. The tests were conducted in this study such as COD, PO_4, and N-NH_4. The optimum COD, PO4, N-NH_4 removal of efficiency during the whole experimental study were 73.22%, 73.62%, 68.76% with HRT equal 24 hours.

Keywords: constructed wetland, vertical constructed wetland, wastewater treatment, pollution, removal efficiency.

1- INTRODUCTION:

The conventional wastewater treatment process consists of a series of physical, chemical, and biological processes. Typically, treatment involves three stages, called primary, secondary and tertiary treatment. Conventional wastewater treatment processes are becoming limiting when facing the growing environmental legislation and increasingly more stringent emission standards for pollutants because they are generally expensive and not entirely feasible for widespread application in rural areas. Therefore, ecological technologies have been attracting more attention as alternative solutions for wastewater treatment and have been significantly developing in these years [**1**].

Constructed wetlands (CWs) are "engineered systems, designed and constructed to utilize the natural functions of wetland vegetation, soils, and their microbial populations to treat contaminants in surface water, groundwater or waste streams [**2**].

A vertical flow constructed wetland is a planted filter bed that is drained at the bottom. Wastewater is poured or dosed onto the surface from above using a mechanical dosing system [**3**]. The water flows vertically down through the filter matrix to the bottom of the basin where it is collected in a drainage pipe.

The earliest form of down suspended flow vertical constructed wetland is that of Seidel in Germany in the 1970s, sometimes called the Max Planck Institute Process (MPIP) or the Krefeld Process. Similar systems in the Netherlands were called "infiltration fields" [**4**]. Interest in the particular process has been revived in the last decade because of the need to produce beds that nitrify and overcome the problem of HF beds.

The beds of vertical constructed wetland commonly are filled with crushed rock on the bottom, the next layer is coarse gravel and the top layer is soil planted with Rice (Oryza sativa) [**5**].

The quantity of domestic wastewater in Sudan, especially in Khartoum state, is very high with a population density of about ten million. The source of domestic wastewater is larger than the capacity of wastewater treatment networks, which makes these networks lack efficient performance. This paper study looks to alleviate the high load capacity on sewage plants using a system that is highly efficient and low cost in the rural areas in Khartoum state. In this study the domestic wastewater treatment system is applied in Khartoum state- Karary University by using vertical constructed wetlands to evaluate the pollutions removal efficiencies such as organic matter, phosphate, and the ammonium nitrogen.

2- MATERIAL AND METHOD

2.1 Research site

The vertical constructed wetland that is studied was implemented at Karary University which is located in the city of Omdurman- Sudan. The system was built inside a faculty of engineering for the university which was done also for wastewater treatment research using constructed wetland systems.

2.2 System set-up

There was a septic tank that collected wastewater from the chemical and civil departments of the engineering college o for the university and then the wastewater was pumped to the storage tank which supplied wastewater to the system. The system consisted of plastic barrels 55 cm in diameter, a larger barrel of 120 cm in diameter were used as storage tanks that contained raw wastewater. Steel stands were built with different heights to put the barrels on them so that the system can be run by gravity without any pumping. The outflow from the first barrels will be inflow in the second barrels and so on until we reach the third barrels (3- stages) which are the final stage as shown in Fig.**1**.

Fig.1. Laboratory scale of VFCW

Each barrel in all stages and the replicated ones were filled with the same media on layers. The first layer consisted of medium gravels whose size was between (2.4-3.2 mm d_{50}) at 30cm height. There was a valve in the bottom of each barrel (stage) which was used for controlling the flow in the system, so it was chosen larger than the entrance of the valve (which was ½ inch) so the valve would not be clogged by small aggregates. The second layer was filled with fine gravel (0.6-1.6cm d_{50}), for a 20 cm depth. The third layer had the same characteristics as those of the second layer but it was mixed with silt and sand (0.02-0.06 cm d_{50}) for a 10 cm depth, this layer was mixed with sand to provide fine media suitable for plants roots. The total thickness (depth) of the media inside each barrel was 70 cm. The constant level of wastewater inside the system was 10 cm for each barrel. There was a perforated 1.5-inch diameter PVC pipe placed inside each barrel with a length of 60 cm. It was put to measure the level of wastewater inside the system and to provide aeration for the system. Fig.**2**. Shows longitudinal section for the treatment cell.

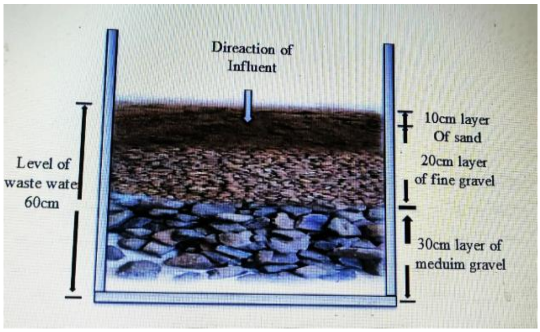

Fig.2. Profile of the system layers media.

2.3 Operational parameters of the system

2.3.1 Flow (Q) and hydraulic retention time (HRT)

There are two types of feeding flow that commonly can be used; they are the single-fed and multi-fed types [**6**]. In this study, the single-fed was used, and the feeding flow is only carried out from only one influent. The constructed wetland influent wastewater is fed at the storage tank and then pump to the system through the porous media under the vertical subsurface flow (down flow) until the wastewater reaches the third phase of the system. The wastewater samples were collected from the effluent of the third phase of the system in small plastic bottles. The system was operated with different hydraulic retention time (HRT) and flow rate during three sequential months. The operating parameters were shown in Table.**1**.The HRT was calculated according to the equation 1.

$$\text{HRT (day)} = V\ (m^3) / Q\ (m^3/\text{day}) \quad (1)$$ [**7**]

Table 1. System Opreation Parameters (Flowrateandhydraulic Retention Time)

Item	Month	HRT (hours)	Flow rate (L/hour)
1	June	24	3.6
2	July	12	7.2
3	August	6	14.4

2.3.2 Temperature (T)

The constructed wetland system ran during summer and part of the autumn season, the temperature was measured every three days using a temperature meter; the maximum temperature of the atmosphere during the study was (41±1) °C.

2.3.3 Potential of hydrogen (PH)

Potential hydrogen (PH) is a scale used to specify the acidity or basicity of an aqueous solution. PH in wastewater treatment is most effective at a neutral to slightly alkaline pH of 6.5 to 8. The potential of hydrogen was adjusted by adding sodium hydroxide (Na OH) if wastewater with a low pH and added sulfuric acid (H_2SO_4) in case of wastewater with a high PH. Measurement of (PH) was carried out by using a pH meter which was calibrated before the measurement. Samples were collected in glass bottles from the influent and effluent. The samples were mixed with a magnetic stirrer to ensure uniformity.

2.4 System Plant

Jatropha plant was cultivated in the system during the whole experimental study, as shown in Fig.**3**.To evaluate the physical growth parameters two samples of the system plant were tested. The first sample was taken at the Jatropha seedlings cultivation in the system and the second plant sample was taken in the harvesting time at the end of the experiments. The physical parameters that were tested are fresh weight, dry weight, number of leaves, plant height, and roots height.

2.5 System startup

After the system was built, the seedlings of the Jatropha plant were cultivated, and then ran the system and wastewater flow through the Barrels continuously by the gravity. The constructed wetland system was operated in three phases; the first phase (June month) operated with a flow rate of 3.6 liter/hours, meat that the hydraulic retention time is equal to 24 hours. The second phase (July month) operated with a flow rate of 7.2 liter/hours, meat that the hydraulic retention time is equal to 12 hours. The third phase (August month) operated with a flow rate of 14.4 liter/hours, meat that the hydraulic retention time is equal to 6 hours. To assess the treatment processes and efficiency, all parameters were examined every three days. Chemical oxygen demand (COD), NH_4-N, PO_4, Dissolved Oxygen (DO), the potential of hydrogen (PH), and temperature (T) measurements were analyzed on the influent and effluent samples during the whole experiments.

Fig.3. Constructed wetland planted with Jatropha

2.6 Analytical methods

The samples were taken in plastic bottles from the influent tank (raw wastewater) and the system effluent, in which all system stages were grown with Jatropha plant. Wastewater samples taken were usually implemented at around 10 a.m. The tests were performed to examine the quality of the wastewater before and after treatment. COD, PO_4, NH_4-N, PH, tests were conducted throughout the entire experimental study. All samples were analyzed at the Khartoum Petrochemical Company (KPC) laboratory.

2.7 Statically analysis methods

To assess the system performance efficiency for treating domestic wastewater, the effective different operational conditions in constructed wetland performance were evaluated. The percent pollutants removal efficiency was calculated as follows the equation:

$$\text{Removal efficiency (\%)} = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (2)\ [8]$$

Where:
C_{in} = Influent pollutant concentrations.
C_{out} = Effluent pollutant concentrations.

3. RESULTS AND DISCUSSION

3.1 The organic matter removal efficiency

The constructed wetland system was operated with different flow rates 3.6, 7.2, and 14.4 liter/hours, meat that the hydraulic retention time is equal to 24, 12, and 6 hours, respectively. The results illustrated in Fig.**4**, Fig.**5**, and Fig.**6** presented the influent COD, effluent COD concentrations and COD removal efficiency during the whole experimental study (three months), where the influent concentration is ranged between 39 to 224 mg/l with an average influent concentration is 124.24 mg/l. In addition, the COD concentration in the effluent during experimental time is ranged from 0 – 108 mg/l, and the average effluent concentration was almost stabilized to below 50 mg/l, which was 42.02 mg/l.

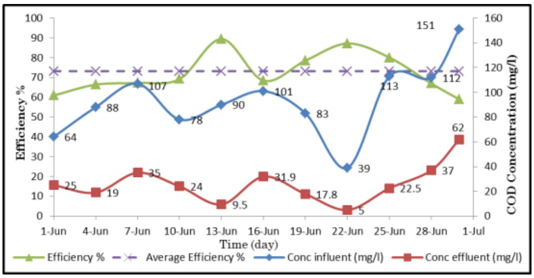

Fig.4. Influent, effluent COD concentration and removal efficiency (first phase- June).

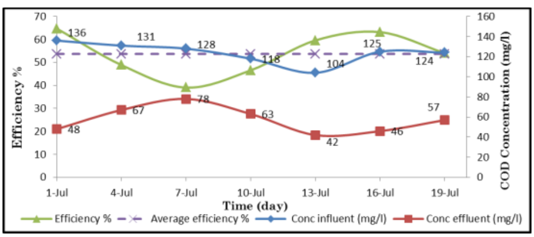

Fig.5. Influent, effluent COD concentration and removal efficiency (second phase-July).

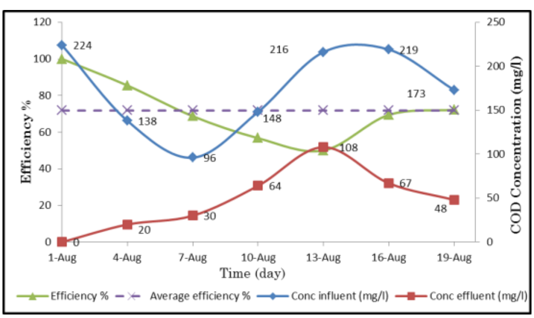

Fig. 6. Influent, effluent COD concentration and removal efficiency (third phase- August).

Furthermore, the result demonstrated that the removal of COD increased with decreasing the organic loading rate (OLR) and increasing the hydraulic loading rate (HRT). The organic matter is reduced in the constructed wetland by aerobic and anaerobic bacteria, and also the plants and the media have a positive effect on the treatment performance [**9**].

The results demonstrated that the optimum HRT during the whole experimental study is 24 hours. The optimum result of the COD removal efficiency showed in the first phase of the system operation, that the average influent COD concentration is 93.27mg/l and the average effluent concentration is 26.24 mg/l, where the system performance for COD removal efficiency is 73.22 %, as shown in Fig.**7**.

In contrast, the COD removal efficiency result observed was similar to that obtained study conducted by Sara G.Abdel Hakeem، who concluded that the percentage of COD removal efficiency by vertical constructed wetland units located in Giza [**10**], Egypt, is ranged between (72-75) percent.

COD removal efficiency results identified were higher than that study by Atif Mustafa, who conducted treatment performance of a pilot-scale constructed wetland in Karachi, NED University of engineering and technology from pretreated domestic wastewater, the wastewater contains domestic sewage and low flows from laboratories of various university departments, use plant (Phragmites karka), he obtained COD removal efficiency is 44%. [**11**]

The result showed that the average concentration of COD reduce from (93.27 to 26.24) mg/l influent effluent respectively, the COD concentration result observed were lower than that study conducted by Denny Kurniadie [**12**], who concluded that the average concentration of COD reduced from (460.82 to 68.50) mg/l in the influent and effluent, by vertical flow constructed wetland for domestic wastewater treatment from family Subandi house located in Indonesia.

The results obtained in this study showed the average COD effluent concentration is 26.24 mg/l that meets the Sudanese standard of wastewater treated is 30mg/l [**13**] and the international standard of the wastewater treated quality.

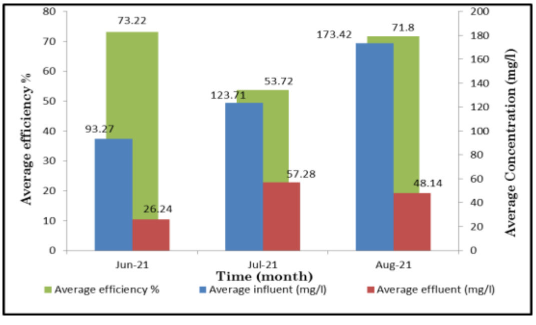

Fig.7. The average COD removal efficiency with different operation parameters.

3.2 PO_4 Removal Efficiency

The results showed in Fig.8, Fig.9 and Fig. 10 presented the influent, effluent concentrations and PO_4 removal efficiency during the full experimental study (three months), where the influent's concentration is ranged between (2.03 to7.26) mg/l with average influent's concentration is 4.86mg/l. Additionally the PO_4 concentration in the effluent during experimental time is ranged of (0 – 3.29) mg/l, with average effluent concentration is1.93mg/l.

The feeding regime and the frequency of the loadings affect PO_4 removal, it is reported that in VFCWs[**14**] under the fill and drain regime, PO_4 removal increased with HRT, due to increased contact time, this indicates that the HRT is a crucial parameter for the effective PO_4 removal.

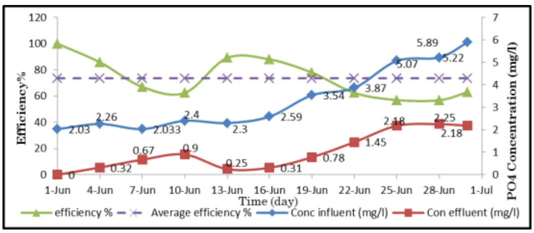

Fig. 8. Influent, effluent PO_4 concentration and removal efficiency (first phase- June).

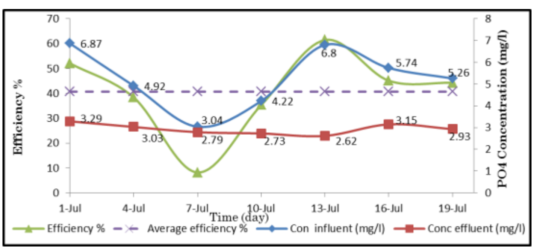

Fig. 9. Influent, effluent PO_4 concentration and removal efficiency (second phase- July).

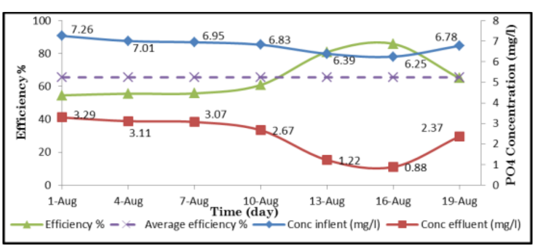

Fig. 10. Influent, effluent PO_4 concentration and removal efficiency (third phase- August).

The results demonstrated that the optimum HRT during the whole experimental study is 24 hours. The optimum result of the PO_4removal efficiency showed in the first month of the system operation, that the average influent PO_4 concentration is 3.38mg/l and the average effluent concentration is 1.02 mg/l, where the system performance for PO_4 removal efficiency is 73.62 %, as shown in Fig .11.

The main transformation removal mechanisms of PO_4 in CWs include adsorption, desorption, precipitation, plant uptake, and microbial uptake.

Plants utilize PO_4 present in wastewater to cover their growth needs, PO_4 uptake by plants takes place at a slower rate compared to adsorption to the substrate, mainly through their root system [**15**].

Bacteria and other microorganisms (e.g., algae, fungi) can rapidly assimilate and store PO_4, which is the partly reversible mechanism. Microorganisms take up organic PO_4 and transform it to inorganic PO_4 through catabolic activities, while during their growth PO_4 is stored in the microbial biomass. Thus, only a small portion of the assimilated PO_4 is permanently removed [**16**].

The temperature has little effect on Phosphorous removal due to the most important removal mechanisms are chemical precipitation and Physical-chemical sorption processes that are not temperature-dependent [**16**].

Additionally, the PO_4 removal efficiency result observed was higher than that obtained study conducted by Yadav and Jadhav [**17**], who construct a wetland unit combined with the surface flow and planted with Eichhornia crassipes was built near the technology department, Shivaji University, and Kolhapur. Maharashtra is situated in the Western part of India. Obtained PO4 removal efficiency is 49%.

The PO_4 removal efficiency result observed was lower than that obtained study conducted by M C Perdana et.al [**18**], who are designed a vertical flow constructed wetland system located in Sewon District, Bantul, and Yogyakarta. The study was conducted in the laboratory of Ecology of Duta Wacana Christian University (DWCU) for three months from March to May 2015. This experimental study applied four treatments control (unplanted), single species Iris pseudacorus, single species Echinodorus palaefolius, and combination (Iris pseudacorus and Echinodorus palaefolius) with three days of retention time. They had obtained the best PO4 removal efficiency with 99.5%.

The results obtained in this study showed the average PO_4 effluent concentration is 1.02 mg/l, where meet the Sudanese standard of waste water treated 2mg/l [**13**] and the international standard of the wastewater treated quality.

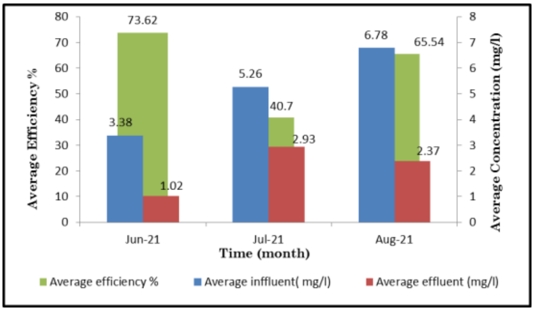

Fig. 11. The average PO_4 Removal efficiency with different operating parameters.

3.3 Ammonium nitrogen (NH_4-N) removal Efficiency

The results illustrated in Fig.12, Fig.13, and Fig. 14 presented the influent, effluent concentrations, and NH_4-N removal efficiency during the whole experimental study (three months), where the influent concentration is ranged between (17.5-35.2) mg/l with an average influent concentration is 26.77mg/l, besides the NH_4-N concentration in the effluent during experimental time is ranged of (3.7 – 29.17) mg/l, with an average effluent concentration is 11.88 mg/l.

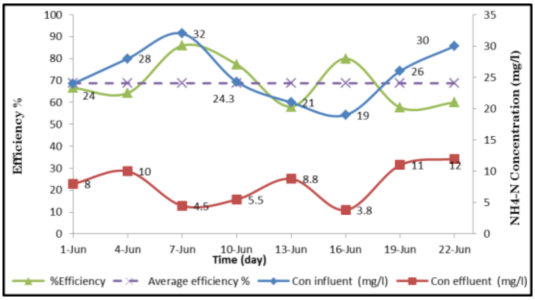

Fig .12. Influent, effluent NH_4-N concentration and removal efficiency (first phase-June).

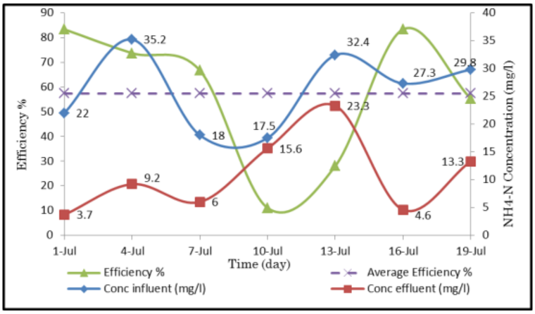

Fig. 13.Influent, effluent NH_4-N concentration and removal efficiency (second phase-July).

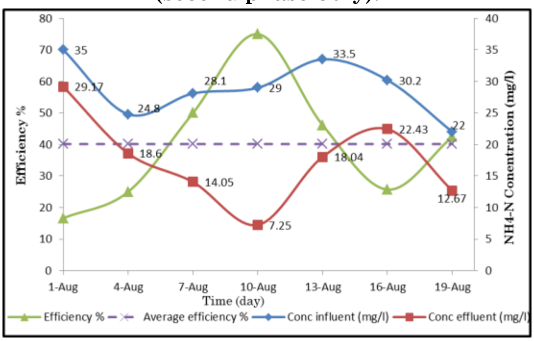

Fig. 14.Influent, effluent NH_4-N concentration and removal efficiency (third phase-August)

The major processes responsible for nitrogen removal in constructed wetlands are nitrification, denitrification, and plant uptake [**19**]. Wetlands promote the process of nitrification/denitrification which removes nitrogen from the water. Bacteria in the water oxidize ammonia to nitrite in aerobic reactions. The nitrite is then oxidized aerobically by another bacteria (Nitrobacteria) forming nitrate. Denitrification occurs as nitrate is reduced to gaseous forms under anaerobic conditions in the litter layer of the wetland substrate [**20**].

Parameters that affect nitrification and denitrification are temperature and pH value. That the optimum temperature range for nitrification is from 25 to 35 C and optimum PH range is from 6.5 to 8. [**21**] The results demonstrated that the optimum condition operation (average PH, average temperature) during the full experimental study are (7.41, 33.08°C) respectively.

Plants play an important role in nitrogen removal by providing biofilm attachment points and by supplying oxygen for nitrification in the root zone [**20**] [**21**].

The optimum result of the NH_4-N removal efficiency presented in the first month of the system operation, that the average influent NH_4-N concentration is 25.53mg/l and the average effluent concentration is 7.95 mg/l, where the system performance for NH_4-N removal efficiency is 68.76 %, as shown in Fig .15.

NH_4-N removal efficiency results identified were higher than study by S.MIMIS and P.GAGANIS, who are conducting constructed wetland at the American farm school using two pilot scale VF reed beds planted with native reeds. The experiments were carried out from April 2006 to July 2006. He obtained small removal efficiency which was in average 20% [**22**].

The results obtained in this study showed the average NH_4-N effluent concentration is 7.95mg/l, which meets the Sudanese standard of wastewater treated is10mg/l [**13**] and the international standard of the wastewater treated quality.

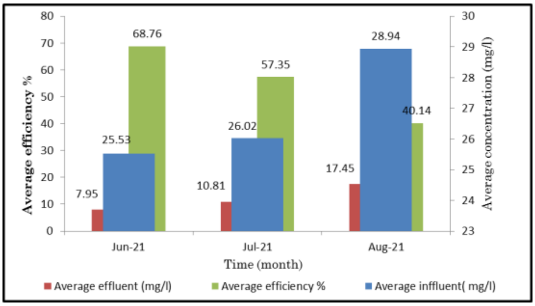

Fig.15. The average NH_4-N Removal Efficiency with different operating parameters.

3.4 Physical growth parameters

Plant growth is affected by some parameters within an applied system; those parameters are categorized according to cultivation time and harvesting time. The Jatropha plant was cultivated in (month of May), eight samples were taken to specify the mean value of the fresh weight, dry weight, number of leaves, plant height and roots height, then the plant harvested in (month of August), above parameters were measured and reported. The study concluded that there was a noticeable increase as mentioned in Table .2.

Table 2. Physical Growth Parameters NGRDU the Cultivation and Harvesting Time

Parameter	Average				
	Fresh weight (gm.)	Dry weight (gm.)	Number of leave (No.)	Plant height (Cm.)	Roots height (Cm.)
Cultivation time	25.65	13.10	10	43.56	12.37
Harvesting time	49.84	27.65	17.25	73.40	25.18

4. CONCLUSIONS

In this paper, the study concentrated on the treatment of wastewater using VF-Sub surface constructed wetland for three-stages with Jatropha plant and showed the effect of using this method on the treatment process. The researcher did tests for COD, PO_4 and N-NH_4 and showed the effect of the system in removing these pollutants by taking samples before and after the treatment process. The research got very good and promising results by using this treatment technique. The results obtained from this study point out several important conclusions.

The main conclusion of the study is summarized in:

1. Optimum removal efficiency for all pollutants that were tested in the first phase (month of June), average COD (73.22%), average PO_4 (73.62%), and average N-NH4 (68.76%).
2. Results suggested that optimum removal efficiency for all pollutants when used hydraulic retention time (HRT) equal 24 hours.
3. The advantages of using systems that contain several stages are that we can do maintenance works without the need to shut down the whole system.
4. The cost for design and construction can be considerably lower than other conventional wastewater treatment options. These systems also enhance the aesthetic value of the local environment.
5. This system is cost-effective with good performance efficiency for the removal of pollution from domestic wastewater.

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