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VERTICAL SUBSURFACE FLOW AND FREE SURFACE FLOW CONSTRUCTED WETLANDS FOR SUSTAINABLE POWER GENERATION AND REAL WASTEWATER SELECTIVE POLLUTANTS REMOVAL

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Abstract: A vertical subsurface flow constructed wetland (VSSFCW) and a free surface flow constructed wetland (FSFCW) were set for the objective of comparison the performance of two systems in order to make a decision of the better one for future installation of wastewater treatment system and power generation. Both of the constructed wetlands were planted with Cyperus Alternifolius. During the observation period (19 days or 456 hours), environmental conditions such as pH, temperature, total chemical oxygen demand (COD), phosphate (PO_4), nitrate (NO_3) ,total suspended solids (TSS), total dissolved solids (TDS), Pb, Cu, and Cd removal efficiencies of the systems were determined. According to the results, final removal efficiencies for the VSSF and FWSF, respectively, were: COD (94.3% and 94.3%),PO_4 (84.3% and 75.3%), NO_3 (100% and 100%), TSS (96.8% and 85.6%), Pb (65.8% and 81.4%), Cu (more than 94.7% and 89.4%), Cd (85.7% and 88%). The treatment performances of the VSSF were better than that of the FWSF with regard to the removal of suspended solids and nutrients. In FWSF systems, electricity generation performed better than VSSF of 31.4 mV especially with batch system during one wastewater feed is loaded among all of the nineteen days with maximum voltage of 33.7 mV and decreased gradually as oxygen depletion in cathode chamber and less metabolism processes has occurred.

Keywords: *Constructed wetland, microbial fuel cell, subsurface flow, sediment, Heavy metals, vertical flow.*

1. Introduction

People around the world are demanding for any green technology as global worming issue is being a wide spread serious phenomena which affirms its bad effect on human health and biodiversity of living beings and planet in a whole. Several merits were observed by using green technology for instance, it is simple to be constructed, safe to handle, less energy consumption, and cost-effective in operation and maintenance. One of these technologies is Constructed Wetland Microbial Fuel Cell(CW-MFC) which utilizes natural processes and only demands simple construction with low maintenance, in addition of being eco-friendly [1].

Constructed wetlands are defined as a man-made aquarium engineered as a simulation for ecological conditions that any of natural wetlands have. The main purpose is treating wastewater in ideal biological, physical, and chemical conditions. It is a sustainable process due to its utilization for natural energy to degrade or uptake specific pollutants, hence the

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low construction and operational costs in comparison with the conventional wastewater treatment system and it is usable in rural areas with limited capital to supply themselves with costly and skilled requirements conventional wastewater treatment plants. [2].

The planted constructed wetlands comprise many various pollutant removal pathways like sedimentation, filtration, precipitation, and uptake, adsorption, absorption, volatilization, etc. [3,4].These processes are influenced by the loading rates, temperatures fluctuation, sediment types, operation strategies, and redox conditions within wetland bed [5,6].

CWs are categorized into three types, free water surface flow (FSF), subsurface flow (SSF), and hybrid flow [7]. In FWS systems, water flows above the sediment by several centimeters, while in SSF systems, water flows through natural or synthetic porous media such as gravels, zeolites, sludge, or aggregate and based on macrophytes which could be either submerged, emerged or floated. These macrophytes are able to induce the performance of up-taking pollutants through editing exudates to the sediment near the rhizosphere [8]. The horizontal subsurface flow constructed wetland (HSSF-CW) is most widely used due to its design simplicity. The HSSF-CWs are mainly anaerobic (deeper or inner portion of the bed) in nature [9] but have some redox variations.

Recently, sediment microbial fuel cells (SMFCs) are promising modification of MFC that mix between water purification and energy generation through one unique system of making use of plant and microbial aggregate relationship at the rhizosphere region of a plant and hence converting the solar energy to bioelectricity [10].

Our study is a sample of an experimental study, in which two types of constructed wetlands planted with a common plant were performed and compared to investigate a better output power and wastewater treatment efficiency by measuring COD, TS, pH, EC, nutrients, and several of heavy metals.

2. Materials and methods

2.1. Preparation of constructed wetlands

Two 400 mm diameter and 530 mm height cylindrical aquariums were used, one for vertical subsurface flow and the other for free water surface flow. Three sizes of gravels were used within three layers, from the bottom to top, depths were 100, 100, and 60 mm and gravel sizes were (10-6mm), (30-50mm), and (80-40mm), respectively. The last top layer of 50mm was sieved sand with a diameter of less than 2mm. Using four layers is proportional with the height of aquarium; that means higher aquarium, more layers in order to treat a good quantity of water and taking a sample of 200ml to be tested in laboratory. 20mm diameter nozzle was established above a distance of 10 mm from the bottom of aquarium as shown in Figure 1. The experiment is considered as batch system process as no circulation inside the constructed wetlands is applied.

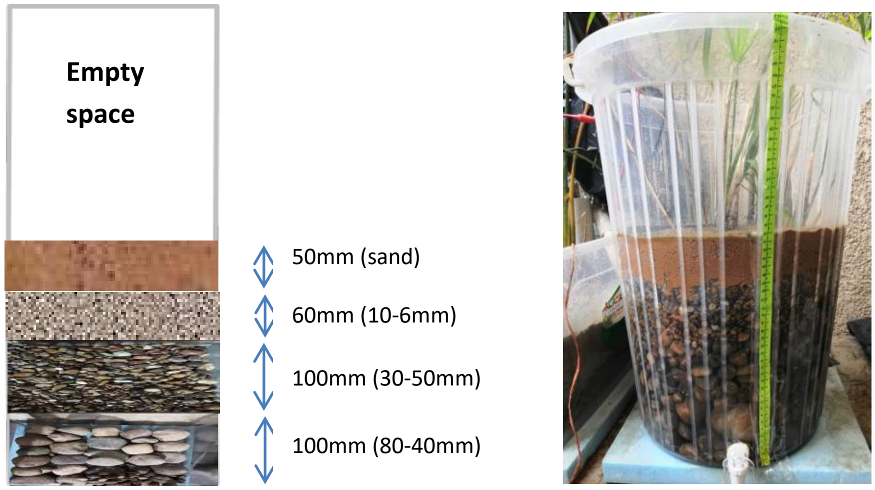

Figure 1. Schematic layers and side view of constructed wetlands

2.2. Preparation of plants

In Figure 2, Cyperus Alternifolius was used in our study. It is Alternifolius common plant in Iraq collected from Public Park in Al-Adamiya, Baghdad. After 5 days of transferring the plant from its source and placing them in water for adaption, the CWs were planted by the end of November with three saplings each in one aquarium and irrigated with domestic wastewater.

2.3. Wastewater collection

Domestic wastewater which is used in this study for the vegetation of CWs was collected from the crude influent of Al-Rustumiyah Wastewater Treatment Plant in Baghdad. For vertical subsurface flow and free surface flow, 15 and 30 liters were used to fill CWs, respectively. Figure 3 illustrate the position of the up-taken wastewater.

Figure 2. Cyperus Alternifolius

Figure 3. Crude wastewater intake basin

2.4. Electrodes Preparation

For applying the object of power generation, two graphite electrodes with high conductivity were employed in electrons transfer from acceptor (anode) to donor (cathode). They are connected with copper wire and resistance of 220 **Ω**. The purpose of resistance is to enable us obtaining a stable voltage.
Soldering has been used to connect the end of copper wire with resistance thus, avoiding any voltages loose.
Anode was distinguished by red copper wire and the cathode by black copper wire. As shown in Figure 4.

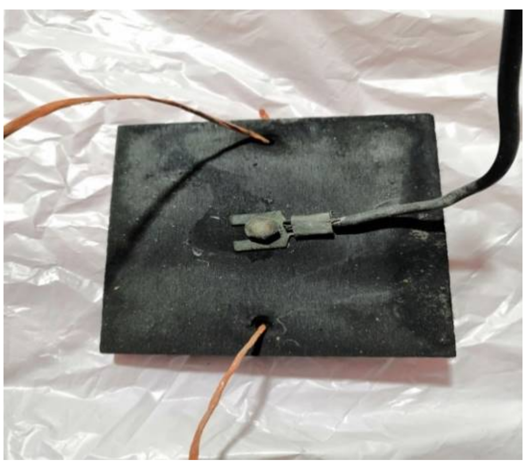

Figure 4. Preparation of electrodes

2.5. Constructed Wetland and Electrodes In Vertical Subsurface Flow

For maintaining subsurface flow, wastewater was poured into the aquarium and kept below sand layer. Anode should be always isolated from oxygen source so that it has been buried in the deepest sand layer or between the interface of sand and (10-6mm) gravel layer whilst cathode was placed on the surface of sand.

2.6. Constructed Wetland And Electrodes In Free Surface Flow

The main deference between subsurface flow and free surface flow is that the water should always cover soil up to several centimeters (70mm) in free surface flow. Anode was buried at the position in vertical subsurface flow aquarium whereas cathode was hanged above soil surface by 20mm.

2.7. Laboratory Analysis

pH (pHep, HI98107, Hanna, Romania), electric conductivity (EC) (Multi-3430 SETF, WTW, Germany), nitrate (NO_3) using cadimium reduction methode, phosphate (PO_4) using ascorbic acid method (Multi parameter photometer, C99 & C200, Romania) , chemical oxygen demand (COD) using open reflux method (COD thermo reactor, Lovibond ET 125, Germany), total suspended solids (TSS), total dissolved solids (TDS), lead (Pb), copper (Cu), and cadmium (Cd) using acid digestion and analysis by atomic absorption spectrometry method for heavy metals (Atomic absorption flame spectrophotometer, AAS 6300, Shimadzu, Japan) , were all measured initially and in parallel with treatment process.
However, it should be put into consideration that crude influent of Al-Rustumiyah Wastewater Treatment Plant is a mixture of diluted domestic wastewater so that we must expect low range of pollutants. All characteristics are shown in Table 1.

Table 1. Properties of initial concentration of used wastewater in the study, from Al- Rustumiyah Wastewater Treatment Plant

Parameter	Value	Unit
pH	6.89	-
EC	1217	μS/cm
COD	390	ppm
TSS	125	ppm

TDS	778	ppm
NO_3	10.1	ppm
PO_4	3.2	ppm
Pb	0.431	ppm
Cu	0.095	ppm
Cd	0.084	ppm

3. Results and discussion

3.1. Sediment Microbial Fuel Cell (SMFC) As Energy Source

The experiment was run for 456 hours with mean temperature of 21 ± 2 °C for VSSFCW and FSFCW. Voltages and currents have been measured by Auto Range Multi-Meter at two different periods per day, at 1AM (during the dark) and 1PM (during the light). These two periods was considered to find the effect of solar radiation on voltage variation.

No enough reports available on the performance of photosynthetic behavior of a system which explains the fluctuation in output voltages as the system is stimulated by different parameters such as electrode materials, growth of plant, and other operating parameters [12]. Figure 6 and Figure 7 show the output voltage during the dark and light periods. Overall, the output voltages during the sun light are higher than being in dark; it is obviously because photosynthesis process is taken place in the presence of sun radiation and thus transferring more oxygen into roots which are utilized in metabolism. plant physiology, atmospheric conditions (sunny or cloudy), temperature, redox conditions, and number of microorganisms within the sediment, etc. are all other causes of variation in voltages.

As shown in Figure 5, Total Dissolved Solids (TDS) in wastewater affect the transfer of electrons. Highest (TDS), more electric conductivity (EC) and more electrons transfer to produce more voltages [13]. At the beginning of experiment, TDS was recorded to be 778 mg/l and EC of 1217 µS/cm. After the first sampling test (day 6), TDS and EC increased to 1735mg/l and 2720µS/cm for vertical subsurface flow; and to 1736 mg/l and 2680µS/cm for free surface flow.

By the end of 19 days, final TDS and EC were 2778mg/l and 3040µS/cm for vertical subsurface flow; and to 2293 mg/l and 3050µS/cm for free surface flow.

In vertical subsurface flow, no liquid medium (wastewater) were coexist for electrons to transfer between two electrodes as samples were taken off. so that we can notice how the voltage was decreased and faded from day 9 and up before being 31.4 mV in day 5.

For free surface flow, voltages were fluctuated between 33.7-4.1 mV. This type of flow hit the highest trend to reach 33.7 mV in day 14 during sun light periods as shown in Figure 6. Maximum voltages were recorded whenever samples were taken (suction of water for test), hence water level would decrease and cathode would be posed to atmosphere, thus more oxygen will transfer.

In Figure 7, during the darkness periods, Sediment microbial fuel cell showed the same pattern as being exposed to sun light. It recorded 30 and 25.2 mV for VSSF and FWSF, respectively.

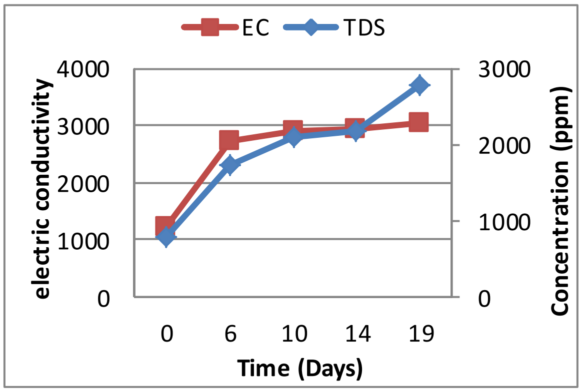

Figure 5. Relationship between total dissolved solids (TDS) and electric conductivity (EC)

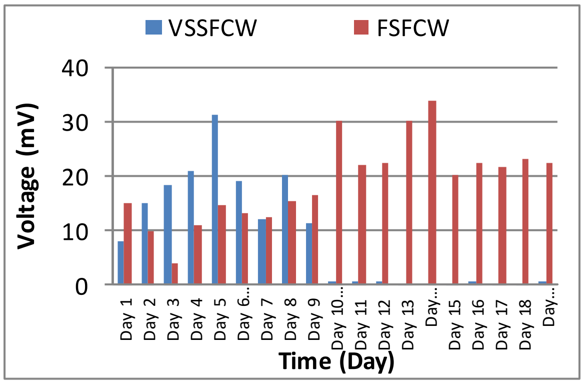

Figure 6. Voltage per day changes according to type of flow during the light.

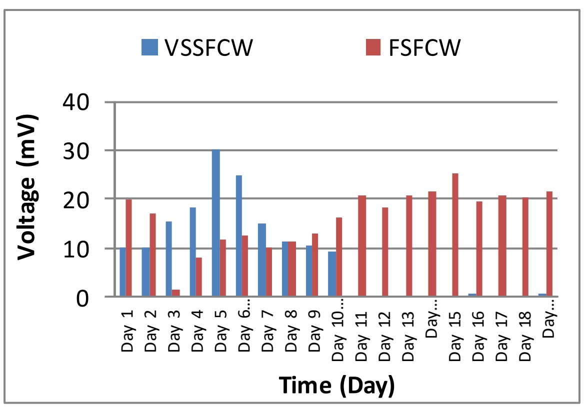

Figure 7. Voltage per day changes according to type of flow during the darkness.

3.2. Sediment microbial fuel (SMFC) as wastewater treatment

Since the SMFCs have possibilities to be applied in wide range of wastewater, it seems that this technology is promising to be used as wastewater treatment units in the near future. Two types of flow would be conducted to test final COD, TSS, PO_4, NO_3, and heavy metals. After each taken samples for measurements, no additional wastewater was added. Thus, water level was decreased.

3.2.1. COD removal

COD removal decreased at low temperatures but SMFC still has a good removal efficiency. Long resistance time of wastewater showed significant removal. **Figure 8** shows removal efficiency percentage of COD by two flows with respect to 19 days. Samples test were taken to the laboratory at the beginning of experiment, day 6, day 10, day 14, and at the final of experiment (day 19).

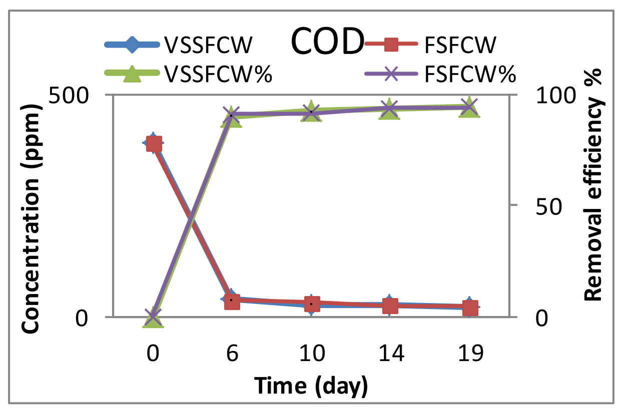

Figure 8. COD removal efficiency according to type of flow for 19 days

VSSFCW and FSFCW recorded the same COD removal efficiencies by the end of experiment which was 22 ppm after being 390ppm. COD removal started from the first four days in VSSFCW and FSFCW. This is in contrast to the results which are reported by Li et al.(2008) [14] and in agreement with the results reported by Lim et al. (2001) [15], which indicated that the organic matter removal in sub surface flow systems was better than that in free water surface systems..

3.2.2. NO_3 removal

NO_3 removal in **Figure 9**, the influent NO_3 was 10.1 ppm before entering to VSSFCW and FSFCW, yet it decreased into 0.2 ppm on day 6, 0 ppm on day 10, 14, and 19. It showed that the removal efficiency was 100% after being treated in VSSFCW and FSFCW system with Cyperus a. The high percentage of nitrogen removal indicated the decomposition of pollutants contained in wastewater, the perfect amino-organic nitrogen, and the adequate nitrification process in the system.

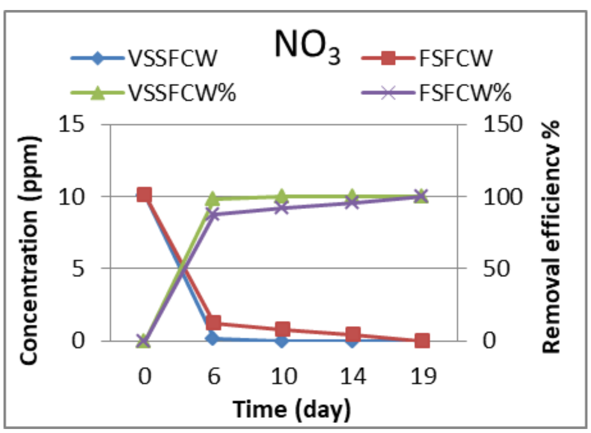

Figure 9. NO_3 removal efficiency according to type of flow for 19 days

3.2.3. PO_4 Removal

As shown in Figure 10, phosphate can be up taken by plants and converted to tissues or may become sorbed to sediment or wetland soil [16]. Studies has reported that wastewater with low Phosphate concentration, removal efficiency could reach 70% [17]. This variation was probably caused by microbial activity and pH supporting plant growth, which are the main cause of optimizing the phosphate removal.

Vertical subsurface flow outperformed free surface flow by minimizing the concentration from 3.2 ppm to 0.5 ppm with removal efficiency of 84.3% whereas free surface flow also showed a suitable removal percentage of 75.3%. However, removal efficiencies for both flows ranged between 60-85% which is within Iraqi standards of rivers.

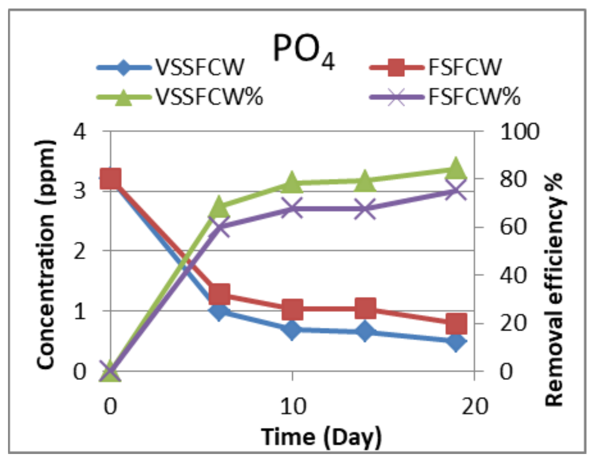

Figure 10. PO_4 removal efficiency according to type of flow for 19 days.

3.2.4. Total suspended solids removal

TSS removal methods are quite different in subsurface and free water surface systems. VSSFCWs act like vertical gravel filters and thereby give opportunities for total suspended solids separations by gravity sedimentation, physical capture and straining, and adsorption on biomass film attached to root system. On the other hand, TSS are removed and also produced in the same time for FSFCWs systems. The predominant physical mechanisms for suspended solids removal are flocculation, sedimentation, and filtration ,whilst suspended solids production could occur because of invertebrates death, fragmentation of detritus from plants, and plankton and microbes production. The USEPA [18], found that chemical precipitates formation is one of the causes of suspended solids production such as iron. Excessive algal formation results in high TSS in the FWSF. Therefore, as can be seen Figure 11, VSSFCW have lower TSS concentrations during 19 days than those of FWSF thorough treatment processes.

TSS concentration was recorded to be 125 ppm. Removal efficiency for vertical subsurface flow was 94.4% and increased to 96.8% by day 14 and thus remained stable at the percentage of day14 by the end of experiment. Free surface flow constructed wetland shows an efficient removal from the first period of running the experiment and recorded a removal percentage of 56.8% reaching to 85.6% by day 19. Shown in Figure 11.

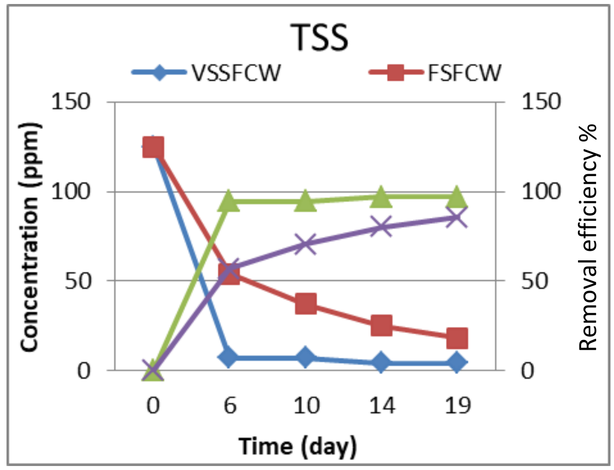

Figure 11. TSS removal efficiency according to type of flow for 19 days.

3.2.5. Heavy metals removal

Minimum concentrations of lead (Pb), cadmium (Cd) and copper (Cu) for VSSF and FWSF were measured at the 19th day to be (0.147, 0.012, and ND ppm), and (0.08, 0.01, and ND ppm) respectively. Removal efficiencies of VSSFCW for Pb, Cd, and Cu were 65.8%, 85.7% and +94.7% respectively, and removal efficiencies of FWSF for Pb, Cd, and Cu were 81.4%, 88% and + 89.4% respectively.

The effluent concentrations of Cd and Pb for VSSF are slightly higher than the maximum allowable concentration to throw in the river (0.01, and 0. 1 ppm), while Pb and Cd for FSFCW and Cu for both types of flow are lower than the maximum allowable concentration (0.05 mg/l) for Cu [19]. Four mechanisms are involved in heavy metal removal in constructed wetlands such as, adsorption to fine textured sediments or soil and organic matter, precipitation as insoluble salts, and absorption [20].

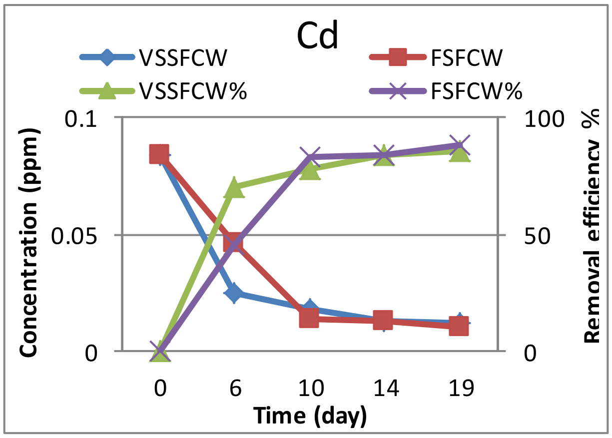

Figure 12. Cd removal efficiency according to type of flow for 19 days

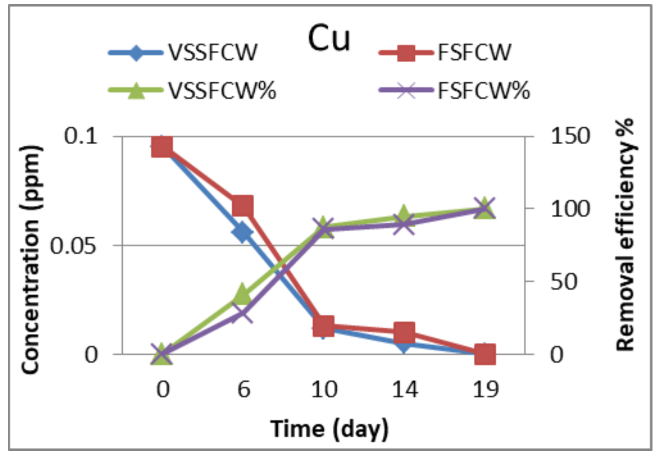

Figure 13. Cu removal efficiency according to type of flow for 19 days

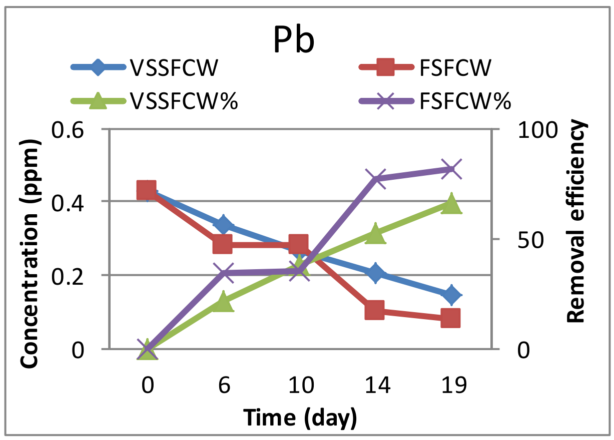

Figure 14. Pb removal efficiency according to type of flow for 19 days

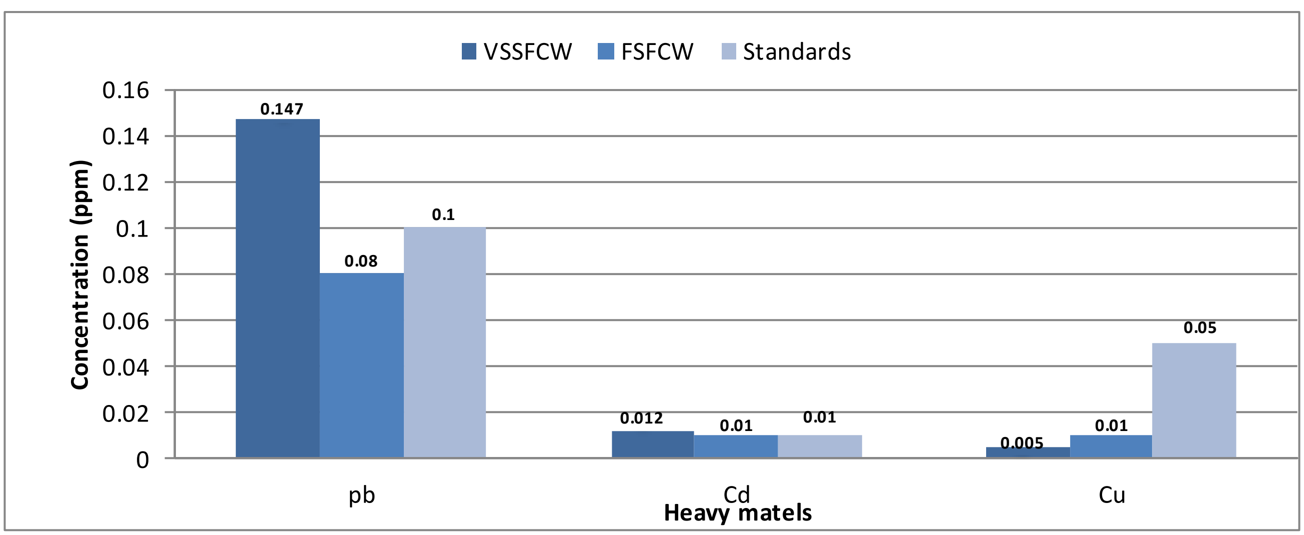

Figure 15. Final concentration of heavy metals treated in VSSFCW and FSFCW in comparison with maximum allowable concentration

Results showed that pH increased from 6.8 to 7.7 and 7.5 for VSSFCW and FSFCW, respectively, on retention day 6. PH value for both type of constructed wetlands were stable on retention day 10, after that they decreased on day 14 and day 19 by recording a pH value of 6.7 and 7.3 for VSSFCW and FSFCW, respectively, with temperature range between 23-18 °C as it showed in **Figure 16** .

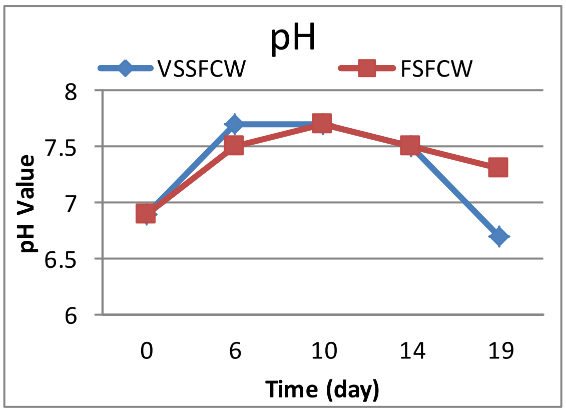

Figure 16. pH change according to type of flow for 19 days

pH of entire run ranged between 7.5-6.5 which is suitable for plant survival, remediation process, and microorganisms activities [21]. pH fluctuations correlated with weather differences during sampling and gave impact to biota in the CW. Although of gradual increase in pH in first ten days, decreasing in pH during next showed the domination of anaerobic condition.

4. Conclusions

Constructed wetland system not only enhances the ability of pollutants removal, but also converts the chemical energy generated by microbial metabolism into electrical energy, which improves the efficiency of electricity production by combining sediment microbial fuel cell.

Based on the results of this study, the below conclusions can be drawn:

- Successful performance of the VSSFCW for the treatment of real domestic wastewater with respect to TSS, PO_4, NO_3, Cd, Cu, Pb and COD.
- For both VSSF and FWSF systems, COD removal rates seemed to be efficient. Over 90% organic matter removal was at each system.
- VSSFCW had higher potential for total suspended solids removal compared to the FSFCW of our study because of the growth of algal.
- Heavy metals removal was too close between the two types of flow but VSSF is more reliable as lower total suspended solids are produced
- Phosphate and nitrate removals were close, but VSSFCW outperformed FSFCW by 10% difference for PO_4 removal.
- For generating energy, FWSF is better in case of batch system is applied in VSSFCW feeding as no transition medium (water) was performed for electrons transmitting.
- The table below shows that both types of flow are comply with Iraqi rivers maintaining system

Table 2. Influent, effluent and permissible concentrations of different contaminants using VSSFCW and FSFCW

Parameter	Inletfluent conc.	Effluent conc. VSSFCW	Effluent conc. FSFCW	Max. permi-ssion
pH	6.89	6.7	7.3	6-9.5
EC(μS/cm)	1217	3040	3050	-
COD (ppm)	390	22	22	100
TSS (ppm)	125	4	18	20
TDS (ppm)	778	2778	2293	-
NO_3	10.1	0	0	50
PO_4	3.2	0.5	0.79	3

Pb	0.431	0.147	0.08	0.1-0.5
Cu	0.095	ND	ND	0.05
Cd	0.084	0.012	0.01	0.01

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Conflict of interest

There are not conflicts to declare.

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