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Evaluation the Efficiency of Subsurface Flow Constructed Wetland (SSF) for Wastewater Treatment and Reuse in Semi-arid Environment

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Abstract

The efficiency of subsurface flow (SSF) constructed wetlands was evaluated on the treatment of secondary treated wastewater to improve the quality of the effluent for reuse purposes. A horizontal SSF system was constructed to evaluate the efficiency to enhance the quality of secondary treated wastewater effluent from Ramtha wastewater treatment plant WWTP and its potential uses for crop production at Hydrulic retention time HRT of 1 day. The SSF was planted with barley crop (*Hordium vulgare*), retrieved from the Arab Center for the Studies of Arid Zones and Dry-land (ACSAD) variety followed by corn crop (*Zea mays* L.), using BONANZA, F1 variety in the other season. Weekly physicochemical and microbiological analyses were carried out on the outlet from the wetlands in addition to the TWW treated wastewater effluent (inlet) in order to assess the removal efficiency of each stage of the treatment process and the total treatment system and it was used for irrigation of a fodder crop field. The SSF wetland subsequently influenced the physicochemical parameters. The SSF reduced the concentration of COD, NO-3, and TKN by 48%, 18%, and 20% respectively. Water use efficiency (WUE) for corn and barley were improved tremendously compared to the traditional irrigation techniques used in the field. The results showed a great possibility of using the SSF wetlands for the growth and production of fodder crops.

Keywords: wastewater reuse, constructed wetlands, HRT, wastewater treatment, water use efficiency, irrigation

1. Introduction

1.1 Water Scarcity

Water scarcity is considered a major challenge facing the entire world, especially in arid regions (Alcamo, Doell, Kaspar, & Siebert, 1997). It arises from the relatively uneven distribution of precipitation (climate change), imbalance in water demand and supply (demand surpasses the supply), and rapid population growth in urban and developed areas. Therefore, the need for appropriate water management practices is indispensable (Bakir, 2001; Ungureanu, Vlăduț, & Voicu, 2020). Jordan faces a severe shortage in freshwater resources to match the increasing demands for freshwater consumption and use by different sectors ((MWI), 2016; Al-Hadidi & Sweity, 2022; El Kharraz, El-Sadek, Ghaffour, & Mino, 2012). It is considered as one of the most water scarce country worldwide (Hadadin, Qaqish, Akawwi, & Bdour, 2010). Wastewater recognized as a inventible, fast growing, and reliable alternative water resource to cope water scarcity (Hussain, Muscolo, Farooq, & Ahmad, 2019). Currently, the increase in wastewater reuse globally has pushed for the development of wastewater treatment technologies and techniques in order to achieve high-quality effluent for reuse purposes (Cheremisinoff, 2001; Jiménez-Cisneros, 2014; Muga & Mihelcic, 2008; Salgot, Folch, & Health, 2018). Jordan has 33 wastewater treatment plants with an estimated annual production of 159.5 Million Cubic Meters (MCM) of secondary treated wastewater. More than 91% of the secondary treated wastewater is being used mostly for irrigation and other non-domestic purposes. More than 40% of the entire annual freshwater budget is used in the agriculture sector (Ministry of Water and Irrigation MWI, 2019). Using unconventional water resources and enhancing water use efficiency (WUE) in water-scarce countries, make agriculture practices more abundant, money-spinning, and viable (Chand, Hewa, Hassanli, & Myers, 2020). In Jordan, water reclamation and reuse have rapidly increased in recent years, clearly indicating the recognition and commitment at the highest level of the government in Jordan to the full value of reclaimed water for the overall water resources of the country (Carr, Potter, & Nortcliff, 2011; Schyns, Hamaideh, Hoekstra, Mekonnen, & Schyns, 2015). Depending on how it is practiced; the wastewater reuse in Jordan could widely contribute to solving the problem of quality and quantity. The reuse will have a major influence on the agricultural economy, the population well-being, and the health of the society (Carr et al., 2011). Constructed wetlands appear to be an attractive and cost-effective phyto-technology that can be used for treating several types of wastewater (Bharagava, Saxena, & Chowdhary, 2017). Constructed wetlands are defined as engineered systems that are designed and constructed to mimic the natural processes involving wetland vegetation, soils, and the related microbial communities to treat wastewater (Jan Vymazal, 2010). Constructed wetlands are classified according to the wetland hydrology as (free water surface and subsurface systems) and the flow direction as (horizontal and vertical) (Jan Vymazal & Kröpfelová, 2008). Surface and subsurface flow (SSF) constructed wetland being widely used in arid and semi-arid areas as a post-treatment technique which has been approved as a promising technology for wastewater treatment and management (Ulsido, 2014). Constructed wetlands became a reliable treatment technology that can be implemented to all types of wastewater, it can be applied as a primary unit process in a treatment system to treat primary, secondary, and even tertiary treated domestic and industrial wastewater (landfill leachate and petrochemical industries), and storm water runoff (Cheremisinoff, 2001; Knight, Payne, Borer, Clarke, & Pries, 2000; Lee & Scholz, 2007; Rahman et al., 2020). Pre-or post-treatment stages are essential for the wetland to treat wastewater to meet reuse and regulations requirements, the wetlands will be a major element of the central treatment element. As a result of both extensive research and practical application, the focus will be directed into selected design parameters, performance, operation, and maintenance of constructed wetlands for efficient wastewater treatment hence, effluent quality improvement. (Bastian, 1993; Rahman et al., 2020)Constructed wetlands have four parts: the liner, distribution media, plants, and under-drain system. The liner keeps the wastewater in and groundwater out of the system. Although the liner can be made from a number of materials, 30 mm polyvinyl chloride (PVC) is the most common and the most reliable (Gustafson & Wang, 2002). Plant selection is a very important element in the design process and the plants must be capable of tolerating toxicity and wastewater variation. Also, vegetation plays a significant role in nitrogen and phosphorus removal in constructed wetlands (Akratos & Tsihrintzis, 2007). One of the most common plants used in constructed wetlands is *Cyperusalternifolius*, it is a multiyear old plant that can tolerate extreme wastewater and can grow in humid soil (Ebrahimi et al., 2013). Moreover, substrate porous media selection is an important factor for nitrogen and phosphorus removal. It was found that finer porous media from a river bed (igneous rock) has shown higher nitrogen and phosphorus removal compared to coarser one (Akratos & Tsihrintzis, 2007). Furthermore, higher HRT has efficient organic matter, nitrogen, and phosphorus removal (Ebrahimi et al., 2013; S. Toet, Bouwman, Cevaal, & Verhoeven, 2005; Sylvia Toet, Van Logtestijn, Kampf, Schreijer, & Verhoeven, 2005).

1.2 Research Justification and Objectives

Constructed wetlands are rarely examined in arid and semiarid environments for wastewater treatment and ruse purposes. This study is assumed to evaluate subsurface SSF constructed wetland treatment performance to improve treated wastewater effluent quality with barley and corn for reuse purposes.

2 Methods

2.1 Site Description

The field experiments were conducted in 2007 at the National Agricultural Research Center at Ramtha research station near Ramtha wastewater treatment plant in the north of Jordan, where irrigation with secondary treated wastewater is highly practiced in the surrounding area. The climate is characterized by a cold winter (average temperature of 9 C°) and hot summer (average temperature of 24.5 C°) with an average annual rainfall of ~275.

2.2 Site Construction and Preparation

A horizontal subsurface flow system (SSF) wetland was constructed. Its dimensions were 2 m width, 4 m length and 0.85 m media depth (Figure 1). The excavated soil below the SSF was compacted by a manual compactor and then covered by a 600 micron polyethylene plastic layer to prevent leakage. Four different layers of washed gravel bed media were placed in the body of the cell as a treatment media. The size of the first; second, third and fourth layer ranged between 1.8-2, 1-1.2, 0.6-0.8 and 0.2-0.3mm, respectively from bottom to top. Larger gravel media of both the distribution and the collection zones were placed around the influent and the effluent pipes. For this purpose, a small-sized rock media was used for the first and last two 60 cm of the bed media to allow a uniform flow and more surface area available in-terms of more pores and crevices for the microorganisms to interact with the wastewater. The surface slope of the bed was flat while the bottom of the cell was designed at a slope of 0.5%. A partially subsurface pipe is used as an inlet structure. Four pipes with adjustable valves-one for each media layer-were used as outlet structure and were connected directly to the final discharge (collection) reservoir (Figure 1). The suggested design assures water level to be easily adjusted and maintained. The outlet pipes placed within each layer of the bed media allowed complete drainage of the bed and the development of maximum hydraulic gradient in the system.

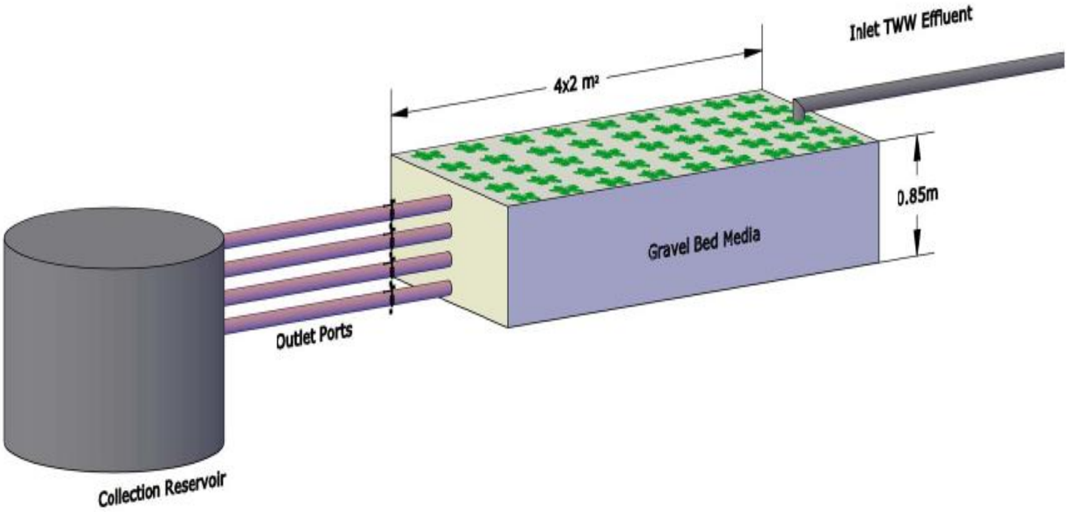

Figure 1. Sketch of the sub surface flow constructed wetland used in the study

The secondary treated wastewater from Ramtha wastewater treatment plant was fed in at the inlet through a pipe network with a measuring analog water flow meter (DN 20 mm) (Lotaflow Systems Private Limited, India) and a valve. The treated wastewater flows from the inlets to the outlet zones where it was collected under the surface through a porous media of gravel. The volume and the porosity of the SSF wetland were estimated after flooding the SSF wetland with secondary treated wastewater in order to calculate the volume of wastewater required to fill up the entire system. Then, the wetland was allowed to drain layer by layer and the porosity was calculated. Following the initial stabilization period which took about two months, a gradual increase in wastewater flow was completed to allow the system to adjust to the new wastewater chemistry which is often recommended rather than immediately operating the system at the ultimate flow. Barley crop (*Hordium vulgare*) was planted in the wetland in the winter season (December 2007) and corn crop (*Zea mays* L.) was planted in the summer season (July 2008) to examine the potential of the SSF wetland to support crop production. The SSF wetlands are planted by hand and the seeds were placed in the gravel medium at a depth equal to the expected operational water level. The water level in the bed was maintained slightly above the media surface during planting and for few weeks' thereafter to suppress weed development and promote growth of the plant (Allen, Pereira, Raes, & Smith, 1998). Then, the volume of the treated wastewater required to fill up the SSF wetland was adjusted and the porosity of the used media was calibrated in order to retrieve a one-day hydraulic retention time HRT. Water chemical, physical and biological characteristics such as (Turbidity, pH, EC, TKN, P, BOD_5, COD, heavy metals contents, and pathogens that compromise; fecal coliform, total coliform,) were analyzed and monitored weekly for the feed and for the effluents of the SSF wetland from April 2007 to September 2008. All statistical tests were conducted using SAS software. In all cases, significance was defined by ($P< 0.05$) and a test for significant difference in water quality was tested using a regression model. The salinity and the turbidity of the wastewater were measured in situ for both inlet and the outlet effluents for the SSF wetland.

2.3 Field Experiment for Forage Crop Production

The effluents of the SSF wetland and the secondary wastewater effluent of Ramtha WWTP were used to irrigate two fields of a forage crop of 4×4 m^2 plots replicated three times in a randomized complete block design. The field experiment was planted for two consecutive seasons similar to the standard practices of the commercial fields in the area. Barley crop (*Hordium vulgare*) variety (ACSAD) was planted in the first season in the field experiment in late November 2007 with a seeding recommended rate of 100 Kg/ha under irrigated agriculture. Irrigation scheduling was calculated according to the United Nations Food and Agriculture Organization (FAO) reference evapotranspiration and crop coefficients based on crop water requirements (Allen et al., 1998). In-line drip irrigation lines (20 mm in diameter) were installed at every plant row. GR drip irrigation pipes with emitters were used with 4 L/hr flow rate and with 40 cm emitter spacing. Irrigation was terminated two weeks before harvesting and the barley crop was allowed to dry. The yield was harvested on the 4th of June, 2008 and harvesting was carried out for the whole plot. The biological yield was separated into grain and straw and the weight for each was measured. Grain and straw samples were analyzed for selected chemical parameters and for the crude fiber percentage.

In the second season, the field was planted with corn crop (*Zea mays* L.), using (BONANZA, F1) variety with a seeding rate of 70 Kg/ha. The seeding rate was calculated based on the amount of seeds used according to planting distance between emitters under the drip irrigation system. The field was irrigated to establish germination after which, the different treatments were introduced. Corn crop was grown for 85 days only to be collected as green forage. Irrigation scheduling was based on crop water requirements using FAO reference evapotranspiration and crop coefficients (Allen et al., 1998). Irrigation was terminated two weeks before harvesting, and the biological yield was harvested on September 14, 2008 also for the whole plot. The biological yield was weighted, and selected samples from both the leaves and corn ears were taken to be analyzed for selected biological and chemical parameters and also for crude fiber analysis. Standard statistical analysis (ANOVA all at $P < 0.05$) was used to evaluate differences between treatments.

3. Results

3.1 Wastewater Characterization

Results of the physical chemical and biological analysis for secondary treated wastewater effluent from Ramtha WWTP are shown in Table 1.

Table 1. Chemical and Biological parameters of the analysis of secondary treated wastewater effluents from Ramtha WWTP

Parameter	Secondary TWW
pH	7.3±1.2
EC (dS m^{-1})	1.8±0.3
Ca (meq L-1)	2.2±0.31
Mg (meq L-1)	2.7±.35
Na (meq L-1)	14.9±2.9
K (meq L-1)	1.2±0.2
Cl (meq L-1)	12.5±2.3
HCO_3(meq L-1)	3.5±0.8
SO^-_4(meq L-1)	5±1.2
Sodium Adsorption Ratio	9.5±2.1
Fe (mg/L)	0.07±0.003
Cu (mg/L)	0.01±0.002
Zn (mg/L)	0.06±0.006
Mn (mg/L)	0.03±0.005
Cd (mg/L)	<0.002
Pb (mg/L)	<0.01
P (mg/L)	2.6±0.6
TKN (mg/L)	74±12.5
NO_3^- (mg/L)	16.3±3.5
TC/100ml-1	800±112
(FC) E.coli 100 ml-1	40±8
BOD_5(mg/L)	15±2.6
COD (mg/L)	73±7.9

The effluent results exhibited a high value of Na and Cl. Phosphorus (PO^{-3}_4), nitrate and total Kjeldahl nitrogen (TKN) concentrations in (mg/l) were (2.6, 9.4, 74) respectively. The results of the physical-chemical and biological analysis demonstrated excellent biological standards for the secondary treated wastewater from Ramtha WWTP in terms of fecal coliform, BOD5, and COD (Saeed, Alam, Miah, & Majed, 2021). Regression analysis was performed to study the changes in some of the physical-chemical and biological water quality parameters. Changes in the inlet and the outlet concentration were figured to find the best fit relationship with the removal equation (Knight, Gu, Clarke, & Newman, 2003; Jan Vymazal, 2009). Statistical analyses were performed regarding the linear regression model and significance was defined by P<0.05.

3.1.1 pH

The results showed a negative and weak linear correlation between the input and the output pH (data are not presented). This means that the system was unable to adjust the pH over the entire research period at shorter HRT of one day.

3.1.2 Salinity

The results of the salinity indicated similar concentrations of the inlet-outlet as shown in the linear model with a high R^2 of 0.96 (Figure 2). Nevertheless, the system was inadequate to reduce the salinity and very small removal was achieved at HRT of one day, the chosen plants in the system showed low tolerance to salinity in the treatment wetland.

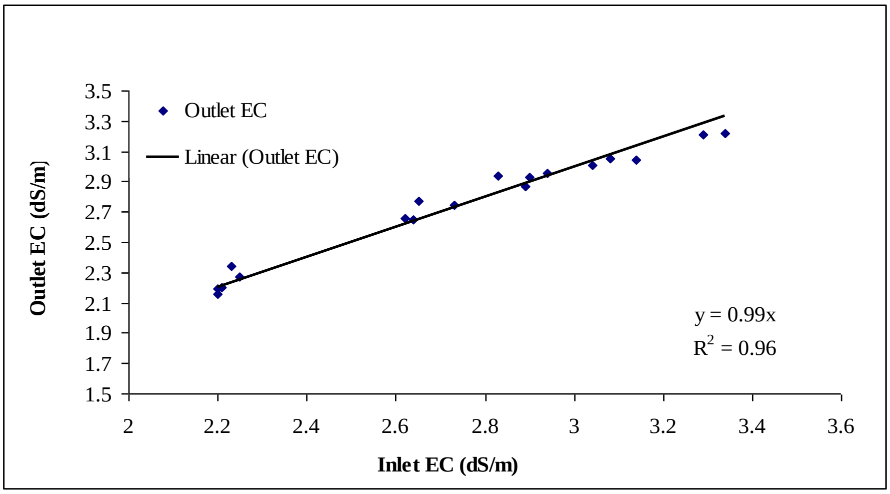

Figure 2. Inlet – Outlet linear regression of salinity (dS/m) of the SSF wetland system

3.1.3 Total Suspended Solids TSS

The TSS results of the inlet-outlet concentrations were similar as shown in the linear model and with a high R^2 of 0.95 (Figure 3). The system showed a good tendency to remove 20% of the inlet TSS.

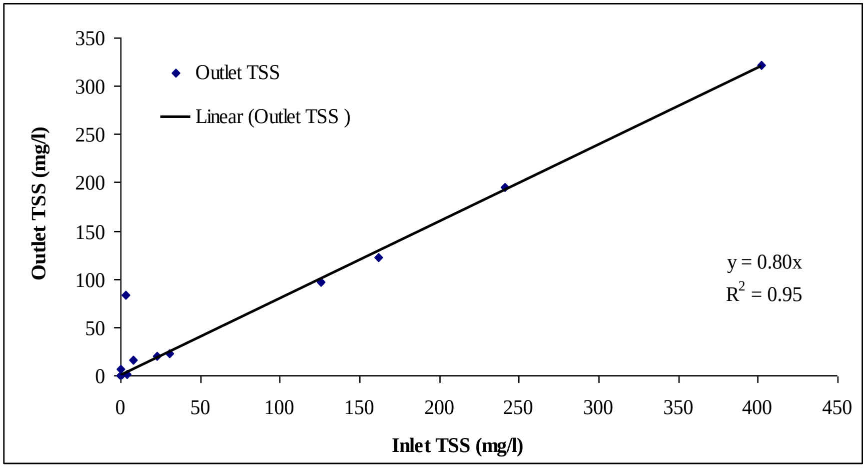

Figure 3. Inlet - Outlet Relationship for Total Suspended Solids (mg/l) of the SSF wetland system

3.1.4 Total Kjeldahl Nitrogen

The TKN Results indicated that the SSF has a low tendency to remove nearly 2% of the inlet TKN which could be a result of the release of N from the granular media used in the system. The inlet-outlet concentrations were similar as shown in the linear model and with a high R^2 of 0.76 (Figure 4). Figure 4 showed a net production of TKN as the wastewater passes through the media bed.

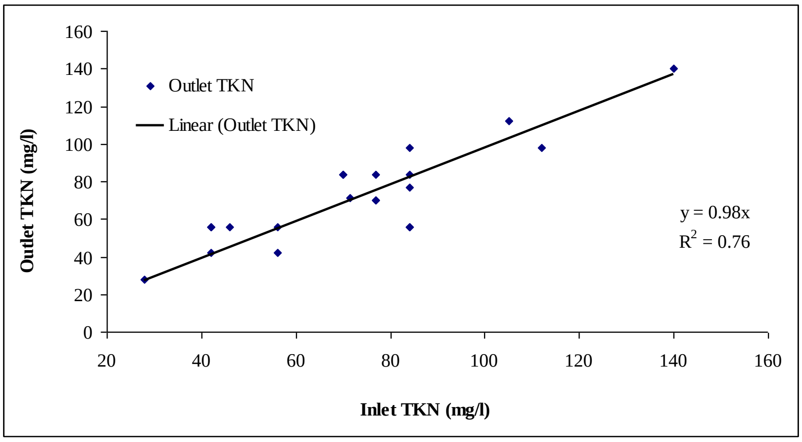

Figure 4. Inlet - Outlet Relationship for Total Kjeldahl Nitrogen in (mg/l) for the SSF wetland system

3.1.5 Nitrate

Results of the nitrate analysis showed the SSF was able to remove 18% of the inlet NO3. Moreover, the inlet-outlet NO3 concentrations were equal as shown in the linear model and with a low R^2 of 0.25 (Figure 5).

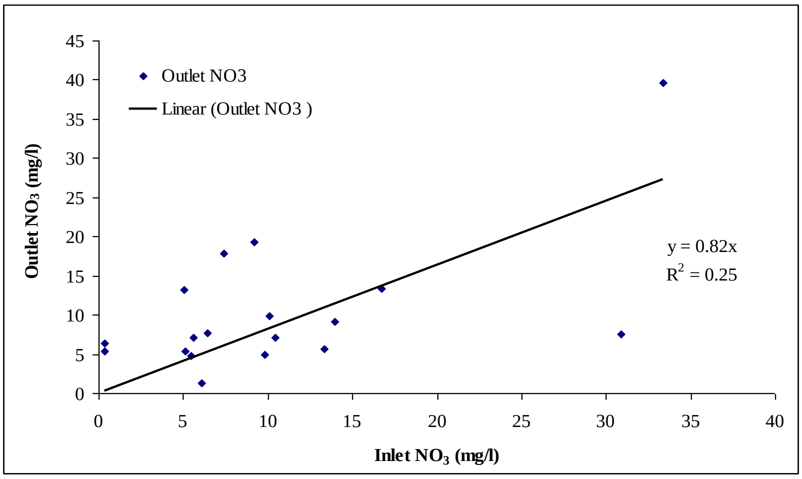

Figure 5. Inlet - Outlet Relationship for Nitrate in (mg/l) for the SSF wetland system

3.1.6 Phosphorus

Results of the phosphorous analysis from the SSF wetland showed very low removal of PO^{-3}_4 but there was a tendency to accumulate it. Inlet-outlet concentrations were similar as shown in the linear model and with a high R^2 of 0.89 (Figure 6). Since the SSF was operating at a low HRT of one day, P removal was very low. It was reported that increasing the HRT in SSF to 20 days enhanced the removal of P up to 88.1% as a result of the high uptake by plants (Akratos & Tsihrintzis, 2007).

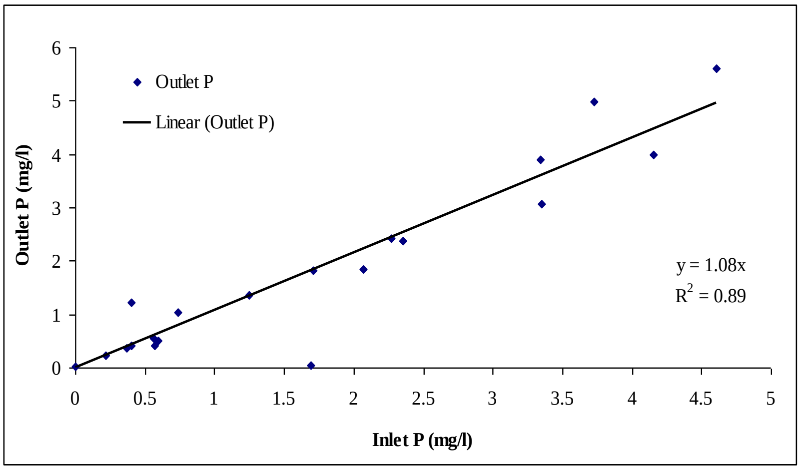

Figure 6. Inlet - Outlet Relationship for Phosphorous P in (mg/l) for the SSF wetland system

3.1.7 Heavy Metals

Heavy metal concentrations of the effluent were very low. However, since the SSF wetland is dominated by anoxic/anaerobic conditions, the opportunity for heavy metal retention was very low. The insoluble metal sulfides are probably the most extensively formed. The removal of the inlet Fe in the SSF wetland was around 30%. Inlet-outlet concentrations were almost the same as presented in the linear model and with R^2 of 0.52 (Figure 7A). While the inlet Cu removal in the SSF wetland was 10%, Cu Inlet- outlet concentrations were comparable as depicted in the linear model with R2 of 0.73 shown (Figure 7B). Also, inlet Zn removal by the SSF wetland was 28%. Zn Inlet- outlet concentrations were the same which is shown in the linear model and with a low R^2 of 0.33 (Figure 7C). The SSF was unable to remove Mn to any extent. The Mn Inlet- outlet concentrations were matched as prevailed in the linear model with a low R^2 of 0.35 (Figure 7D).

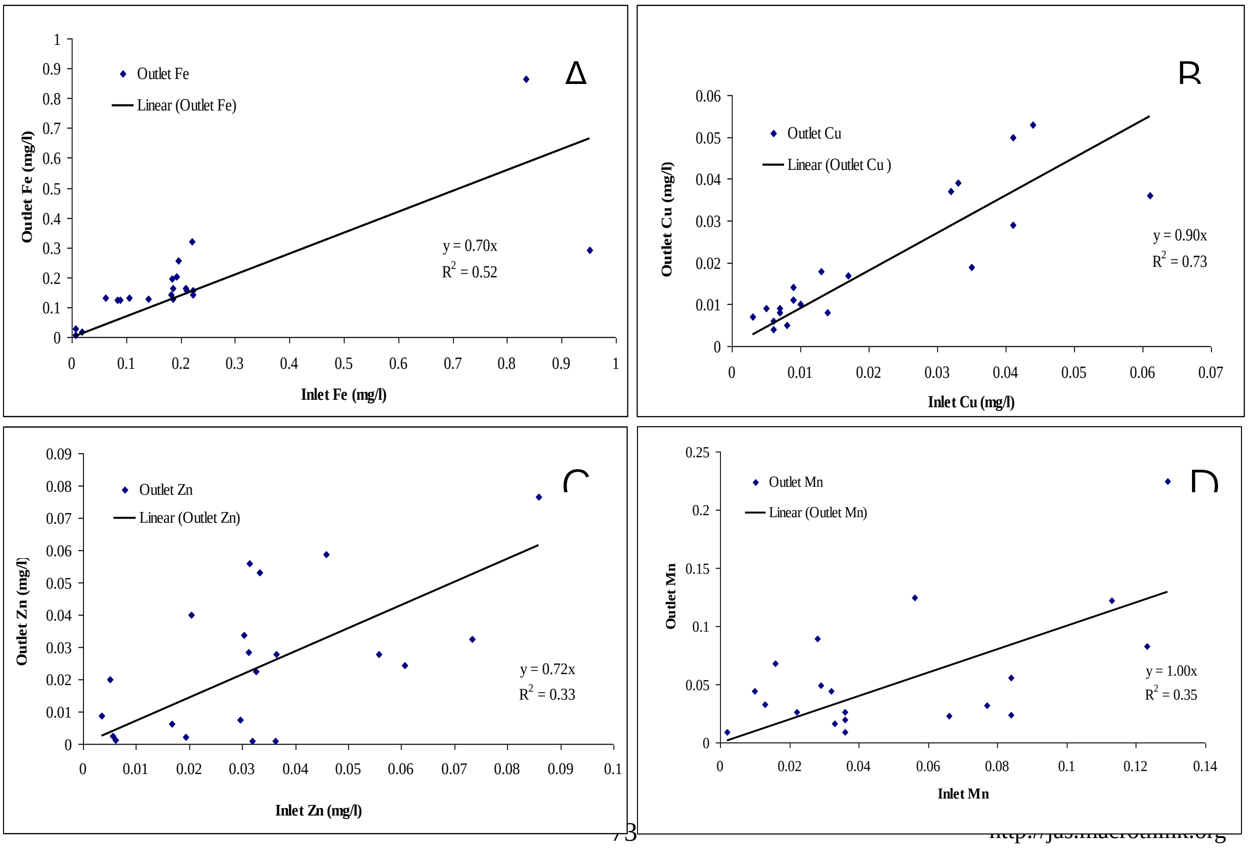

Figure 7. A) Inlet - Outlet removal relationship for Iron Fe (mg/l), B) cupper Cu (mg/l), C) Zinc Zn (mg/l) D) manganese Mn (mg/l) TWW for the SSF wetland system

3.1.8 Fecal Coliform (Thermotolerant Coliforms) (E.coli/100 ml)

The fecal coliform Inlet- outlet concentrations were comparable as seen in the linear model and it was negatively correlated (Figure 8). It was previously approved that anaerobic conditions, which are commonly dominant in the unplanted gravel bed of the SSF wetland, can prolong the survival rate of coliform in the environment (J. A. N. Vymazal, 2005).

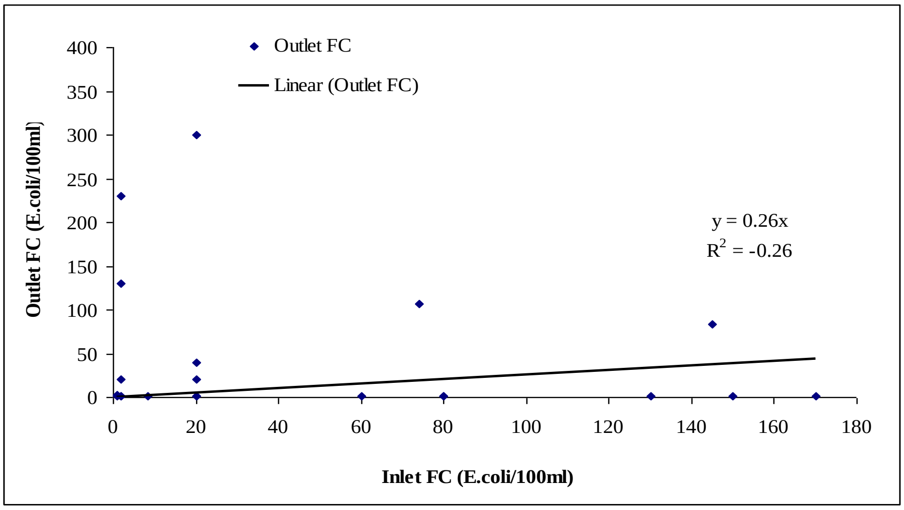

Figure 8. Inlet - Outlet Relationship for Fecal Coliform (E.coli/100ml) for the SSF wetland system

3.1.9 Biochemical and Chemical Oxygen Demand

BOD5 Inlet- outlet concentrations were also the same as seen in the linear model and the correlation was negative. This means as the inlet BOD_5 increases, the outlet BOD_5 decreases and vice versa (Figure 9A). Chemical oxygen demand: The SSF wetland was capable to remove 48% of the inlet COD. Inlet-outlet concentrations were similar as shown in the linear model and with a very low R^2 of 0.16 (Figure 9B)

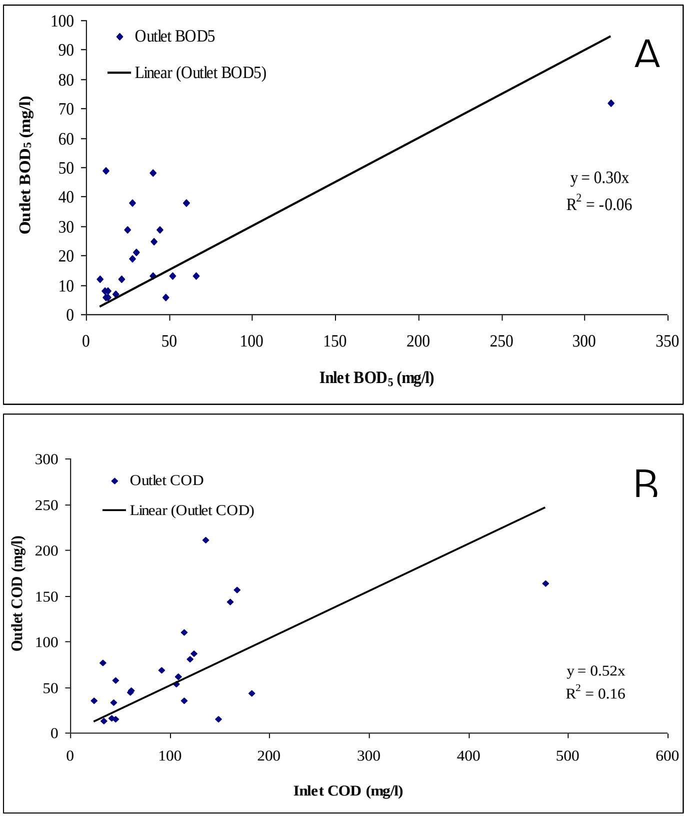

Figure 9. A) Inlet - Outlet Relationship for Biochemical Oxygen Demand BOD_5 (mg/l) with its Reduction Equation and B) Inlet - Outlet Relationship for Chemical Oxygen Demand COD (mg/l) with its Reduction Equation TWW

3.2 Efficiency of SSF Wetland to Reduce Turbidity

Sub-surface wetland was successful in achieving high solid removal. Turbidity changes (%) ranged from 8.5 to 97.1 all over the study period (Table 2). The relationship with respect to each planted crop within the SSF wetland was also studied. During barely season, the system was new and it was efficient in solid removal. Reduction % ranged from 40 to 97.1 and improved gradually during the season, and increased with the rapid growth of the crop. During the corn growing season, reduction % ranged from 8.5 to 91.8. The efficiency of the system increased during both the planting and seedling stages and remained constant all over the growing season (Table 3). Corn crop showed a bad response to wetland planting, and no remarkable yield was achieved.

Table 2. Treatment Efficiency of SSF Constructed Wetland for Turbidity during Barley Growing Season

Season 1			Season 2		
Inlet (NTU)	Outlet (NTU)	Reduction (%)	Inlet (NTU)	Outlet (NTU)*	Reduction (%)
1.05	0.32	69.38	1.75	0.3	83
0.85	0.27	68.91	1.68	0.24	85.74
0.94	0.23	75.86	1.78	0.56	68.5
0.95	0.12	87.11	1.16	0.49	57.54
0.9	0.23	74.24	1.77	0.21	88.1
0.92	0.2	78.47	2.78	0.32	88.57
0.84	0.24	70.96	0.72	0.24	67.13
0.92	0.29	68.03	0.76	0.2	73.51
0.92	0.12	86.61	1.41	0.45	67.97
0.95	0.15	84.51	0.94	0.21	77.72
0.8	0.21	73.98	1.05	0.23	77.99
1.3	0.52	60.31	1.25	0.38	70
1.88	0.3	84.33	1.16	0.54	53.88
1.11	0.31	72.4	0.85	0.29	66.18
2.48	0.07	97.07	0.95	0.2	78.84
2.64	0.24	90.99	0.92	0.19	79.35
0.82	0.23	71.95	2.86	1.4	51.01
0.29	0.17	40	0.94	0.24	74.2
0.3	0.18	40	0.29	0.16	45.61
0.88	0.17	81.3	0.24	0.14	44.33
1.01	0.24	76.24	0.53	0.2	61.61
0.52	0.13	75	0.76	0.19	75.25
0.75	0.18	75.59			

*(NTU)=Nephelometric Turbidity Unit

Table 3. Treatment Efficiency of SSF Constructed Wetland for Turbidity during Corn Growing Season. *(NTU)=Nephelometric Turbidity Unit

Season 1			Season 2		
Inlet (NTU)*	Outlet (NTU)	Reduction (%)	Inlet (NTU)	Outlet (NTU)	Reduction (%)
0.84	0.18	78.87	3.16	0.41	87.16
0.97	0.2	79.02	3.49	0.29	91.76
1.18	0.55	53.4	2.39	0.29	87.75
0.58	0.38	33.91	2.69	0.38	85.89
0.87	0.26	69.94	3.14	0.35	88.93
0.75	0.19	74.16	1.61	0.5	69.25
0.78	0.18	76.77	1.31	0.87	33.59
0.88	0.18	80.06	1.85	0.82	55.6
0.82	0.21	74.39	1.41	0.74	47.52
0.61	0.19	68.98	1.19	0.51	56.75
0.65	0.21	67.95	0.79	0.86	-9.18
0.77	0.23	70.55	1.07	1.16	-8.45
0.9	0.27	69.72	0.94	0.79	15.51
0.58	0.17	70.39	0.97	0.75	22.68
1.08	0.28	74.25	0.84	0.57	31.74
0.84	0.21	75.52	0.91	0.76	16.48
1.2	0.3	74.69	1.07	0.92	14.02
0.94	0.22	76.8	1.04	0.8	23.56
1.11	0.28	74.55	0.92	0.34	63.22
1.13	0.21	81.42	0.79	0.41	48.57
0.98	0.26	73.85	1.08	0.81	25
1.06	0.33	68.96	1.05	0.78	25.95
1.06	0.19	81.88	0.96	0.69	28.2

3.3 Efficiency of SSF Wetland to Reduce Salinity

The SSF wetland had almost no effect on salinity. Reduction % all over the research study ranged from 9.7 to 16.8. A linear regression model showed that the system was capable of reducing a small fraction (2%) of the inlet soluble salts with high R^2 of 0.88 (Figure 10). Studying this relationship with respect to each crop indicated that during barely season, the system was new and due to the presence of salt on the gravel media, the system was not efficient in reducing salts. On the contrary, the system achieved some salts accumulation. Reduction % ranged from 9.7 to 16.8 and it improved gradually during the season, and then increased with the rapid growth of the crop. Regression analysis was carried out on the data with high R^2 of 0.84. Results showed that the system was capable of reducing a small fraction (2%) of the soluble salts (Figure 11A). During the corn growing season, reduction % ranged from 0.9 to 6.1. Results showed that the system was capable to reduce a small fraction (3%) of the soluble salts. It is clear that salinity reduction was not affected by crop type as indicated by the relationship between inlet and outlet concentrations but with low R^2 of 0.56 (Figure 11B).

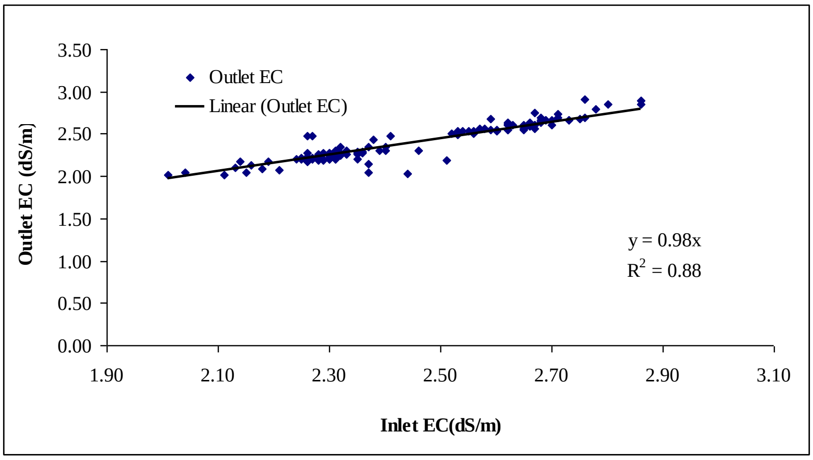

Figure 6. Inlet - Outlet Relationship for Salinity (dS/m) with its Reduction Equation

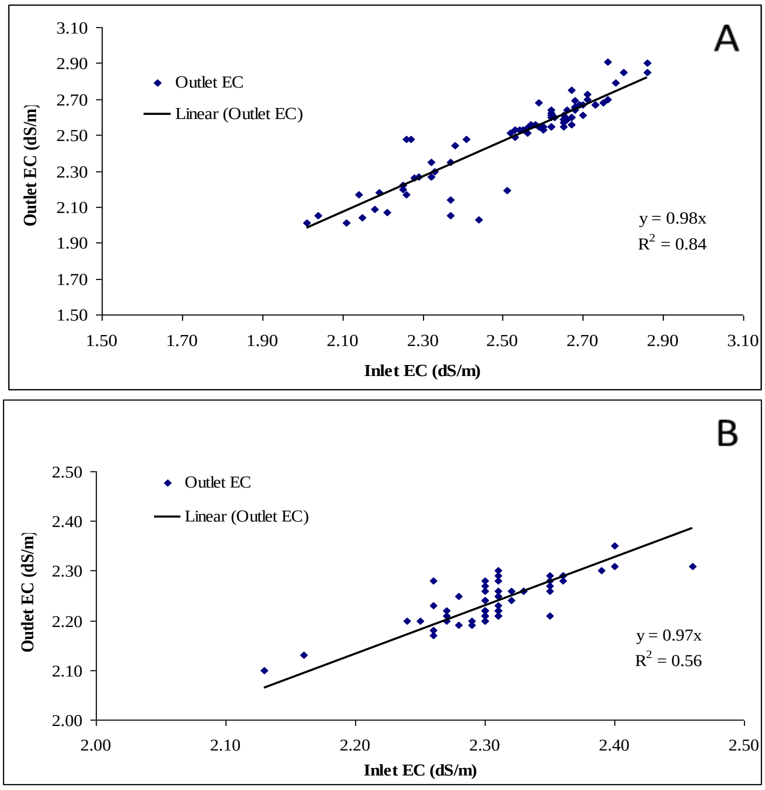

Figure 7. A) Inlet - Outlet Relationship for Salinity with its Reduction Equation during Barley Growing Season and B) Inlet - Outlet Relationship for Salinity (dS/m) with its Removal Equation during Corn Growing Season

3.4 Water Balance and the Potential Uses of Subsurface Wetland for Crop Production

A water balance analysis was carried out to assist variability in retention times and hydrologic conditions of the SSF wetland. The theoretical HRT was equal to 1 day and the volume of the bed was equal to 2.358 m3 with a porosity of 0.35%. The actual HRT was reported to range from 95.8 to 99.3% of the theoretical HRT corresponding to 23 - 23.8 hrs, and a percentage effluent of 92.4 to 98.6, respectively. When taking the crop into consideration, HRT's were similar and ranged from 23.0 to 23.8 hrs for both barley and corn crops. This corresponded to a percentage effluent ranging from 92.4 to 98.6 and 91.6 to 97.1 for barley and corn crops respectively. Results for the first season indicated the possibility of using the SSF wetlands for the production of specific fodder crops (Figure 12A). SSF wetland was able to give a reasonable yield (5.4 ton/ha) which was higher than the two treatments and very close to that produced under the third treatment at the field. The same quality parameters were tested on yield components (grain and straw). SSF barley samples showed a high crude fiber % as 27.4 and 37.2 for grain and straw, respectively. The other field treatments (T1 and T2) showed relatively low CF% for grains ranging from 4.1 to 5.3, while CF % for the straw samples ranged from 34 to 38.6 (Figure 12B). During the second season, corn crop did not perform well within the SSF wetland. Visual observation indicated that the corn crop was affected by the salinity of the wastewater as the plants were stunted with small leaves and with little coverage inside the SSF bed. Results showed very low yield (5 ton/ha) in comparison with corn yield for the other field treatments (Figure 12C). Regardless of the yield achieved, CF% was high in both yield components as 10.2 and 27.4 for ears and leaves, respectively. This was relatively high in comparison with other treatments which achieved CF% ranging from 8.2 to 9.2 and 21.6 to 23.5 for ears and leaves respectively (Figure 12D).

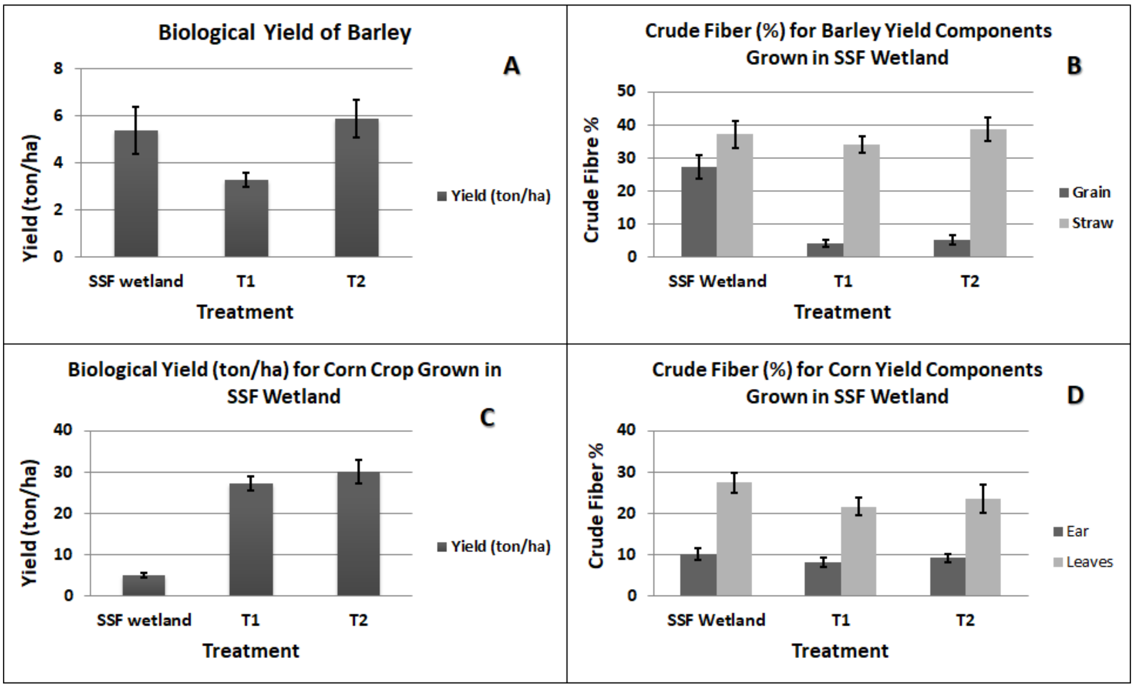

Figure 8. A) Biological Yield (ton/ha) for Barley Crop Grown in SSF Wetlands, B) Crude Fiber (%) for Barley Yield Components Grown in SSF Wetland, C) Biological Yield (ton/ha) for Corn Crop Grown in SSF Wetland and D) Crude Fiber (%) for Corn Yield Components Grown in SSF Wetland (T1 treated wastewater effluent from the SSF wetland, and T2 secondary treated wastewater effluent of Ramtha WWTP)

Results from the field experiment indicated that the barley crop consumed 2550 mm/ha, while the corn crop consumed 3850 mm/ha. On the other hand, results from the SSF wetland indicated that both crops utilized more water as 6610 mm/ha and 6710 mm/ha for barley and corn, respectively (Figure 13A). Corn was grown during the summer season which increased the amount of water used, besides the poor distribution of the crop in the SSF bed which resulted in higher losses than barley crop. It was obvious that crops grown within the SSF bed consumed more water due the depth of the media and the porosity of the system which affected the total amount applied. Water use efficiency (WUE) for both crops was calculated. WUE for barley in SSF wetland was 0.82 kg/m3, while WUE for other field treatments ranged from 1.14 to 2.31 kg/m3. For corn crop the results of WUE were different, as it was 0.74 kg/m3 for SSF wetland with higher WUE values obtained for the field treatments ranging from 7.06 to 7.09 kg/m3 (Figure 13B).

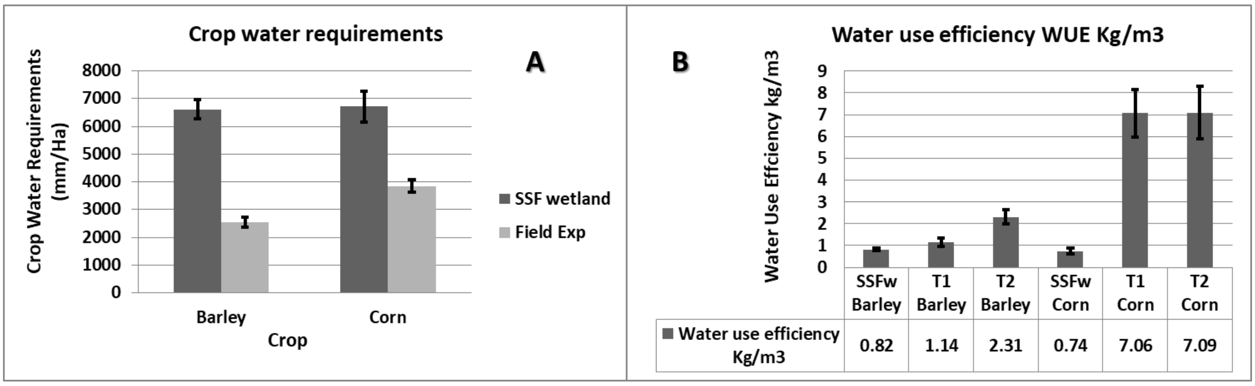

Figure 9. A) Crop Water Requirement in mm/ hectare for Barley and Corn Grown in the Field in Comparison with the SSF Wetland and B) Water Use Efficiency (kg/m3) for the Different Crops Grown in the Field in Comparison with the SSF Wetland (T1 treated wastewater effluent from the SSF wetland, and T2 secondary treated wastewater effluent of Ramtha WWTP)

4. Discussion

The SSF system has shown a great affinity as a simple technology in reducing the concentrations of BOD_5, total suspended solids, nitrogen, and fecal coliforms (Kivaisi, 2001; Jan Vymazal & Kröpfelová, 2008). The capability of the SSF wetland process for effective removal of metals and other priority pollutants were limited and could be attributed to the low HRT operational time as the plants didn't have enough time to absorb the entire pollutants. Nitrogen is removed through denitrification, adsorption and plant uptake (Mayo & Bigambo, 2005; Saeed & Sun, 2011). However, the SSF wetland in this study has limited capacity for the removal of phosphorus in short HRT (1 day). A one-or two-log reduction in fecal coliforms can be reliably achieved with this process; lower levels may require post disinfection (Bastian, 1993; Knight et al., 2003; Jan Vymazal, 2009).

It was reported that SSF wetlands have the ability to moderate and buffer the pH variation due to interactions between the substrate and its biofilms (Hammer & Knight, 1994). Nevertheless, the increase in pH of the outlet in the SSF in this study is due to the lower microbial nitrification activity which halted the release of H^+ ions in the wetland also, it could be related to the generation of $HCO^-{}_3$ due to denitrification as some nitrate removal have occurred (Ghosh & Gopal, 2010). Most of the removal of the total suspended solids in the SSF system has probably occurred within the first few meters of travel distance from the inlet zone (or first couple of days) in the system and the system properly sized for BOD5 removal would be properly sized for volatile suspended solids VSS removal as well (Bastian, 1993; ElZein, Abdou, & ElGawad, 2016; Margaret Greenway, 2005; Jan Vymazal, 2010).

Results indicated that there is a net production of TKN as the wastewater passes through the bed. The source of this is the “extra” ammonia which is believed to be from the anaerobic decomposition of the organic nitrogen trapped in the bed as particulate matter (Bastian, 1993; Mayo & Bigambo, 2005). In the wetlands, the vast majority of organic nitrogen is being converted to ammonia due to two processes, decomposition and mineralization. Moreover, it is associated with particulate matter such as organic wastewater solids and/or algae (Mayo & Mutamba, 2004). Since the bed of the SSF is anaerobic, the oxygen concentration in the bed is inadequate to oxidize ammonia to nitrate (Kivaisi, 2001). The organic N that is associated with particulate matter can be removed by the VSS. Retention time is also a factor in ammonia removal whereby a longer HRT can significantly increase the ammonia removal (Ghosh & Gopal, 2010; Vera, Verdejo, Chávez, Jorquera, & Olave, 2016). The system performance on 1day HRT and no other HRT (s) were tested.

The difference is again believed to be the lack of oxygen (Ottová, Balcarová, & Vymazal, 1997). The SSF wetland is good for nitrate removal (denitrification), but not for ammonia oxidation (nitrification), since oxygen availability is the limiting step in nitrification at lower HRT value (Mayo & Bigambo, 2005; Mayo & Mutamba, 2004; Ottová et al., 1997). The phosphate removal was very low; one of the most dominant mechanisms of orthophosphate compounds is adsorption and precipitation in the porous media (Margaret Greenway & Woolley, 1999; Knight et al., 2000). Sand or fine river gravel with iron or calcium oxides is highly favorable for significant P removal (Knight et al., 2003; Jan Vymazal, 2009). P removal in the SSF wetland is a combination of bacterial activities and plant uptake. Bacteria removal and plant uptake are responsible for $PO^-{}_4$-P removal, while precipitation and adsorption are responsible for the removal of all phosphorus forms (Margaret Greenway & Woolley, 1999; Knight et al., 2000).

Heavy metals presented in the effluent were very low. Fe removal was through abiotic conditions (sorption) followed by formation of ferric oxides and hydroxides (Saeed et al., 2021). The removal of Zn, Cu, and Fe correlated abiotic and biotic routes (Marchand, Mench, Jacob, & Otte, 2010) which assumed to be inter-related, whereas removal of Mn and the abiotic oxidation of manganese requires a pH higher than 8 (Stumm & Morgan, 2012), which is clearly not achievable within wetland treatment systems.

The main mechanisms for fecal coliform removal are flocculation, sedimentation, and the effects of temperature, solar radiation, adsorption and filtration (Khatiwada & Polprasert, 1999). Also, macrophyte's may also have a toxic effect on fecal indicators by producing root exudates which eliminate bacteria, including E. coli (Ottová et al., 1997). In this study solar radiation and macrophyte's role was negligible in the inactivation process of Fecal coliform and bacteria in the SSF. It was reported that longer HRT's typically provide greater bacteria removal efficiency (Díaz, O’Geen, & Dahlgren, 2010). In this study the HRT was one day and it was shown that bacterial removal can also be achieved with operating the SSF at HRT below 1 day (Díaz et al., 2010; Liao, Jin, Chen, & Li, 2020).

The majority of BOD_5 is removed in the first one-third of the constructed wetland length or in the first couple of days in the system and longer HRT do not result in significant additional removal (Merlin, Pajean, & Lissolo, 2002; Jan Vymazal, 1999). BOD_5 removal occurred promptly through settling and entrapment of organic particulate matter between gravel or rock media spaces and voids (Reed, 1993). Soluble BOD_5 is removed by microbial activities and biofilm formation which are attached to the rock media, plant roots and rhizomes penetrating the bed (Reed, 1993). It is also possible that BOD5 could be produced within the wetland as a result of plant litter decomposition and other naturally occurring organic materials which make the wetland systems incapable to achieve 100% of BOD_5 removal (Juwarkar, Oke, Juwarkar, & Patnaik, 1995; Ottová et al., 1997; Reed, 1993).

SSF wetlands are used to treat small flows that have low-solid content (turbidity) (Bastian, 1993; Reed, 1993). It is believed that the media provides greater available surface area for treatment than the FWS wetland so the treatment responses may be faster in the SSF type (Bastian, 1993). Late in the season, the efficiency of the system decreased and witnessed some accumulation of (fine particles) due to the possibility for the porous bed to be plugged with solids (Davis, 1995). A water balance analysis was carried out to assist variability in retention times and hydrologic conditions of the SSF wetland. The small differences found between the HRT's for the two crops indicated that the crop root system did not play a major role in the hydrodynamics of the media (El Hamouri, Nazih, & Lahjouj, 2007) Barley and corn forages are potential livestock feeds. Under some economic conditions cereal forage is more profitable than cereal grain. Barley crop is considered tolerant to wastewater salinity (> 7dS/m), while corn is considered sensitive to wastewater salinity (< 2dS/m) (Fipps, 2003). Crop water requirements for both crops were computed using FAO reference evapotranspiration and crop coefficients (Allen et al., 1998). Water use efficiency (WUE) for both crops was higher than the conventional irrigation practices in the field. Both crops in the SSF wetland treatment utilized more water (as evapotranspiration Et_c) than the same crop in the field.

5. Conclusion

The treated wastewater effluents of the SSF wetland were in accordance with the Jordanian standards for irrigating purposes of corn and barley crops. Effluents were suitable for irrigation purposes without creating negatively impacting the soil, crop, irrigation system, animals, and human health. However, the effluents must be used rationally to ensure a long-term application to the agricultural fields to avoid any future possible problems such as an increase in soil salinity, alkalinity, or the clogging of the irrigation system. The SSF-constructed wetland showed a great tendency in improving the quality of the treated wastewater effluent. Better phosphorus removal can be achieved by placing sand or fine river gravel coated with iron or aluminum oxides. The results of the first season of this research showed a great possibility of using SSF-constructed wetlands to produce specific fodder crops. Both crops in the SSF wetland treatment utilized more water (as evapotranspiration Et_c) than the same crop in the field. For future work, it is suggested to choose crops which are tolerant to treated wastewater salinity and choose a media depth equal to the depth of the root zone of used crops. SSF Constructed wetland attracted wildlife. It was observed that some birds, mammals, frogs, snakes, and a variety of insects were more abundant in the area and made the wetland as their home. There is a need to use plants which reduce the SAR ratio, especially the Na.

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