Evaluation of gradual hydroponic system for decentralized wastewater treatment and reuse in rural areas of Palestine

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Abstract: A pot experiment was conducted to evaluate the performance of a gradual multi-stage vertical flow hydroponic system as an option for decentralized wastewater treatment and reuse. The low cost of such option and the ease of its application make it feasible for rural areas where low cost decentralized options of wastewater treatment and reuse have a great potential in improving environmental and economic conditions in these areas. To evaluate the performance of such option, a five-stage vertical flow gradual hydroponic pot experiment was conducted in a greenhouse in the new campus of An-Najah National University. The experiment included five types of plants: two types of corn, barely, alfalfa, and sunflowers. Wastewater flow was applied through a drip system for the five types of plants. Wastewater was drained by gravity from one pot to the next through a gradual vertical flow hydroponic system. Quality of wastewater entering the first pot and leaving the last pot for each set of plants was monitored throughout the growing season. Results showed an over 90% removal efficiency of soluble organics and suspended solids, and about 60% removal efficiency of nitrogen through the system. The proposed gradual hydroponic treatment system proved to be a successful alternative method to treat and reuse wastewater. Thus, gradual hydroponic systems could be successfully used as small decentralized wastewater treatment systems. This system could be used in producing crops with economic returns in Palestinian rural areas, where agriculture has a significant contribution in the income and employment of communities.

Keywords: hydroponic system, wastewater treatment, wastewater reuse, rural communities, Palestine
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1 Introduction

Wastewater collection and disposal continue to be one of the most public health and environmental hazards in the West Bank and Gaza. However, the status of wastewater treatment and collection services varies from one locality to another. Wastewater collection systems are available in most of the major cities of the West Bank and Gaza Strip. Few wastewater treatment plants have been constructed in the past 15 years for a number of cities in the West Bank and Gaza Strip, while untreated wastewater still flows in the wadis (valleys) from many other cities including major urban centers such as Nablus. However, more than half of the population of the West Bank lives in more than 500 villages. Most of these villages lack wastewater collection systems and rarely have wastewater treatment systems. In most of these villages, wastewater is disposed through cesspools. Due to the spread of the rural population in the West Bank in a large number of villages and the high cost of wastewater conveyance systems, decentralized wastewater treatment plants are of great value for the local population and are expected to be feasible alternatives for wastewater treatment in the West Bank. Therefore, there are many activities in the West Bank to use decentralized treatment

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systems. Many projects have been implemented in the different parts of the West Bank utilizing small house units for the treatment and reuse of wastewater[1,2].

Existing data for wastewater quality in the West Bank showed that Biochemical Oxygen Demand (BOD) values exceed 600 mg/L and reach 1200 mg/L in some areas. The high strength of the wastewater in the West Bank results in high operating costs which might restrict the performance of treatment systems. At the same time, there is a good potential for waste water reuse in the rural areas of the West Bank. As the treatment is expected to be limited and restricted by operation costs, restricted crops should be allowed in reuse systems. Such crops could be mainly forage crops and trees. Forage crops are viable as the costs of animal feed are high in the West Bank and usually most animal feed crops are imported. Such restricted crops could be utilized in the treatment as well as in the reuse through hydroponic plant growth systems. In such systems, the reuse itself will be part of the wastewater treatment itself which will significantly reduce the running cost. In constructing hydroponic plant growth systems, the land utilized is not considered a loss as the land is also utilized in producing crops of relatively high values (forage crops). For local farmers, forage crops are of high importance for integrated rural development.

A recent study for utilizing hydroponic systems in the treatment and reuse of wastewater was conducted at An-Najah National University[3]. The study included constructing and testing pilot hydroponic systems utilizing horizontal and vertical flow systems in wastewater treatment in An-Najah University. The study showed that it is feasible to utilize vertical and horizontal flow hydroponic systems in wastewater treatment and reuse. However, the low removal efficiency of these systems did not allow achieving the treatment objectives of wastewater in accordance with local standards. Thus, modifications to the design of these systems were needed to improve the quality of treated wastewater. Therefore, this study was performed to evaluate the performance of gradual vertical flow systems in treating wastewater.

Hydroponic systems utilize plants which are grown without soil. These plants are usually provided with irrigation water and fertilizers which are applied to the plant according to their needs. It is possible to apply treated or partially treated wastewater to the root system of the plant. Nutrients are added to the water to satisfy plant nutrient requirements. Wastewater moving through plant roots will either be utilized by the plant or will flow through the rooting system receiving additional treatment which makes it suitable for other reuse options[4-6]. The type of structural support and the method of water application provide many options for hydroponics of which are the nutrient film technique (NFT) used in this study.

The use of hydroponics in the West Bank is very limited and restricted to few crops and few areas. The growing media is usually Tuff (different sizes and gradations of crushed volcanic rock aggregates) placed in polypropylene containers. Water is applied through drip lines, and drainage water is monitored to determine the amount of nutrients to be added to satisfy the needs of crops.

2 Methods and materials

2.1 Experimental setup

The experiment was conducted in the new campus of An-Najah University. Wastewater from the scientific faculties of AN-Najah University was collected to a storage tank from which it was pumped to the wastewater collection system in Nablus. A submersible pump was placed in that storage tank to pump wastewater to an elevated storage tank of 15 m^3 in size which was utilized to regulate wastewater flow to the experiment. From that regulation elevated tank, wastewater was supplied to a set of five containers of 45 cm in diameter and 90 cm in height. Each container supplied water to a row of five barrels, each of which was used as a growth cell for the different plants used in the treatment. The barrels were placed on a metal frame as shown in Figure 1.

In each row of five barrels, wastewater flow from one barrel to the following allowing gradual flow and thus five steps of treatment. The steps of treatment improve the treatment efficiency of the system. Since the barrels were on a frame with steps, it allowed gravitational flow of wastewater in the system and thus no pumping was needed to operate the system.

Figure 1 Gradual hydroponic system

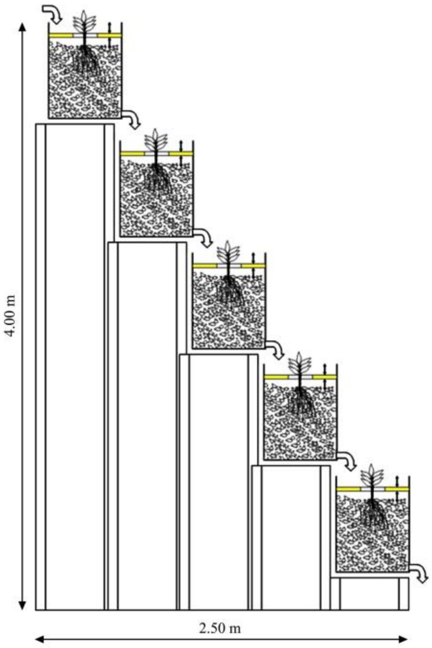

Figure 2 Schematic of the gradual hydroponic system

Plastic barrels with 45 cm in diameter were used in the experiment and each barrel was filled with three layers of coarse aggregates. The first layer consisted of big aggregates with sizes between 10 cm and 15 cm and a height of 13 cm placed in the bottom of each barrel to work as a drainage outlet for the barrels as the size of the aggregates is larger than the openings of the outlet. The second layer was filled with aggregates of sizes of (1-2) cm with a thickness of 27 cm. The third layer had the same characteristics as the second layer but it was mixed with sand at a ratio (3 : 1 = aggregates : sand) and this layer was 10 cm in height as shown in Figure 3. The total thickness of the media inside each barrel was 50 cm as shown in Figure 3. The level of wastewater was kept constant at 40 cm in height and thus the height of 10 cm was left for aeration.

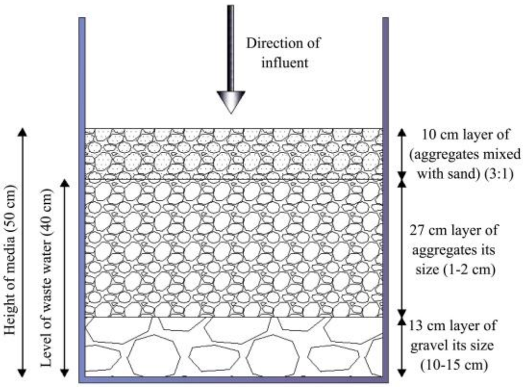

Figure 3 Profile of the hydroponic treatment cells

The flow in each barrel was kept at 12 mL/min or 17.28 L/day obtaining a hydraulic loading rate (HLR) of 0.11 m^3/m^2 day. This flow maintains a hydraulic retention time of six days which was achieved in the system. The level of water in each barrel was maintained constant by raising the outlet valve for each barrel to the height of 40 cm in the barrel. Thus the rate of water flowing into the barrel will be equal to that of water draining from the barrel. A perforated 1.5-inch diameter pipe was placed inside each barrel with a length of 60 cm to measure the level of wastewater inside the barrel and for aeration purposes.

The porosity in the system was 45%, this high porosity has many benefits including (1) preventing the clogging in the system especially in the future which results in a more durable system; (2) increasing the quantity of wastewater in the system, which means increasing quantity of the wastewater treated; (3) maintaining very good aeration for the wastewater in the system which results in fast removal for BOD and Total Nitrogen (TN) because Dissolved Oxygen (DO) will be more.

2.2 Experimental program

Five types of plants were grown in the system. These plants were chosen to be seasonal crops and the experiment was extended for six months. These crops were corn brooms, alfalfa, sweet corn, barley and sunflower. Every crop was planted in the row of five barrels, each barrel represented a stage of treatment; the highest is the first stage and the lowest is the final treatment stage.

The flow in the system was vertical flow from top to the bottom in all the five stages. The flow was kept at 12 mL/min and the storage capacity each barrel was 25.6 L of wastewater considering the level of wastewater was 40 cm in each barrel (10 cm beneath the surface). The hydraulic retention time for each barrel was one and a half day, which added to six days for all stages.

Wastewater quality was monitored before and after treatment. Monitored quality parameters included Total Suspended Solids (TSS), Total Dissolved Solids (TDS), BOD, Chemical Oxygen Demand (COD), Nitrogen (N) and chlorides (Cl). Monitoring of these quality parameters continued through the period of the experiment for all types of plants grown in the system.

Samples were collected in glass bottles from the wastewater inlet and from the outlet (treated wastewater) after the last stage. Sampling was usually performed around 10:00 a.m., and the tests were started within half an hour from sampling.

The temperature of the atmosphere during the study was (32±4) ℃ while the temperature for the wastewater in the treatment plant was (24±2) ℃. Testing was done in accordance to the standard methods for the examination of water and wastewater[7].

It should be noted that no chemical nutrients were added to the wastewater and/or to plants during the experimental program to evaluate the unaltered effect of hydroponic nature and wastewater on plant growth and uptake.

3 Results and discussion

3.1 TSS removal performance

The TSS removal attained was from 90% to 97%, with the HLR of 33.23 kg/ha day. There were small variations among plants in TSS removal efficiency; however, those variations were not significant. The removal of suspended solids is a physical treatment process which was efficient when five steps of treatment were utilized. All rows of treatment achieved an effluent concentration rate of 15 mg/L or less as shown in Table 1. The removal efficiency of TSS and the corresponding reduction in suspended solids in the flow are a result of direct filtration by the growth media and plant roots. The variability of TSS in the outflow could have resulted from different root intensities of the different crops and thus different filtration capacities of these roots. Figure 4 shows changes of influent and effluent concentrations of TSS during the experiment. Figure 1 shows that TSS reduced in the effluent with time during the progress of the experiment. This reduction could be attributed to the growth of plant roots during the season which will increase the filtration capacity of the growth media resulting in the reduction of TSS.

Table 1 Performance of TSS removal by plant types

Parameter	Types of plants	Out flow/mg·L^{-1}	Removal/%
TSS Inflow = 150 mg·L^{-1}	Corn brooms	13.8	90.8
	Barley	6.1	95.9
	Alfalfa	12.5	91.7
	Corn	4.4	97.1
	Sunflower	11.5	92.3

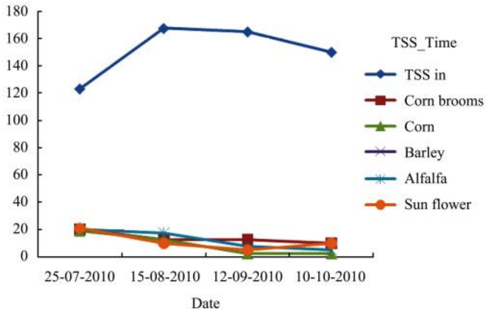

Figure 4 Removal efficiency for TSS during the operation period

3.2 BOD removal efficiency

The experiment setup reached the BOD removal efficiency of 94% to 97% with a HLR of 59.4 kg/ha day. The differences between the types of plants were not significant. The effluent concentration after the five steps of treatment was 16 mg/L or less as shown in Table

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2. The variability in BOD from one plant to another was observed small as shown in Table 2. This could have resulted from the small effects of roots in BOD removal. Plant roots have physical effects on TSS removal; however, their biological effects on BOD removal are usually small. Plant roots do not produce oxygen to encourage BOD removal. The growth media was sand and gravel and thus the effects of roots on the aeration of the media are small. Thus, it is expected that the effect of plant roots on BOD removal is expected to be minimal. Figure 5 shows the removal efficiency for BOD during the operation of the system for the different crops utilized, and the BOD of the effluent nearly constant during the growing season. Thus, the growth of roots and increasing of its intensity through the season do not appear to have an effect on BOD concentrations. Thus, it appears that BOD reduction resulted from the effect of the growth media and the effects of roots was small on BOD reduction. Therefore, Table 2 and Figure 5 show that the impacts of plant types and roots density on BOD are insignificant.

Table 2 Performance of BOD removal by plant types

Parameter	Types of plants	Out flow/mg Ł$^{-1}$	Removal/%
BOD Inflow = 268 mg Ł$^{-1}$	Corn brooms	10	96.4
	Alfalfa	16	94.0
	Corn	10	96.2
	Barley	12	95.4
	Sunflower	8	96.9

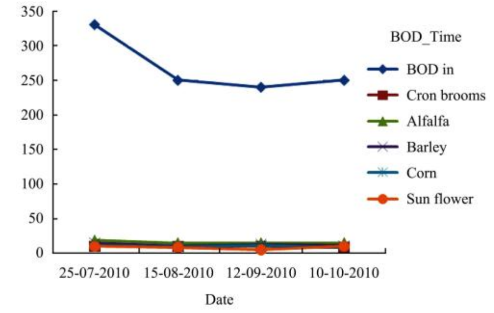

Figure 5 Removal efficiency for BOD during the operation period

3.3 COD removal efficiency

The treatment system achieved a removal efficiency of 80% to 89% at a HLR of 83 kg/ha·day. The variations in removal efficiencies are insignificant among the crops utilized as shown in Table 3. Figure 6 shows the removal efficiency for COD during the operation period for the different types of plants that were grown in the system. The effects of plant roots on COD appear to be similar to those effects on BOD concentration. It appears from Table 3 and Figure 4 that COD removal resulted from the effects of the growth media and not from plant roots. Thus, the increasing density of plant roots as a result of changes the plant type or through the season as a natural growth of the plant itself did not affect COD and BOD removal efficiencies.

Table 3 Performance of COD removal by plant types

Parameter	Types of plants	Out flow/mg Ł$^{-1}$	Removal/%
COD Inflow = 375 mg Ł$^{-1}$	Corn brooms	43.3	88.5
	Barley	51.3	86.3
	Alfalfa	51.3	86.3
	Corn	76.3	79.7
	Sunflower	77.3	79.4

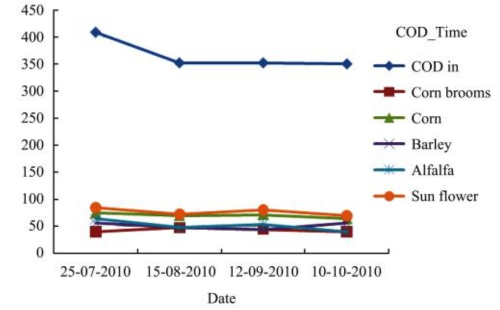

Figure 6 Removal efficiency for COD during the operation period

3.4 TN removal efficiency

A TN removal efficiency of 62.5% to 65.4% was achieved at a HLR of 3.7 g/m^2·day (28.5 kg/ha·day). There were no significant differences between the crops grown in the removal efficiency of N. This could be attributed to the fact that all crops have high N requirements for their growth. We achieved high removal efficiency with high HLR which is the highest with respect to the researches that done before for N removal using gradual hydroponic systems (Table 4). The other research published in 2009 achieved a removal 53% with HLR= 2.7 g/m^2·day (986 g/m^2·yr), which was done in Vienna, Austria.

Table 4 Performance of TN removal by plant types

Parameter	Types of plants	Out flow/mg Ł$^{-1}$	Removal/%
TN Inflow = 165.8 mg Ł$^{-1}$	Corn	62.2	62.5
	Corn brooms	57.0	65.6
	Barley	59.6	64.1
	Alfalfa	62.2	62.5
	Sunflower	62.2	62.5

3.5 Cl and salinity

Due to the use of crops in the hydroponic systems, total salinity and concentration of Cl in wastewater increased in the system. Since plants do not utilize Cl during the growth, evapotranspiration from the system would result in increasing salinity and Cl content of passing water as shown in Tables 5 and 6.

Table 5 TDS in effluent wastewater from different plants

Parameter	Types of plants	Out flow/mg Ł$^{-1}$	Increase/%
TDS Inflow = 622 mg Ł$^{-1}$	Corn brooms	1019.4	63.9
	Barley	864.4	39.0
	Alfalfa	934.4	50.2
	Corn	720.6	15.9
	Sunflower	755.6	21.5

Table 6 Cl concentration of effluent wastewater from different plants

Parameter	Types of plants	Out flow /mg Ł$^{-1}$	Increase /%	Estimated leaching ratio
CL Inflow = 113.4 mg Ł$^{-1}$	Corn brooms	195	71.9	58%
	Barley	173.7	53.1	65%
	Alfalfa	195.0	71.9	58%
	Corn	195.0	71.9	58%
	Sunflower	187.9	65.6	60%

Table 7 Removal efficiency of chemical parameters by plant types

Parameters	Removal efficiency/%				
	Corn brooms	Alfalfa	Corn	Barley	Sunflower
TSS	90.8	91.7	97.1	95.9	92.3
BOD	96.4	94.0	96.2	95.4	96.9
COD	88.5	86.3	79.7	86.3	79.4
TN	65.6	62.5	62.5	64.1	62.5
TDS	163.9	150.2	115.9	139	121.5
CL	171.9	171.9	171.9	153.1	165.6

Note: The removal efficiency over 100% means no removal was attained; in the contrary, an increase of concentration took place.

Table 6 shows an increase of Cl salinity of about 53% to 72%. This indicates that leaching ratios are 58% to 65% for the different crops. The highest leaching ratio was for barely while other crops showed similar leaching ratios. This is a result of the lower crop consumptive use of barely as compared to the other crops used in the experiment.

4 Conclusions

This study showed that it will be possible to achieve high removal efficiencies for TSS, BOD, COD and TN utilizing step wise vertical flow hydroponic systems. These systems could be utilized as full treatment systems for wastewater. The quality of treated wastewater will be good and will be accepted in accordance with local and international standards for wastewater treatment without utilizing the primary and secondary wastewater treatment systems. The system could be easily utilized in hilly areas where gravity will supply enough head to drive wastewater flow in the system. The system is suitable for small villages and single house system as a decentralized wastewater treatment option. The system could be adapted to the local conditions of the rural areas in the West Bank. The experiment utilized different crops in the treatment; however, those crops showed the similar results in terms of removal efficiency. Thus, for practical uses, farmers could select crops that will be safe in wastewater reuse. Forage crops are appropriate as they will be dried and processed before used in feeding animals.

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