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Wastewater treatment in horizontal subsurface flow constructed wetlands using different media (setup stage)

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Abstract

Wastewater treatment through horizontal subsurface flow (HSSF) constructed wetlands (CWs) using three different treatment media (gravel, pieces of plastic pipes, and shredded tire rubber chips) were investigated in Samaha village, Dakahliya, Egypt. The study focused on the wetland setup stage during the first months of its operation (setup stage). In this stage media porosity, bacterial biofilm, and plant roots growth were in progress and it was prior to the operational steady state stage. Objectives of this paper are to study the change in media porosity of HSSF wetland cells in order to estimate duration of wetland setup stage, and to evaluate the use of different bed media on biological oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solids (TSS) treatment. The results showed that after 180 days of operation, the wetland cells had reached steady porosity and had started stable treatment. Also performance of plastic media bed in pollutants reduction was better than gravel and rubber beds and gravel media was in advanced than rubber media.

Keywords: Constructed wetland; Horizontal subsurface flow; Media porosity; Setup stage

1. Introduction

Wastewater treatment is a global problem since discovering that dumping wastes into surface water can lead to many extra environmental problems. Conventional sewage technology has often been unsuccessful in developing countries

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due to the complex operating supplies and costly maintenance measures (Nilsson et al., 2012). Constructed wetlands are considered a technical, economical, and environmental sustainable solution for wastewater treatment in small communities since they are efficient with diverse pollutants removal (Araújo et al., 2008; Chen et al., 2008). Wetlands can effectively treat municipal; industrial and agricultural wastes; acid mine drainage; contaminated groundwater; and other polluted waters (Hodgson et al., 2004; Gearheart, 2006; Islam et al., 2009; Powell et al., 2009). Subsurface flow CWs are designed to keep the water level below the top of the bed media, thus minimizing human exposure (Tanner and Sukias, 2002).

Bed media in HSSF CWs provide a path, through which wastewater can move, and surfaces on which microorganisms can live. As wastewater passes through the pores between the media particles, the microorganisms living there feed on the waste materials, removing them from the water. Another function of the media is to support the plants growing in the wetlands (Xing, 2012). Wetland beds can have two or more types of media in altered layers. Practically, gravel and soil are the widely media used in subsurface CWs (Zidan et al., 2013). Collaço and Roston (2006) successfully investigated the use of shredded tires as a medium for HSSF wetlands for treating domestic wastewater planted with aquatic macrophytes. Cordesius and Hedström (2009) investigated the use gravel and plastic pieces on treating domestic wastewater with advances for plastic media. Recycled plastic pipes and shredded tires pieces have proved to be a good media for treating municipal wastewater (Abdel-Hady, 2014).

Egypt, like most of the developing countries is facing an increase of the generation of wastes and of accompanying environmental problems with the disposal of these wastes. Total untreated municipal wastewater in Egypt is about 10.7 million m^3/d (1.3 Mm^3/d for urban zone and 9.4 Mm^3/d for rural zone) so, it is clear that a wastewater treatment problem concentrated in rural areas (El-Zoghby, 2010). Recently, there are six projects applying the CWs as treatment systems in Egypt. Abu-Attwa plant, 10th of Ramadan project, and Samaha treatment plant are HSSF wetlands, while lake Manzala, Edfina drain, and Al Bahow drain are surface flow wetlands (NAWQAM, 2002; Rashed, 2012). The current research was carried out in Samaha village, Dakahliya governorate, Egypt, where 3 pilot scale HSSF CW cells using gravel, hollow plastic pipes and shredded tiers slices as different media were investigated for treating primary treated municipal wastewater. Using such newly investigated bed media types may has a dual benefit of reducing the treatment plants construction costs and recycling amounts of solid wastes creating currently environmental problems in Egypt. Objectives of this study are: (i) to investigate the treatment media porosity during the initial operational stage of HSSF CWs in order to identify the moving from setup to steady operating stages; and (ii) to evaluate the corresponding performance in treating BOD, COD, and TSS using 3 media types (natural gravel, plastic pipes pieces, and shredded tires pieces) during the initial operation stage.

2. Methodology

2.1. Field and experimental work

Samaha HSSF wetlands plant which located in Dakahliya governorate, Nile Delta, Egypt (30°52′09.81″ N and 31°16′55.28″ E) was built in 1995 for treating 1000 m^3/d of primary treated domestic wastewater. Eight gravel bed cells (33 m long, 7 m wide, and 0.7 m deep each) that suffer from over loading and inefficient treatment performance are forming the plant. A research project between Dakahliya potable water and sanitary drainage company and Faculty of Engineering, El-Mansoura University, has been set to enhance the plant treatment efficiency. One cell was divided into three parallel micro cells (10 m long, 2 m wide, and 0.65 m deep each). Each cell had an inlet zone, main treatment zone, and outlet zone, Fig. 1.

Three types of treatment media were used, one in each cell. These were rubber made from shredded tires (each chip is about 30–60 mm length, 25–55 mm width, and 5–15 mm height), corrugated pieces of plastic pipes 50 mm length and 19 mm diameter and gravel placed in 3 layers. The gravel media were stratified by coarse gravel (40–60 mm diameter) layer at the bottom, medium gravel (20–40 mm diameter) at middle layer, and fine gravel (less than 20 mm diameter) layer at the top. On top of each cell, a plastic screen covered by 10 cm coarse gravel was placed to prevent rubber and plastic media floating.

2.1.1. Media porosity measurement

An innovating method was adapted to measure the field media porosity. A porosity measuring apparatus was designed and a long term porosity inspections were carried out for the three treatment cells (Fig. 2). Each cell was

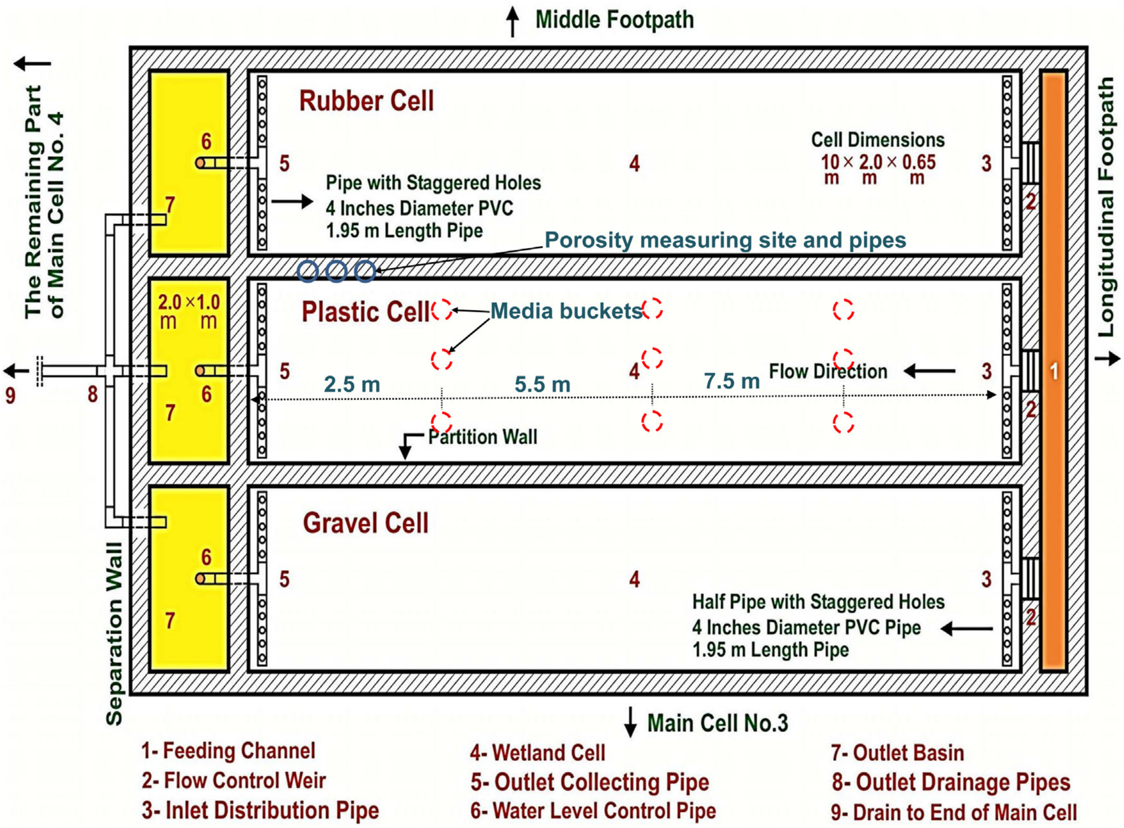

Fig. 1. Plan of HSSF CW cells.

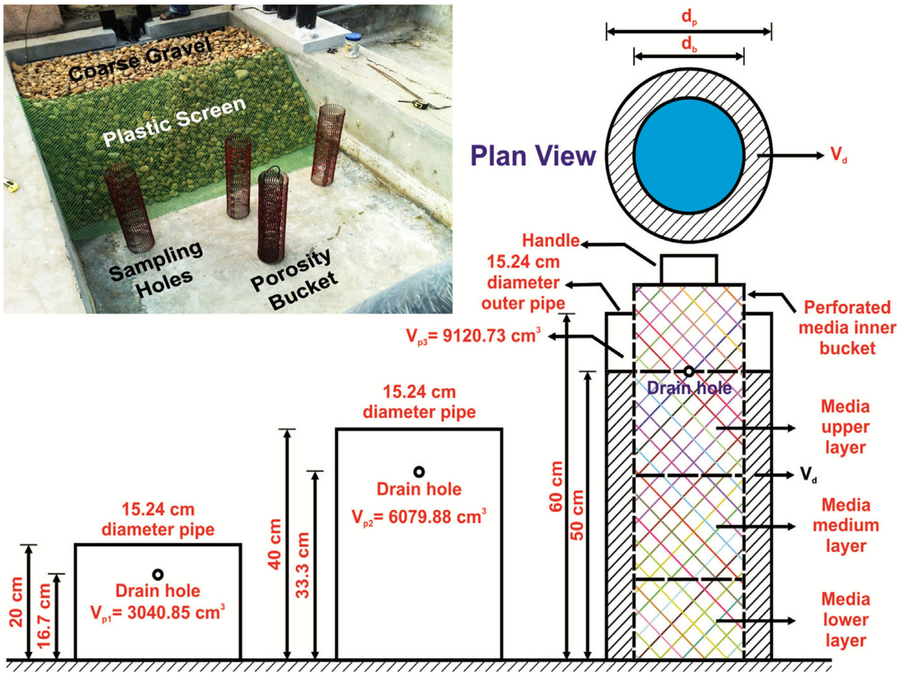

Fig. 2. Sketch of porosity measuring apparatus.

provided with three steel perforated cylindrical buckets, solid base and side holes area smaller than the media size. The cylindrical buckets were put in a wider one. The inner buckets were filled with bed media at the same gradation, and sequence found in the surrounding cell. Inside each cell, three porosity sets were placed at 2.5, 5.5, and 7.5 m from inlet (Fig. 1).

Measuring media voids volume was practiced above the cells side walls through 3 PVC pipes, 15-cm diameter each, and 20, 40 and 60 cm height. The media buckets were removed from its original places in cells and placed inside these pipes. The 20 cm height pipe was used to measure the porosity of bottom media layer. After lifting the media bucket from the 20 cm pipe, the 40 cm pipe was used to measure the porosity of both first and second media layers. The longer pipe was used to measure the porosity of the three layers. The following procedure was applied:

(i) The initial pre-treatment porosity of the 3 clean media was measured before operation of HSSF constructed wetlands for 3 media layers (20, 40, and 60 cm).

(ii) Volumes of the three PVC porosity apparatus V_p with 176.63 cm^2 cross-sectional area, were computed as:

$$V_p = 176.63\,cm^2 \times \text{pipe height}, \quad cm \tag{1}$$

Volumes of the 3 PVC pipes were computed as 3040.9, 6079.9, and 9120.7 cm^3, respectively.

(iii) Volumes of buckets filled with media (V_b) were calculated as:

$$V_p = \text{cross-sectional area of media bucket, } m^2 \times \text{height of media layer, m} \tag{2}$$

(iv) The space volume between fixed pipe and media bucket (V_d) is considered at various layers and distances as:

$$V_d = V_p - V_b \tag{3}$$

(v) Each cylindrical bucket was put in the 20 cm height pipe then water was added up to the drainage hole edge with measured volume, V_w (Fig. 2). The same procedure is repeated with the other longer two pipes (40 and 60 cm height). The added water volume was measured by 1000 cm^3 scaled bottle with accuracy of 10 cm^3.

(vi) The volume of media voids was calculated as:

$$V_v = V_w - V_d \tag{4}$$

(vii) The porosity is obtained as:

$$n = \frac{V_v}{V_b} \tag{5}$$

Eight media porosity runs were performed during 8 months. The porosity was measured for the 16.67, 33.33, and 50 cm media depths; and at 2.5, 5.5, and 7.5 m distances in the longitudinal direction measured from wetlands inlets. In each cell 9 sampling well points were provided along its length to collect water samples in addition to one inlet and three outlet samples (Fig. 1). The average value of 27 porosity records (9 wells × 3 depths) is presented in the media porosity comparisons as 1 figure in addition to standard deviation (St. Dev.) and standard error (St. Err.). The experiment was stopped when the difference between porosity results became small along time. This indicated that the transition from setup stage to the steady condition as the biofilm media growth reached maturation stage.

2.1.2. Water sampling and data analysis

Biweekly 4 water samples were collected manually in 500 ml in clean bottles; one from inlet and 3 from the 3 cells outlets. Water samples were stored in ice tanks, sent to laboratory and analyzed for BOD, COD, and TSS. A total of 48 water samples (4 samples × 12 rounds) were collected during this work. Water sampling was started from the 8th month of wetland operation to give the biofilm layers attached to both the media surfaces and the newly grown planted reeds roots and stems enough growing rate to act effectively in treatment processes. Statistical analysis for each pollutant concentration results was carried out using stochastic package for social science (SPSS software version 17) (SPSS, 2007). Tests for data linearity, and significances between the behavior of beds media on the water treatment were also practiced. The tested groups were for rubber, gravel, and plastic media; rubber and gravel; rubber and plastic; and gravel and plastic media pairs as well as testing the significance of group of the 3 media materials for each pollutant.

Table 1
Average values of porosity for the coarse gravel and used media.

Time from starting operation, T_0 (days)	Average value of porosity (St. Dev./St. Err.)			Porosity reduction %		
	Gravel media	Plastic media	Rubber media	Gravel media	Plastic media	Rubber media
0	0.431 (0.028/0.001)	0.866 (0.019/0.001)	0.576 (0.051/0.009)	0	0	0
15	0.404 (0.030/0.011)	0.842 (0.018/0.009)	0.558 (0.048/0.016)	3.12	6.26	2.77
31	0.393 (0.018/0.010)	0.827 (0.016/0.017)	0.544 (0.062/0.026)	5.56	8.82	4.5
40	0.381 (0.021/0.007)	0.819 (0.023/0.024)	0.533 (0.053/0.015)	7.47	11.6	5.43
77	0.374 (0.021/0.009)	0.812 (0.020/0.022)	0.527 (0.050/0.022)	8.51	13.23	6.24
107	0.365 (0.023/0.010)	0.799 (0.024/0.027)	0.516 (0.052/0.021)	10.42	15.31	7.74
155	0.362 (0.030/0.018)	0.795 (0.028/0.032)	0.512 (0.054/0.018)	11.11	16.01	8.2
218	0.358 (0.022/0.011)	0.788 (0.021/0.024)	0.505 (0.062/0.017)	12.33	16.94	9.01

2.2. *Hydraulic representations*

Inlet flow and retention time were fixed during the study period. An average discharge of 6.61 m^3/d was passed through each of the three cells. The influent BOD concentration varied between 168 and 232 mg/l (1.110–1.533 kg BOD/d). The removal efficiency was calculated according to the following equations (Kadlec and Wallace, 2009):

$$\mathrm{RE} = \left(1 - \frac{C_0}{C_\mathrm{i}}\right) \times 100 \tag{6}$$

where RE = removal efficiency, %; C_i = influent concentrations, mg/l; C_0 = effluent concentrations, mg/l.

3. Results and discussion

3.1. *Estimating setup stage period and media porosity*

Average values of the measured porosity along cell length for the three media cells are presented in Table 1 and graphically shown in Fig. 3. After 6 months from start of operation, it was noticed that reduction in porosity values was very small and may be considered as the end of setup stage and the beginning of steady stage of treatment media. The initial media porosity values were 0.866, 0.576 and 0.431 for plastic, rubber and gravel respectively. The plastic porosity was twice the gravel and 1.5 times the rubber porosity. Gradual and remarkable porosity reductions were observed during the first 90 days of wetlands operation due to sedimentation of degradable fine particles and suspended solids, development of reeds roots as well as growing of bacterial biofilm attachment to the media surface. Slight porosity reductions were observed during the next 30 days of wetlands operation (days 80–110) as media pores gradually filled with fine solids clear from degradable matter and both reeds rhizomes and attached biofilm layers were nearly in stable size. During the next period (days 110–218) porosity reduction was very small in all media and reduction trends were almost flat starting from day 180.

Porosity reduction was worth in gravel media followed by rubber, then plastic. After 218 days, the media porosity values were 0.788, 0.505 and 0.358 for plastic, rubber and gravel respectively. Reductions in media porosity were 12.33%, 16.94%, and 9.01% for gravel plastic and rubber wetlands respectively. The plastic porosity was 2.2 and 1.56 times the gravel and rubber porosity respectively. As for plastic media contains of hollow plastic bits with double surface area, the bacterial biofilm may take longer time to be build inside the bits surface compared with the outer bits surface. Hence, porosity reduction in both the solid, one face gravel and rubber decreased rapidly than the double faces plastic media. The plastic and rubber media have an anti-clogging potential better than the gravel media due to its light weight and easy floating feature. The change in media porosity after 218 days was observed to be minor due to the dynamic stability of bacterial biodegradation, reed roots growing and settlement of both dead and suspended mater. In a previous study (Zidan et al., 2013), the calculated values of gravel specific surface area were based on initial porosity equal to 0.431 (porosity of clean pretreatment gravel). For 1.0 m^3 of gravel media, the corresponding specific surface area was estimated as 177 m^2/m^3 for gravel media (three sequent layers). For rubber media, as the shape of shredded

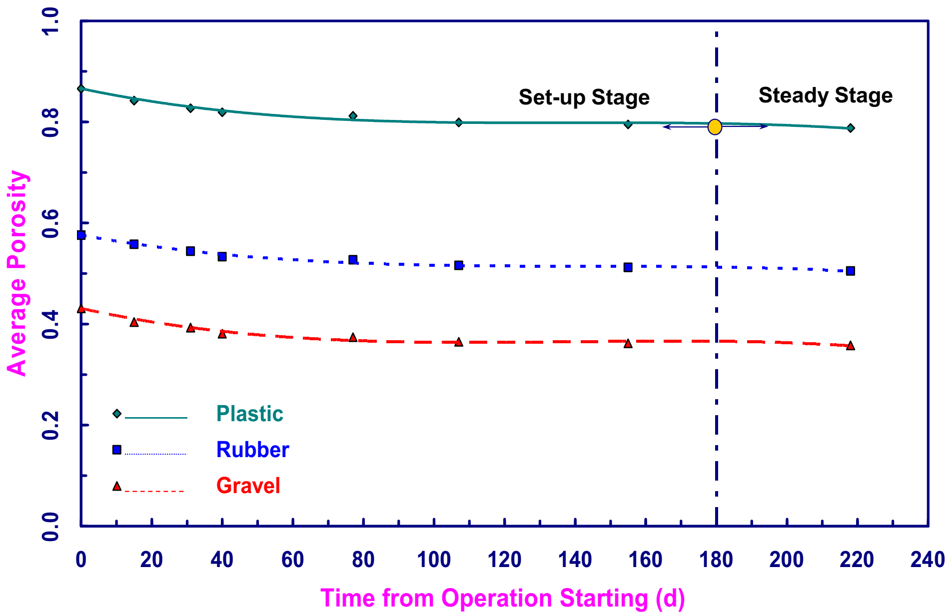

Fig. 3. Relationship between average porosity and time from operation starting.

tires pieces will considered as a parallel piped having average dimensions of 45 mm × 40 mm × 10 mm, the specific surface area was estimated as 130 m^2/m^3 for 1.0 m^3 of rubber media. Plastic media that had hollow cylindrical shapes with an outer diameter of 19 mm, thickness of 0.5 mm, and length 50 mm, the specific surface area was estimated as 283 m^2/m^3 for 1.0 m^3. The porosity values vary with time in a polynomial function of the third degree for the three media types (Fig. 3). Eq. (7) represents the general form of this function. Table 2 shows the values of constants in this equation in addition to the determination coefficients (R^2).

$$n_i = b_1 + b_2 \times T_0 + b_3 \times T_0^2 + b_4 \times T_0^3 \quad (7)$$

where n_i = porosity value; b_i = constants i = 1, 2, . . ., 4; T_0 = time from start of operation, d.

Estimating porosity of the treatment media can be carried out applying equation (7), at any time during the setup operation stage. The obtained media porosity may be used to estimate the HSSF CW treatment performance along the setup stage. For example, the porosity values after 50 operation days were 0.372, 0.814, and 0.531 for gravel, plastic and rubber respectively. The corresponding porosity on day 200 might reached 0.271, 0.806, and 0.516 respectively.

The main weakness of HSSF CWs is the unexpected bed media blockage due to either design miscalculation or overloading. Media blockage is mainly a function in porosity status and volume of trapped solids in media voids. Generally majority of papers and review articles at CWs field did not study or mention a little about the early months of wetlands operation (as for the knowledge of the authors). During this stage (setup stage) the bed media is in an instability condition and huge changes in bed porosity and growing stage of bacterial biofilms usually exists in this stage.

Table 2
Values of parameters in Eq. (7) and R^2 for the media under study.

Media	b_1	b_2	b_3	b_4	R^2
Gravel	0.431	−0.0016	1E−05	−3E−08	0.972
Rubber	0.576	−0.0013	9E−06	−2E−08	0.984
Plastic	0.866	−0.0015	1E−05	−2E−08	0.976

R^2 = determination coefficient.

Table 3
BOD, COD, and TSS treatment through plastic media during setup stage.

Run no.	T_o (day)	BOD_{in} (mg/l)	BOD_{out} (mg/l)	COD_{in} (mg/l)	COD_{out} (mg/l)	TSS_{in} (mg/l)	TSS_{out} (mg/l)
1	56	220	167	344	263	150	66
2	70	211	157	325	244	148	64
3	84	232	168	368	269	162	70
4	98	198	139	300	213	180	76
5	112	205	139	331	226	146	61
6	126	191	125	285	188	143	59
7	140	172	110	257	166	156	64
8	154	180	109	273	167	166	67
9	168	194	106	308	170	172	69
10	182	184	95	297	155	138	55
11	196	174	89	264	136	144	57
12	210	168	85	251	128	155	61

Table 4
BOD, COD, and TSS treatment through gravel media during setup stage.

Run no.	T_o (day)	BOD_{in} (mg/l)	BOD_{out} (mg/l)	COD_{in} (mg/l)	COD_{out} (mg/l)	TSS_{in} (mg/l)	TSS_{out} (mg/l)
1	56	220	173	344	272	150	86
2	70	211	163	325	253	148	84
3	84	232	178	368	285	162	91
4	98	198	148	300	226	180	100
5	112	205	149	331	242	146	80
6	126	191	135	285	203	143	77
7	140	172	117	257	176	156	83
8	154	180	118	273	180	166	88
9	168	194	119	308	190	172	91
10	182	184	106	297	172	138	72
11	196	174	99	264	151	144	75
12	210	168	95	251	143	155	80

3.2. Treatment of BOD, COD, and TSS during setup stage

Tables 3–5 present the treatment performance of BOD, COD, and TSS during the first 7 months of starting operation for plastic, gravel and rubber media wetlands respectively. It is clear that pollutants treatment performance improved along the setup operating period. On day 56 of operation (1st sampling event), influent BOD reduced from 220 mg/l

Table 5
BOD, COD, and TSS treatment through rubber media during setup stage.

Run no.	T_o (day)	BOD_{in} (mg/l)	BOD_{out} (mg/l)	COD_{in} (mg/l)	COD_{out} (mg/l)	TSS_{in} (mg/l)	TSS_{out} (mg/l)
1	56	220	177	344	278	150	91
2	70	211	169	325	262	148	88
3	84	232	184	368	294	162	96
4	98	198	154	300	235	180	105
5	112	205	156	331	253	146	85
6	126	191	142	285	213	143	82
7	140	172	125	257	188	156	89
8	154	180	126	273	192	166	93
9	168	194	127	308	203	172	96
10	182	184	116	297	188	138	77
11	196	174	108	264	165	144	80
12	210	168	103	251	155	155	85

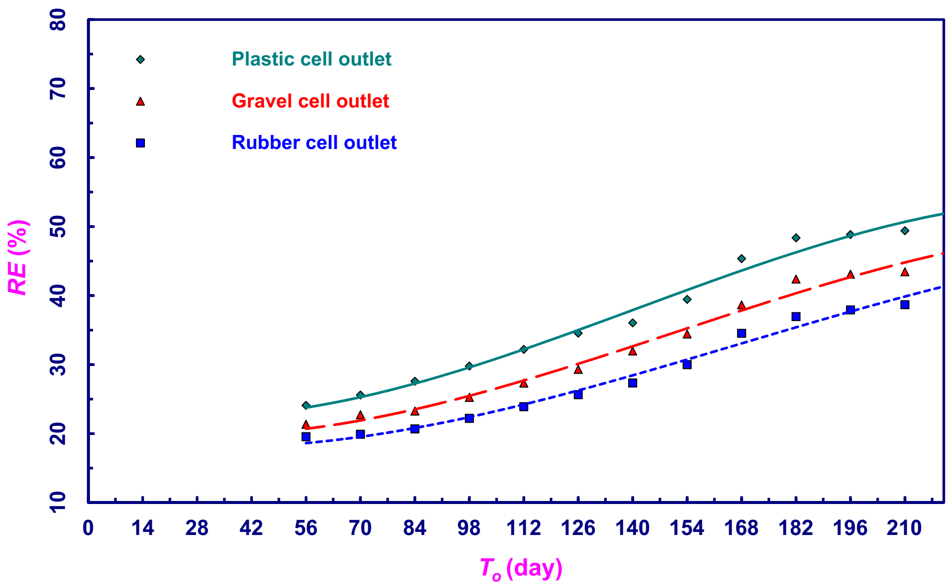

Fig. 4. Development of BOD removal efficiency and setup stage operating time.

to 167, 173, and 177 for plastic, gravel and rubber media respectively. On day 210 of operation (end of setup stage); influent BOD, reduced from 168 mg/l to 85, 95, and 103 for plastic, gravel and rubber media respectively presenting more than double the treatment efficiency of day 56. Similarly initial influent COD, reduced from 344 mg/l to 263, 272, and 277 for plastic, gravel and rubber media respectively. On day 210 of operation (end of setup stage); influent COD, reduced from 251 mg/l to 128, 143, and 155 for plastic, gravel and rubber media respectively presenting nearly double the treatment efficiency. As for TSS the change in treatment performance was differ from BOD and TSS and the development in treatment efficiency increased by about 10%. Influent TSS, reduced from 150 mg/l to 66, 86, and 91 for plastic, gravel and rubber media respectively on day 56. On day 210 of operation (end of setup stage); influent TSS, reduced from 155 mg/l to 61, 80, and 85 for plastic, gravel and rubber media respectively.

The relationship between pollutants RE % and HSSF CW cells operating time is shown in Figs. 4–6 for BOD, COD, and TSS respectively. It is clear that pollutants RE improved along the setup operating period. The BOD RE values were improved from 24.09, 21.36, and 19.55% for plastic, gravel and rubber media respectively on day 56 of operation (1st sampling event), to 49.40, 43.45, and 38.69% on day 210 of operation (end of setup stage). The RE values of COD were similarly to BOD improved from 23.55, 20.93, and 19.19% for plastic, gravel and rubber media respectively on day 56 of operation (1st sampling event), to 49.00, 43.03, and 38.25% on day 210 of operation (end of setup stage). Treatment of TSS started with a better performance but it was improved with slower trend comparing with BOD and COD. The TSS RE values were improved from 56.00, 42.67, and 39.33% for plastic, gravel and rubber media respectively on day 56 of operation (1st sampling event), to 60.65, 48.39, and 45.16% on day 210 of operation (end of setup stage). The high TSS RE at the setup starting is attributed to the wide pores space and higher media porosity comparing with the relatively smaller porosity at the setup stage end. Much TSS was trapped at the cells media pores during the setup stage and amounts of trapped TSS were gradually reduced with time up to ending of setup stage.

Removal efficiency of BOD and COD was developed sharply comparing with RE of TSS (Figs. 4–6). Treatment of BOD and COD is mainly through biodegradation and secondarily by sedimentation into media pores. The RE of TSS was solely by accumulation of suspended matter into the media pore spaces.

Statistical tests were carried out for BOD, COD, and TSS groups of data. One-way ANOVA is used at 5% level of significance. No significant differences were found between each pair of groups and the total 3 media types for both BOD and COD indicating that treating those pollutants have not affected by the bed media. As for TSS, significant differences are found between each 2 media pair and between the lumped media beds. The voids and media grain structure which is clearly visible in gravel, plastic pieces and rubber chips has remarkable impact on suspended solids retaining and trapping during the flow path.

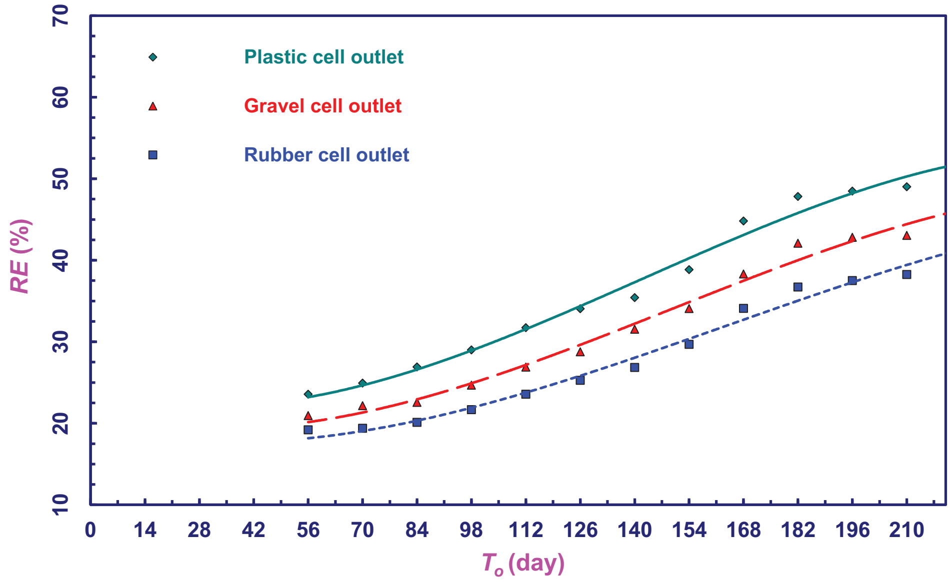

Fig. 5. Development of COD removal efficiency and setup stage operating time.

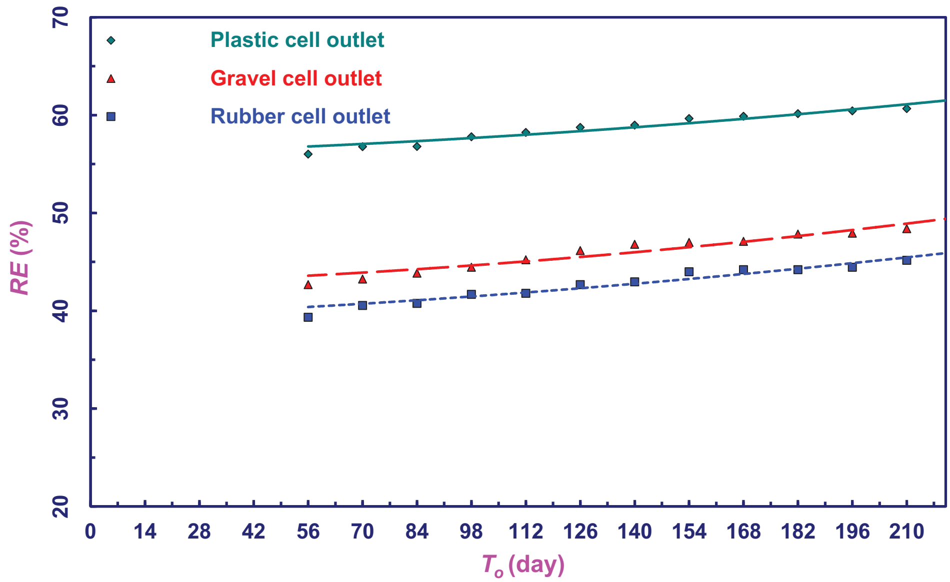

Fig. 6. Development of TSS removal efficiency and setup stage operating time.

4. Conclusions

A simple field approach is presented to periodically measure and estimate the porosity of HSSF CW media through measuring the media voids volume comparing with the initial pre-treatment porosity. During wetland operating setup stage, media porosity, bacterial biofilm, and plant roots growth are dynamically in progress until reaching the operational steady state stage. The reduction in porosities for wetland beds are related to the development of reeds roots and the growth of attached biofilm on the bed media surfaces in addition to periodical accumulation of suspended matter. The HSSF CW media porosity values reached the steady stage after nearly 6 months from start of operation for the wetland system in this study. Through 218 days from start of operation, the porosity decreases by 16.94% for gravel media, 12.33% for rubber media, and by 9.01% for plastic media. This indicates that the plastic and rubber media have a clogging ability smaller than the gravel one. At the end of setup stage, porosity values were 0.358 for gravel media, 0.505 for rubber media, and 0.788 for plastic media. During the setup stage, the growth of planted reeds roots and the increase of bacterial biofilm attached to the media surface and plant parts, enhanced the pollutants accumulation, biodegradation, and the treatment efficiency. Total suspended solids had the highest treatment performance in the 3 studied wetlands (39–61%) comparing with relatively smaller treatment performance for both BOD (20–49%) and COD (19–49%). Through the wetlands setup stage, plastic media had the best treatment performance for BOD, COD, and TSS followed by gravel then rubber.

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