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BOD Treatment in HSSF Constructed Wetlands Using Different Media (Set-up Stage).

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BOD Treatment in HSSF Constructed Wetlands Using Different Media (Set-up Stage)

معالجة الاحتياج الأكسوجيني الحيوي في الأراضي الرطبة المشيدة أفقية السريان باستخدام أوساط مختلفة خلال مرحلة الإعداد

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خلاصـــة:

يهدف البحث إلى دراسة الاحتياج الأكسوجيني الحيوي (BOD) للأراضي الرطبة المشيدة تحت السطحية أفقية السريان التي تستخدم في معالجة مياه الصرف الصحي وذلك خلال مرحلة الإعداد. استخدمت ثلاثة أوساط معالجة مختلفة لهذا الغرض في محطة سماحة للصرف الصحي بالدقهلية وهي الحصى، قطع من أنابيب البلاستيك وقطع من المطاط من الإطارات المستعملة. أثناء مرحلة الإعداد تم دراسة تغير مسامية الوسط المستخدم ومدى تأثير معالجة الاحتياج الأكسوجيني الحيوي بنوعية هذا الوسط. اوضحت النتائج أن خلايا المعالجة قد أتمت مرحلة الإعداد ووصلت إلى مرحلة التشغيل المستقر بعد حوالي ستة أشهر من بداية التشغيل بثبات المسامية ونمو النبات المعالج وسمك الطبقة المعالجة بيولوجيا. تم تحليل عينات المياه في معمل شركة الدقهلية لمياه الشرب والصرف الصحي لدراسة نسبة إزالة BOD للأوساط الثلاثة وقد أظهرت النتائج أن نسبة الإزالة للبلاستيك أكبر من وسط الحصى بحوالي ٤.٨٣% وأكبر من وسط المطاط بحوالي ٨.٦٦% خلال هذه المرحلة.

ABSTRACT:

Municipal wastewater treatment through horizontal subsurface flow (HSSF) constructed wetlands using three different treatment media (gravel, pieces of plastic pipes, and shredded tire rubber chips) were investigated in Samaha wastewater treatment plant, Dakahlia, Egypt. This study focused on the wetland set up stage during the first months of wetland operation. In this stage media porosity, bacterial biofilm, and plants 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, to evaluate the use of different bed media on BOD treatment and to study the relationships between wetland hydraulic properties and pollutant removal rates during set up stage. The results showed that after 180 days of operation the wetland cells had reached steady porosity. Also, plastic cell gave more BOD reduction than gravel and rubber cells by average values of 4.83% and 8.66%, respectively.

1. INTRODUCTION

Wastewater treatment is a problem that has faced man ever since he discovered that discharging his wastes into surface water can lead to many additional environmental problems.

The export of conventional sewage technology to developing countries has often been unsuccessful due to the complex operating requirements and expensive maintenance procedures (Butler and Williams, 1997).

Constructed wetlands (CWs) are technique aim to improve water quality and reduce the harmful effect of effluent water (Sarafraz et al., 2009).

Constructed wetlands are considered a technical, economical, and environmental subtainable solution for wastewater treatment in small communities since they are efficient with diverse pollutants removal (Araújo et al., 2008; and Chen et al., 2008).

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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; and 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). The direction of the water flow provides the names of the two most known designs for the subsurface flow systems as: horizontal and vertical flow systems (Kadlec and Wallace, 2009).

In Egypt, until 2012 there are six projects applying the CWs as treatment systems. Abu-Attwa plant, 10th of Ramadan project, and Samaha treatment plant are subsurface wetlands, while Manzala Lake, Edfina drain, and Al Bahow are surface flow wetlands (NAWQAM, 2002; and Rashed, 2012).

Bed media in CWs provide a path, through which wastewater can flow, 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 (Vrhovšek et al., 1996). When choosing fill media, the following properties must be considered for reactive media as its bulk porosity should not be less than 30%, pore spaces must be large, not breakdown over the time, and particles must be small enough for treatment (Amos and Younger, 2003).

Wetland beds can contain two or more types of media in different layers. Practically, the larger media particles are placed on the bottom and smaller particles are placed on the top. Also, placing larger media at the inlet of the system will reduce the risk of clogging and distribute the wastewater across the inlet (Lesikar et al., 2005).

Collaço and Roston (2006) investigated the use of shredded tires as a medium for HSSF wetlands for treating domestic wastewater with aquatic macrophytes from typha species. The results indicated a potential use of shredded tires to substitute the conventional media (gravel).

The destination of used tires has been delineated as a great environmental problem, as it is not degradable, and thus cannot be disposed in landfills and end up accumulating in rivers and public designations or burned releasing contaminated gases into the atmosphere.

Cordesius and Hedström (2009) investigated the use of two types of bed media (gravel and plastic pieces) on treating domestic wastewater. Their analyses showed a little increase in treatment efficiency for plastic pieces (large surface area) than gravel media.

2. FIELD AND EXPERIMENTAL WORK

Samaha HSSF wetlands plant is located in Dakahlia governorate, about 100 km northeast of Cairo. The plant is treating about 1000 m^3/d primary treated domestic wastes of 7000 inhabitants. The HSSF consists of 8 gravel bed cells (33 m long, 7 m wide, and 0.7 m deep each) that suffer from over loading and inefficient treatment performance.

Cooperation between Dakahlia potable water and sanitary drainage company and Faculty of Engineering, El-Mansoura University, has been conducted to find out solutions for raising the plant treatment efficiency. One cell was chosen to fulfill this target. The 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, Figures (1) and (2). The aspect ratio is 5:1 taken as Samaha cells.

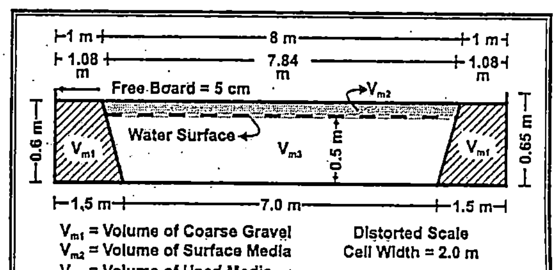

Figure 1: Longitudinal section in wetland cell.

The purpose of cell inlet zone is to spread and regulate the wastewater evenly across the bed for effective treatment. Plate (1) illustrates the inlet control structure which consists of three main parts; (a) flow control weir which receives wastewater from the main distributing channel of plant, (b) perforated distribution pipe, 4 inches diameter, and (c) 40:60 mm diameter inlet gravel to limit the potential of clogging.

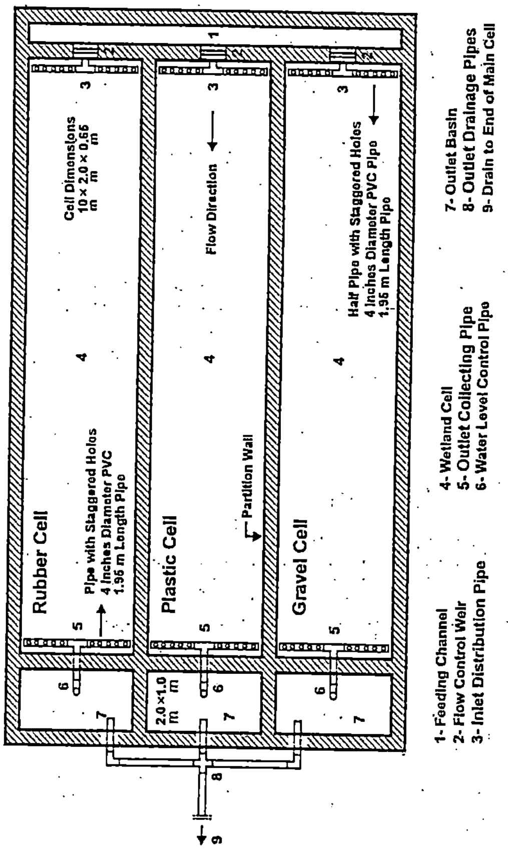

Figure 2: Experimental setup for wetland cells.

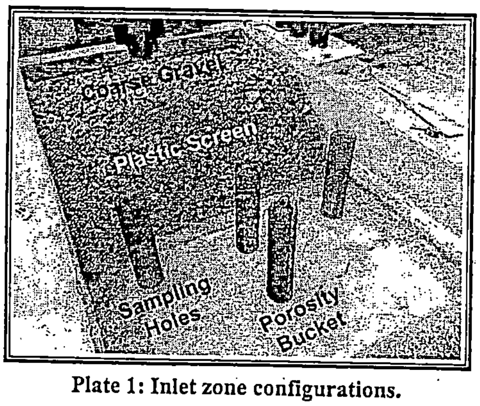

Plate 1: Inlet zone configurations.

The task of the outlet zone is to control the depth of water in the wetland cells and to collect the effluent water. It consists of; (a) perforated outlet collecting pipe 4 inches pipe, at the end bottom of wetland cells. A coarse gravel is placed at end part to regulate water flow, (b) water level control sump, has a movable elbow, Plate (2), and (c) outlet basin receiving effluent water from water level control to outlet collector pipes (2.0 m length, 1.0 m width, and 0.70 m depth).

Plate 2: Water level control.

Three types of treatment media were used. The first media was rubber made from shredded tires (each chip is about 30 to 60 mm length, 25 to 55 mm width, and 5 to 15 mm height). The second media was made of corrugated pieces of plastic pipes 50 mm length and 19 mm diameter. Natural washed gravel was used as the third bed media. The gravel media was stratified by coarse gravel (40 to 60 mm diameter) layer at the bottom, medium gravel (20 to 40 mm diameter) at middle layer, and fine gravel (less than 20 mm diameter) layer at the top. Each layer had a thickness of 16.7 cm.

To prevent rubber and plastic media from floating in cells, plastic screen was placed on the top surface and covered by 10 cm coarse gravel. The gravel cell was also covered with 10 cm coarse gravel for similarity.

Porosity Measurement: An innovating method was adapted to measure the field media porosity. A porosity measuring apparatus was designed and a long term porosity examinations were carried out for the three treatment cells, Figure (3). Each cell was 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.

Measuring media voids volume was practiced above the cells side walls through 3 PVC pipes, each 6 inches diameter, Plate (3). The media buckets were placed inside these pipes; as shorter pipe (20 cm height) was used to measure the porosity of bottom media layer. 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.

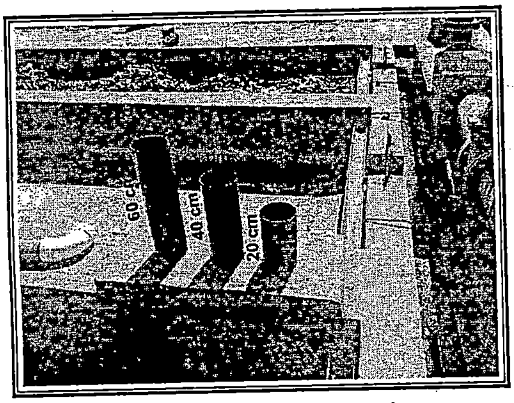

Plate 3: Pipes of media porosity measuring apparatus.

The initial porosity of clean pretreatment media was measured before operation of HSSF constructed wetlands. Firstly, volumes of the three PVC porosity apparatus were computed as (Vp = area of 6 inches pipe × height of drainage hole). Volumes of these PVC pipes were 3040.9, 6079.9, and 9120.7 cm^3, respectively. Secondly, volumes of buckets filled with media were calculated as (V_b = area of media bucket × height of layer). Then the space volume between fixed pipe and media bucket is considered as $V_d = V_p - V_b$ at various layers and distances. Each cylindrical bucket was put in the short fixed pipe then water was added till drainage hole edge with V_w volume. The same procedures are repeated with the other longer two pipes. The added water volume was measured by 1000 cm^3 scaled bottle with accuracy of 10 cm^3. The volume of media voids was calculated as $V_v = V_w - V_d$, and the porosity is obtained as $n = V_v/V_b$.

The experiment was stopped when the difference between porosity results became small along time. This indicated that the transition from set up stage to the steady condition as the biofilm media growth reached maturation stage. Eight media porosity measuring runs were performed during seven months.

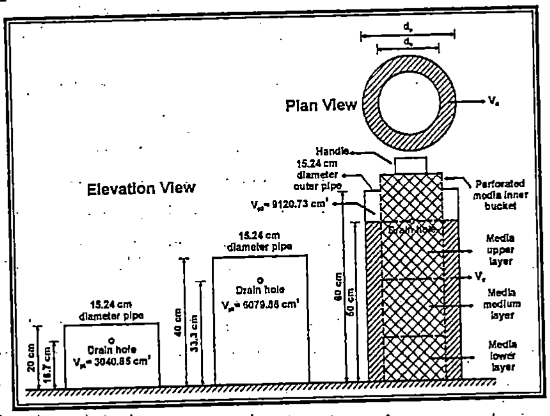

Figure 3: Sketch of porosity measuring apparatus.

Media Surface Area: the surface area of each media can be calculated as follows:

Gravel media: Assuming that, each one cubic meter of gravel is divided into 12 equal parts. Each part is considered as spheres with diameter of 5, 10, 15….., and 60 mm. For each diameter, the specific surface area is calculated by the following equation (Cooke and Rowe, 1999):

$$A_s = \frac{6(1-n_i)}{d_p} \qquad (1)$$

where:

A_s = area per unit volume, m^2/m^3
n_i = initial porosity
d_p = diameter of sphere, m

The calculated values of specific surface area were based on initial porosity equal to 0.431 (porosity of clean pretreatment media). 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 media layers) and 66 m^2/m^3 for coarse gravel.

Rubber media: The shape of shredded tires pieces will considered as a parallelepiped having average dimensions of 45×40×10 mm. A sample volume was taken and number of rubber pieces was counted to obtain its surface area. For 1.0 m^3 of rubber media, the specific surface area was estimated as 130 m^2/m^3.

Plastic media: These media had hollow cylindrical shapes with an outer diameter of 19 mm, thickness of 0.5 mm, and length 50 mm. A sample volume was taken and number of pieces was counted to obtain its surface area. For 1.0 m^3 of plastic media, the specific surface area was estimated as 283 m^2/m^3.

Reed Bed Establishment: Operation of CWs began in September 2009 by one month flow stabilizing period followed by starting the set up stage with planting cell surface with reeds. (*Phragmites Australis*). Planting density was 18 rods/m^2 and was transplanted manually, Plate (4). After 3 months, reeds roots were well grown and spread over the bed surfaces to a density of about 200 rods/m^2, Plate (5).

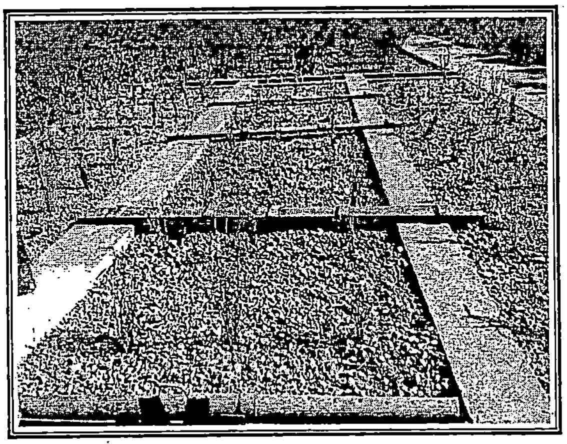

Plate 4: The reed bed establishment (Initial Stage 5/10/2009).

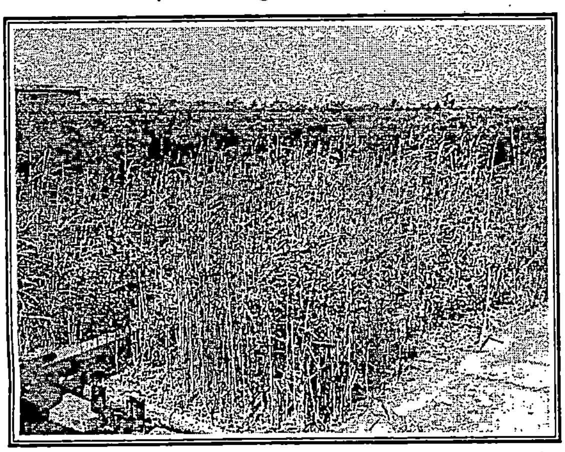

Plate 5: Reed bed after three months from planting (Final Stage 5/1/2010).

Water Sampling: Water samples were collected manually in 500 ml cleaned polyethylene bottles from locations shown in Figure (4). Water samples were stored in ice tanks, sent to laboratory and analyzed for BOD, COD, and TSS. Field water measurements were performed to determine its temperature and hydrogen ion number. A total of 372 water samples (31 samples × 12 rounds) were collected during this set up stage. The sampling round repeated every two weeks. Water sampling started lasted from 31/10/2009 till 3/4/2010.

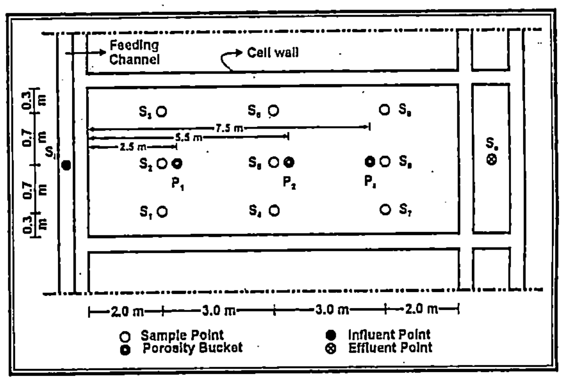

Figure 4: Plan view of water sampling and porosity measuring locations.

3. HYDRAULIC CALCULATIONS

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.

The wetland cell was considered as four basins 2.0 m width and surface areas of 4, 10, 16, and 20 m^2. Equation 2 gives four corresponding values of loading rate at distances of 2, 5, 8, and 10 m from entrance.

$$q = \frac{Q \times 100}{A} \quad \text{.......... (2)}$$

where:

Q = discharge, m^3/d
A = surface area, m^2
q = loading rate, cm/d

The removal efficiency and the hydraulic retention time at any distance could be calculated according to the following equations (Kadlec and Knight, 1996):

$$RE = \left(1 - \frac{C_o}{C_i}\right) \times 100 \quad \text{.......... (3)}$$

$$T_r = \frac{24 \times V_{wx}}{Q} \quad \text{.......... (4)}$$

where:

RE = removal efficiency, %
Q = discharge to wetland cell, m^3/d
T_r = hydraulic retention time, hr
V_{wx} = volume of water at distance x, m^3

The following Equations 5 and 6 give the average difference between pollutant removal efficiency through 12 rounds of the set up stage for plastic cell and both gravel and rubber cells. Whereas *Eqn*. 7 gives this average difference between gravel and rubber cells.

$$AD(P\&G) = \frac{\sum(RE_p - RE_g)}{No.\,of\ Runs} \quad \text{.............................} \quad (5)$$

$$AD(P\&R) = \frac{\sum(RE_p - RE_r)}{No.\,of\ Runs} \quad \text{.............................} \quad (6)$$

$$AD(G\&R) = \frac{\sum(RE_g - RE_r)}{No.\,of\ Runs} \quad \text{.............................} \quad (7)$$

where:
AD = average difference, %
RE_p = removal efficiency of plastic, %
RE_g = removal efficiency of gravel, %
RE_r = removal efficiency of rubber, %

4. RESULTS AND DISCUSSION

Porosity: Figure (5) shows the porosity for the three media versus time progression. After six months from start of operation, it was noticed that reduction in porosity values was very small and may be considered as the end of set up stage and the beginning of steady stage of treatment media.

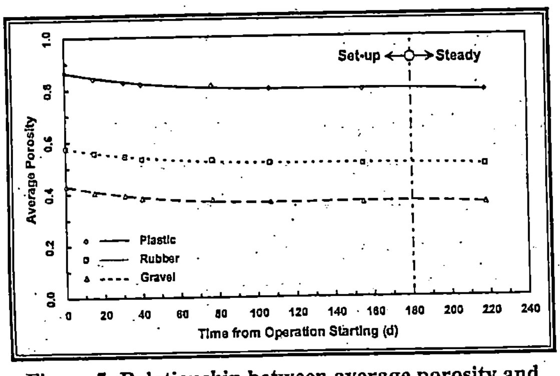

Figure 5: Relationship between average porosity and time from operation starting.

From Figure (5), values of porosity at set up stage end were taken as 0.365 for coarse gravel (decreased from initial value of 0.453 by 19.43%), 0.358 for gravel media (decreased from initial value of 0.431 by 16.94%), 0.505 for rubber media (decreased from initial value of 0.576 by 12.33%), and 0.788 for plastic media (decreased from initial value of 0.866 by 9.01%). The plastic and rubber media have a clogging potential better than the gravel media.

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.

BOD Development: The effluent BOD concentration was studied with distance, loading rate, and influent concentration. The variation of pollutant removal efficiency with retention time and time from start of sampling was also determined.

1- *Effect of Distance on BOD Treatment*:

Figures (6) and (7) give the variation of BOD concentration with longitudinal distance from cells inlet for start and end dates of set up stage. While Figure (8) illustrates this variation for average values of the whole stage.

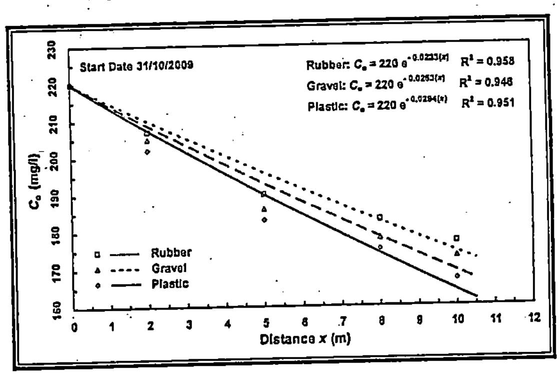

Figure 6: Relationship between BOD concentration and distance from cells inlet (Start Values).

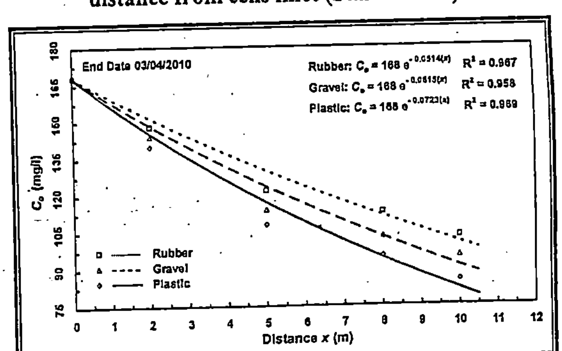

Figure 7: Relationship between BOD concentration and distance from cells inlet (End Values).

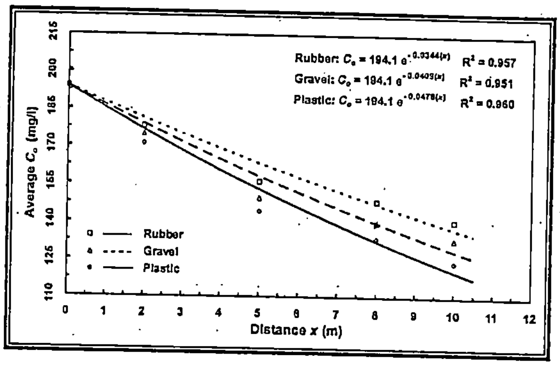

Figure 8: Relationship between BOD concentration and distance from cells inlet (Average Values).

In plastic cell BOD outlet concentration reduces with distance higher than other media. Gravel cell takes the second order in reduction.

At the start of set up stage, the inlet BOD concentration is 220 mg/l which is reduced to 202, 205, and 207 mg/l at 2 m from inlet for plastic, gravel, and rubber media, respectively. These values are 183, 186, and 190 mg/l at 5 m; and 175, 178, and 183 mg/l at 8 m from inlet. The outlet concentrations at the end of the cells are 167, 173, and 177 mg/l.

At the end of the stage, the inlet BOD concentration is 168 mg/l which gives outlet concentrations of 140, 144, and 148 mg/l at 2 m from inlet for plastic, gravel, and rubber cells, in the same sequence; and 108, 114, and 122 mg/l at 5 m. These values are 95, 103, and 113 at 8 m; and 85, 95, and 103 mg/l at 10 m.

During the whole stage, the average inlet concentration is 194 mg/l which gives average values of 171, 175, and 178 mg/l at 2 m; 144, 150, and 156 mg/l at 5 m; 134, 140, and 148 mg/l at 8 m; and 124, 133, and 141 mg/l at 10 m for plastic, gravel, and rubber cells, respectively.

Concentration of BOD, during the stage may be represented by an exponential function which gives the best determination coefficient. The exponential equations for the average values of set up stage are written as follows:

$$Plastic: \; C_o = 194.1\, e^{-0.0476x} \quad R^2 = 0.960 \;\ldots\ldots\ldots\ldots\ldots (8)$$

$$Gravel: \; C_o = 194.1\, e^{-0.0409x} \quad R^2 = 0.951 \;\ldots\ldots\ldots\ldots\ldots (9)$$

$$Rubber: \; C_o = 194.1\, e^{-0.0344x} \quad R^2 = 0.957 \;\ldots\ldots\ldots\ldots\ldots (10)$$

where:

x = distance from cell inlet, m

C_o = outlet concentration, mg/l

Using these equations, the BOD concentration may be determined in-between distances at each cell. Another important application of these equations is to estimate the required cell length for any of the three media types to reach a certain average BOD effluent concentration.

2- *Impact of Loading Rate on BOD Treatment*: Table (1) presents the BOD effluent concentration and the loading rate at different distances for the three media.

Table 1: BOD concentration and q at different distances.

Dis.	Plastic Cell		Gravel Cell		Rubber Cell	
	C_o	q	C_o	q	C_o	q
2 m	171.0	159.4	174.7	166.8	177.8	169.5
5 m	144.3	63.8	149.5	66.7	156.0	67.8
8 m	133.7	39.9	139.8	41.7	148.4	42.4
10 m	124.1	31.9	133.3	33.4	140.6	33.9

Figure (9) gives the relationship between outlet BOD concentration and q values.

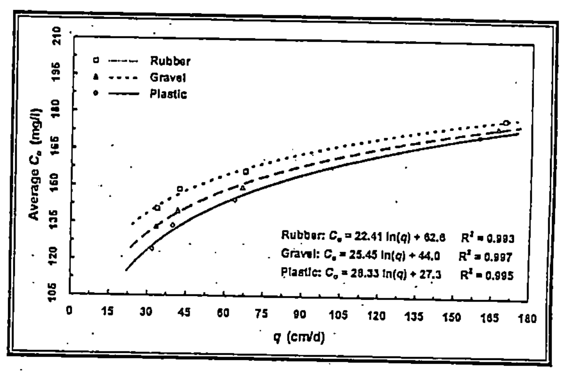

Figure 9: Relationship between Co and hydraulic loading rate for effluent BOD of wetland cells.

The effluent BOD concentration increases with the increasing value of loading load. The q value is maximum near cell entrance and it decreases with increasing the surface area of cells. After 2 m from inlet, the q values are 159.4, 166.8, and 169.5 cm/d for plastic, gravel, and rubber cells with corresponding effluent BOD concentration of 171, 174.7, and 177.8 mg/l, respectively. At cells outlets, the q values are 31.9, 33.4, and 33.9 cm/d and the effluent BOD concentration values are 124.1, 133.3, and 140.6 mg/l.

The BOD outlet concentration is directly proportion to the loading rate and follows a logarithmic function. The logarithmic equations are given as:

$$Plastic: \; C_o = 27.3 + 28.33\, ln\, q \quad R^2 = 0.995 \;\ldots\ldots\ldots\ldots (11)$$

$Gravel: C_o = 44.0 + 25.45 \ln q \quad R^2 = 0.997$ .... (12)

$Rubber: C_o = 62.6 + 22.41 \ln q \quad R^2 = 0.993$ .... (13)

These equations can be used to estimate C_o concentration based on q in the range between 31.9 and 169.5 cm/d with the same aspect ratio.

3- *Inlet and Outlet Concentrations*: Figures (10) through (13) give the relationship between influent and effluent concentrations of BOD for the three media at 2, 5, 8, and 10 m from inlet.

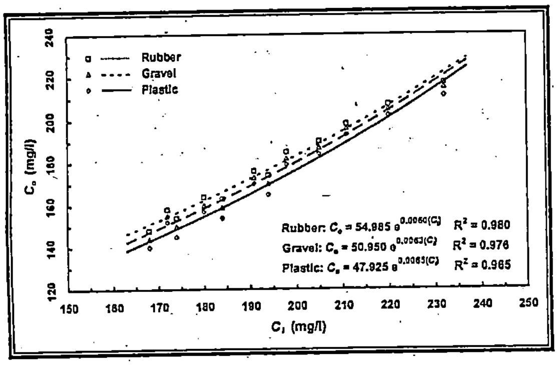

Figure 10: Relationship between inlet and outlet BOD concentrations (2 m from inlet).

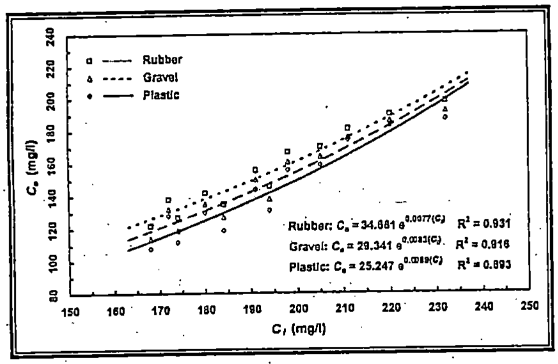

Figure 11: Relationship between inlet and outlet BOD concentrations (5 m from inlet).

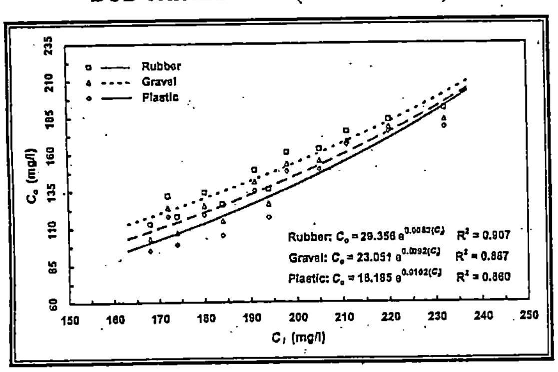

Figure 12: Relationship between inlet and outlet BOD concentrations (8 m from inlet).

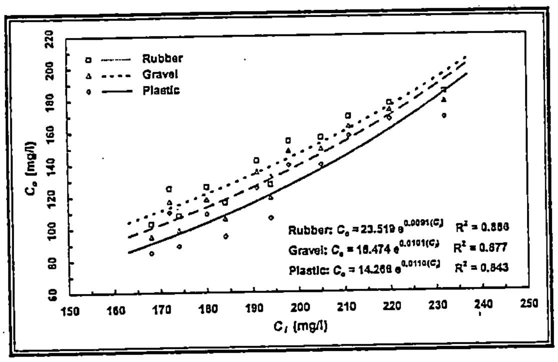

Figure 13: Relationship between inlet and outlet BOD concentrations (10 m from inlet, outlet).

Through this stage, the outlet BOD concentration of plastic media is smaller than the other media at all distances, followed by the gravel. The difference between BOD outlets for the three media was small at the first 2 m then this difference increases going towards cells outlet, due to the little volume of media in this region. The volume of coarse gravel at the inlet of cells is 1.29 m^3 while the volume of media is 0.71 m^3 (the total volume is 2 m^3 at this distance). This means that the media occupies about 35.5% of the region volume as shown in Figure (2). While at 5, 8, and 10 m from inlet, the media occupies about 74.2, 83.9, and 74.2% of the region volume, respectively.

Inlet and outlet BOD relationship for the used media follows an exponential function. The exponential equations at cells outlets are given as:

$Plastic: C_o = 14.266\, e^{0.0110 C_i} \quad R^2 = 0.843$ .... (14)

$Gravel: C_o = 18.474\, e^{0.0101 C_i} \quad R^2 = 0.877$ .... (15)

$Rubber: C_o = 23.519\, e^{0.0091 C_i} \quad R^2 = 0.886$ .... (16)

where:

C_i = inlet concentration, mg/l
C_o = outlet concentration, mg/l

These equations are valid at the inlet BOD concentration ranges from 168 to 232 mg/l to estimate the outlet concentration at 10 m.

4- *Impact of T_r on Removal BOD Efficiency*: Table (2) presents the BOD removal efficiency and the calculated T_r at cells outlets. Each row in this table represents the results of one round of set up stage at time T_s (time from start of sampling).

Table 2: BOD removal efficiency and Tr at 10 m from inlet.

T_s	Plastic Cell		Gravel Cell		Rubber Cell	
	RE	T_r	*RE*	T_r	*RE*	T_r
0	24.09	26.592	21.36	13.728	19.55	17.496
14	25.59	26.472	22.75	13.656	19.91	17.424
28	27.59	26.304	23.28	13.488	20.69	17.256
42	29.80	26.088	25.25	13.320	22.22	17.088
56	32.20	25.944	27.32	13.224	23.90	16.944
70	34.55	25.920	29.32	13.176	25.65	16.920
84	36.05	25.872	31.98	13.152	27.33	16.872
98	39.44	25.824	34.44	13.104	30.00	16.824
112	45.36	25.752	38.66	13.080	34.54	16.776
126	48.37	25.680	42.39	13.032	36.96	16.728
140	48.85	25.656	43.10	12.984	37.93	16.656
154	49.40	25.584	43.45	12.960	38.69	16.632

Figure (14) gives the relationship between BOD removal efficiency and T_r at distance of 10 m for plastic, gravel, and rubber media.

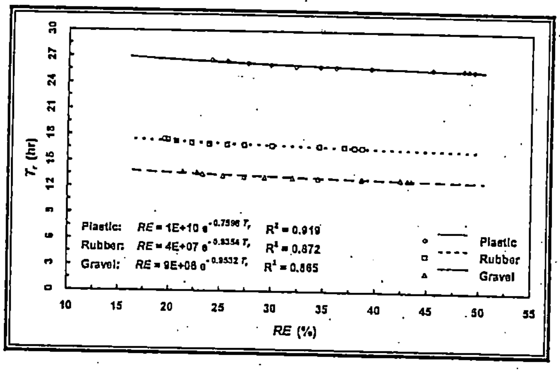

Figure 14: Relationship between BOD removal efficiency and retention time (10 m from inlet).

The gravel cell has the lower retention time followed by the rubber cell and then the plastic cell. This is compatible with the porosity of the three media types as the gravel media has smaller porosity followed by rubber then plastic media. The BOD removal efficiency increases with T_r decrease through the stage. As for gravel cell (at the start of the stage, $T_s = 0$) the removal efficiency at 10 m equals 21.36% ($T_r = 13.728$ hr) while at the end of the stage ($T_s = 154$ day) the removal efficiency equals 43.45% ($T_r = 12.960$ hr). The positive effect on treatment due to the plant and attached biofilm growth are the reason for removal efficiency improvement.

Generally the retention time decreases with time from the start to the end of the set up stage. At the cells outlet, the T_r decreases from 26.592 to 25.584 hr for plastic and from 13.728 to 12.960 hr for gravel and from 17.496 to 16.632 hr for rubber. The reason of such T_r decrease is the reduction in pore spaces volume of media with accumulating of suspended matter and growth of biofilm thickness around particles.

The removal efficiency is found better in plastic followed by gravel and then rubber. In plastic cell the removal efficiency reached 49.40% at stage end ($T_s = 154$ day); and 38.69 and 43.45% in rubber and gravel cells, in the same sequence.

The BOD removal efficiency for the three media is reversely proportional to the retention time according to an exponential function. The exponential equations at outlets are as follows:

$$Plastic: RE = 1E + 10\,e^{-0.7596\,T_r} \quad R^2 = 0.919 \quad (14)$$

$$Gravel: RE = 9E + 06\,e^{-0.9532\,T_r} \quad R^2 = 0.872 \quad (15)$$

$$Rubber: RE = 4E + 07\,e^{-0.8354\,T_r} \quad R^2 = 0.865 \quad (16)$$

where:

RE = removal efficiency, %

T_r = hydraulic retention time, hr

These equations are valid at retention time ranges from 25.584 to 26.592 hr for plastic, from 12.960 to 13.728 hr for gravel, and from 16.632 to 17.496 hr for rubber to estimate the removal efficiency at 10 m.

5- *Treatment Efficiency Progress with Time*: The development of BOD removal efficiency with time progression from start of sampling (T_s) at distance of 10 m from inlet (outlet) is illustrated in Figure (15). The lines in this figure represent the best fit function (third order polynomial).

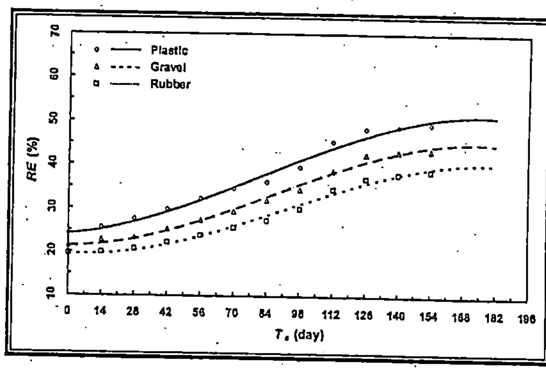

Figure 15: Relationship between BOD removal efficiency and Ts at 10 m from inlet.

At outlets, plastic cell gives average removal efficiency higher than both gravel and rubber cells by about 4.83 and 8.66% (*Eqns* 5 and 6), respectively. Gravel cell gives average removal efficiency higher than rubber cell by about 3.83% (*Eqn* 7) at distance of 10 m from cell inlet.

5. CONCLUSIONS

- The set up stage is a key step of a successful HSSF constructed wetlands. Within 6 months set up period, its media porosity and matured biofilm layers were stable to start the steady state treatment processes.
- During set up stage, media porosity decreased by 19.43% for coarse gravel, 16.94% for gravel media, 12.33% for rubber media, and 9.01% for plastic media.
- Plastic pipes and shredded tires pieces have proved to be a good media for treating BOD in the set up stage. Plastic media showed better treatment performance than gravel and rubber media followed by gravel media.
- Regression equations linking outlet concentrations with distance, loading rate and inlet values could be used as a useful tool in designing HSSF wetlands especially for the initial set up stage in addition to the relationships between removal efficiency and retention time.
- The average BOD treatment efficiency of plastic media is higher than the corresponding rubber and gravel ones by about 8.66% and 4.83%, respectively.
- More investigations are required to identify advantages and disadvantages of using the two examined treatment media in subsurface flow wetlands for longer periods.

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