*Desalination and Water Treatment*
www.deswater.com

doi: 10.5004/dwt.2018.21676

106 (2018) 72–79
February

# Synthesis of polystyrene coated by sand (PCS) as a novel media in modified biological aerated filters (BAF) for advanced municipal wastewater treatment: a comparative assessment

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Received 15 June 2017; Accepted 17 November 2017

**ABSTRACT**

In this study a novel media, polystyrene coated by sand (PCS) was made and then applied in a pilot-scale down-flow biological aerated filter (BAF), named PCS BAF. The efficiency of PCS BAF reactor was compared with efficiencies of puzzolana BAF, gravel BAF, and polystyrene BAF in advanced domestic wastewater treatment through three stages. The inner structure of BAFs consisted of a media with a height of 150 cm for biological attached growth that was modified by a 20 cm layer of silica particles at the bottom of columns to increase the reactors' performance. The physical and chemical parameters of turbidity, $BOD_5$, TCOD, and SCOD, as well as parameters related to backwashing were investigated for BAFs' efficiency. Results of this research indicated that PCS BAF can decrease the turbidity, $BOD_5$ TCOD, and SCOD in the influent, from 20 NTU, 22, 53, and 36 mg/L, to a rate of 1.3 NTU, 9, 26, and 21 mg/L in the effluent, respectively. Moreover, the backwashing time required for PCS BAF was less than half of the other three BAF reactors and the backwashing interval was about once every 19 d.

*Keywords:* Biological aerated filter (BAF); Advanced wastewater treatment; Polystyrene coated by sand (PCS) media

## 1. Introduction

Nowadays, the effluent of advanced municipal wastewater treatment plants presents an available water supply in agricultural and urban applications [1–3]. Biological aerated filter (BAF), known as submerged aerobic bio-filter enjoys several advantages over other fixed-film wastewater treatment reactors [4]. These filters are attractive systems especially where a small area of land is available [5]. Application of submerged biological filters, such as BAF as a polishing and/or post treatment stage can help sanitation improvement to remove pollutants (organic matter, nutrients, pathogens, and trace elements).

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Biological aerated filter reactor contains a high concentration of active biomass that enables degradation of complex compounds, provides better protection against toxic shocks by the biofilm, and enjoys high loading capability, good efficiency of pollutant removal, high filtering capacity in a single-unit process, easy maintenance, and high performance. Further, it does not need sludge recycling. Biomass in the BAF is mostly in the form of biofilm that sticks to media, has high removal efficiency and excellent toxicity endurance. Furthermore, BAF has a small footprint in the removal of turbidity, solids, organic matter, and ammonia-nitrate [6–8].

The main disadvantage of BAF operation is the energy costs associated with aeration and backwashing process. The clogging that is mainly caused by TSS and biological growth can be removed periodically through backwashing process [4,6]. Clogging phenomenon may be minimized by using appropriate media with a porosity ratio of more than 0.4 [6,9]. Backwashing is required when head loss in BAF reaches a specific level, since solids and sludge reduce the media porosity over time [10,11].

Selection of a suitable BAF media is a critical issue, because it plays a significant role in BAFs' porosity, clogging, biological growth, and eventually performance [5,11].

The appropriate media should have a large specific surface area, suitable specific weight, and rough surface. It also needs to be very durable, easy to install, suitable for biological growth, highly porous, resistant to attrition, and chemically stable [12–14]. Rough media provide more sites for biological growth and maintain biofilm better than smooth media, they also increase the sludge retention time in BAF systems [12].

Biological aerated filter media contain both natural and synthetic materials; natural materials like gravel, shale, ceramic, puzzolana, as well as expanded clay, and synthetics such as polystyrene and polyethylene [14,15]. They are designed and operated either in down-flow or up-flow modes. Down-flow configuration with counter current air flow has appropriate efficient oxygen mass transferred to the biofilm which is attached to media [12]. Therefore, the media with appropriate characteristics could promote the BAFs' performance. In this study, a novel media named polystyrene coated by sand (PCS) was produced for potential use in the down flow BAF systems. The main objective of the present study was to evaluate the performance of PCS as a BAF media and to compare it with the three conventional media, i.e., puzzolana, gravel, and polystyrene in the BAFs modified by a 20-cm layer of silica particles at the bottom for advanced wastewater treatment.

## 2. Materials and methods

### *2.1. Media preparation*

In this study, four separate forms of media, namely PCS, Puzzolana, gravel, and polystyrene were used for BAFs. The size of both gravel and puzzolana media were approximately 2.5–3 mm, while the average size of granules of polystyrene media was 2–2.5 mm (Table 1). Furthermore, washed sands with a particle size of 0.2–0.4 mm and crystal granules of polystyrene HIPS7240 with a size of 2–2.5 mm were used as the raw materials for production of PCS as a new media (Fig. 1). To reach this goal, a cylindrical rotating steel container containing mentioned sands was heated to a temperature of about 200°C and then the polystyrene granules were added to the sand particles. The heating continued for 10 min until all polystyrene granules were coated by sand particles. In this temperature, the polystyrene granules reached annealing point and the connection between the sand particles and polystyrene granules became very strong. The size of produced PCS media was about 2.5–3 mm. In addition, to improve the BAFs' performance a layer of silica particles with a height of 20 cm, effective size of about 0.25 mm, and uniformity coefficient of 2.4 was considered at the bottom of each BAF.

### *2.2. Feeding wastewater characteristics*

The secondary treated wastewater used in this study was obtained from Intermittent Cycle Extended Aeration System (ICEAS) plant effluent, Yazd, Iran. Wastewater characteristics in all the four BAFs are summarized in Table 2.

### *2.3. Reactors' description*

The schematic diagrams of four parallel cylindrical down flow BAF reactors made of polyethylene are shown in Fig. 2. The reactors had a diameter of 0.25 m with a height of 1.8 m. Spaces of 0.2, 1.3, and 0.3 m were considered from bottom for silica particles, PCS media, and free space, respectively. Stainless steel net was used to separate silica and media layers from each other in all the BAFs. A piezometer (water level indicator) was applied for measuring the head losses during experiment in all BAF columns. The wastewater influent distributor was set at the top and the pipes used for effluent were set at the bottom. The air was introduced into the reactors with a blower pump and the air flow rate in reactors was controlled with

Table 1
Comparison of BAFs' properties

| BAFs | Media particle diameter (mm) | Total porosity (%) | Media grain density (kg/m$^3$) | Media water absorption (%) | HRT (min) of stage one | HRT (min) of stage two | HRT (min) of stage three |
|---|---|---|---|---|---|---|---|
| PCS | 2.5–3 | 53 | 730 | 1.5 | 118 | 59 | 39 |
| Puzzolana | 2.5–3 | 46 | 900 | 12 | 102 | 51 | 34 |
| Polystyrene | 2–2.5 | 37 | 650 | <0.1 | 83 | 41 | 28 |
| Gravel | 2.5–3 | 43 | 1440 | 4 | 96 | 48 | 32 |

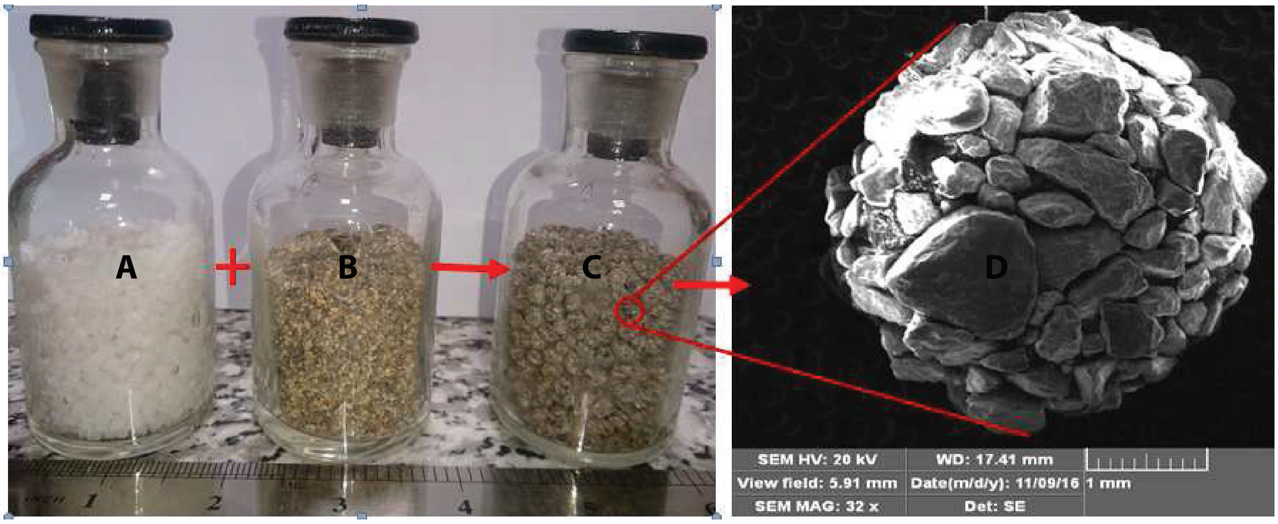


Fig. 1. Production diagram of PCS media. A: crystal granules of HIPS7240 polystyrene, B: sand particles, C: PCS media and D: SEM of PCS media.

Table 2
Summary of the means scores of pollutants' quality in the BAFs' influent and effluents

| Parameter | Turbidity (NTU) | TSS (mg/L) | TCOD (mg/L) | SCOD (mg/L) | $BOD_5$ (mg/L) | FC coliform (MPN/100 ml) | Color (PT-CO) | $NO_3$-N |
|---|---|---|---|---|---|---|---|---|
| Influent | 20 ± 7 | 41 ± 17 | 53 ± 16 | 36 ± 9 | 22 ± 5 | $12 \times 10^6 \pm 3.5 \times 10^4$ | 67 ± 25 | 4.2 ± 1.2 |
| PCS effluent | 1.3 ± 0.5 | 2.2 ± 0.7 | 26 ± 6 | 21 ± 4 | 9.5 ± 2 | 2200 ± 720 | 47 ± 12 | 5.3 ± 2.1 |
| PUzzolana effluent | 3.1 ± 1.1 | 5.1 ± 2.3 | 33 ± 7 | 24 ± 4 | 12.8 ± 3 | 6600 ± 1200 | 50 ± 13 | 4.8 ± 1.8 |
| Gravel effluent | 3.5 ± 1.1 | 6.2 ± 3 | 34.5 ± 8 | 25 ± 5 | 13.4 ± 4 | 6600 ± 4400 | 50 ± 15 | 4.4 ± 1.5 |
| Polystyrene effluent | 4.7 ± 2 | 9 ± 4.5 | 41 ± 8 | 31 ± 8 | 16 ± 4 | $24 \times 10^4 \pm 8200$ | 58 ± 16 | 4.2 ± 1 |

an air flow meter installed in air inlet pipes. Air diffusers were set between silica and media layers. Sampling points were at influent and effluent valves as represented in Fig. 2. Two valves; the bottom backwashing valve and the top backwashing valve, were considered to remove the accumulated suspended solids (SS) and excess biomass. As represented in Fig. 1, air and water pass through the net after getting mixed in the silica layer then enter the media layer. So, both silica and media are cleaned in the backwashing process.

### *2.4. Start-up and operation*

The four BAFs were operated thoroughly under the same conditions and the start-up was about four weeks. The sludge attached to the walls of the Yazd-ICEAS plant, aerated digestion sludge, and approximately 10 g of milk powder were used daily for inoculation. In start-up and during steady state, the ratio of air to water (A/W) flow rate was controlled at 5:1. According to previous studies on secondary wastewater treatment, the ratio of air to liquid (A/L) flow rate was mostly 3:1–15:1 [12,16–18]. Since in the tertiary treatment, the organic loading rate was relatively low, a 5:1 ratio of A/L flow rate was applied. After reaching the steady state the whole operation was divided into three stages. During each stage, the operational conditions of four BAFs were identical which are summarized as follows:

- Stage one (30 d): The flow rate of 0.0055 L $s^{-1}$ and approximately organic loading rate of 0.36–0.45 kg COD/$m^3$/d.
- Stage two (30 d): The flow rate of 0.011 L $s^{-1}$ and approximately organic loading rate of 0.72–0.90 kg COD/$m^3$/d.
- Stage three (30 d): The flow rate of 0.022 L $s^{-1}$ and approximately organic loading rate of 1.44–1.88 kg COD/$m^3$/d.

The water temperature was in the range of 25–29°C, pH 7.5–7.8, dissolve oxygen (DO) above 4–6 mg/l, and the study was conducted in room temperature ranging from 32 to 40°C.

The BAFs' media characteristics and hydraulic retention time (HRT) during each stage are represented in Table 1. According to the literature, the mean of HRT was 45 min which is in the range of 20–120 min for down flow BAF systems [12,18,19].

During the three-stage operations, influent and effluent samples were taken regularly two times a week and concentrations of TCOD, SCOD, $BOD_5$, Fecal coliform, TSS, color, and $NO_3$-N were analyzed according to the instruction of standard methods of 5210-B. Other parameters such as hydraulic head losses, turbidity, DO, temperature, and pH were also measured daily.

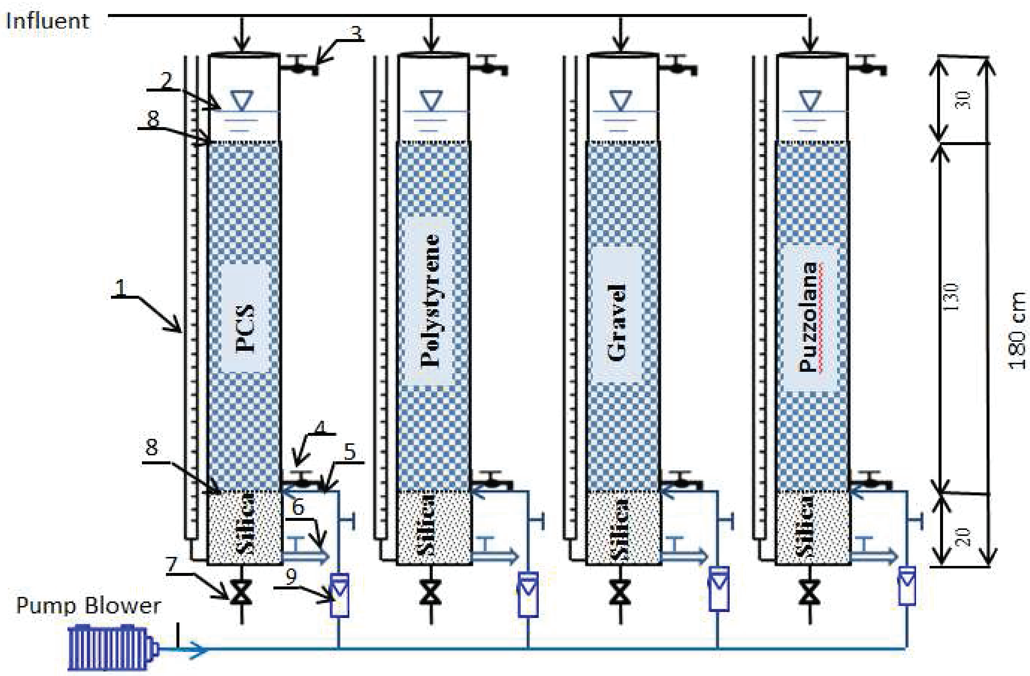


Fig. 2. Schematic diagram of BAFs' configuration system. (1) Piezometer (water level indicator); (2) Water level; (3) Top backwashing valve; (4) Bottom backwashing valve; (5) Air inlet; (6) Effluent; (7) Air and water backwashing inlet; (8) Stainless steel net; ( 9) Air flow meter.

### 2.5. Backwashing process

Head losses in reactors were measured through piezometers daily. The reactors were backwashed periodically when the head loss in BAFs reached approximately 15 cm. The backwashing cycle sequence included air scour and water scour. When the head loss in each reactor reached to about 15 cm, air washing stage was introduced to the bottom of the filters for 5 min to loosen the fouling agents from the media. Then, in the second stage air flow was stopped and clean upward water was kept entering the filters for about 30 min to dislodge the fouling agents. Backwashing process for all the BAFs was operated at the same air flow rate of 7.3 L/m$^2$/s and water flow rate of 1.6 L/m$^2$·s. So, the $\nu_{w/}\nu_r$ ($\nu_w$: volume of backwashing water and $\nu_r$: volume of reactor) was 0.73 through the whole backwashing process.

## 3. Results and discussion

### 3.1. Removal efficiency

After the steady state was reached, all the four BAFs were monitored for 90 d; in three 30-d stages. Fig. 3A shows that the turbidity removal efficiency by PCS BAF was always higher than 93% in all the three stages and it had a higher efficiency than the other three BAFs. With the increase of HRT in stage two, the turbidity removal efficiency remained almost constant in four BAFs. However, with the increase of HRT in stage three, polystyrene BAF removal efficiency decreased about 10%. The results of Fig. 3A represented that temporary increases of turbidity in influent have the least negative effects on the efficiency of PCS BAF and the most negative effects on the polystyrene BAF efficiency. Findings of Table 2 further showed that the average value of turbidity which was 20 NTU in the reactors' influent decreased to 1.3, 3.1, 3.5, and 4.7 NTU in the effluent of PCS BAF, puzzolana BAF, gravel BAF, and polystyrene BAF, respectively.

Results of an investigation revealed that application of non-woven polyester fabric (NWPF) as a BAF media in advanced wastewater treatment could remove 89–92% of turbidity in HRT of 3.2 h [20]. In another study, a media named Zeolite Tailings was used in the BAF system and the turbidity changed from 42–13.2 to 4.84 on average, in other words, that the removal efficiency was 67–88% [18]. Findings of the current research showed superiority of turbidity removal efficiency of the BAFs applied in this study, especially PCS BAF. Certainly, application of a 20-cm silica layer at the bottom of BAFs increased the possibility of turbidity removal efficiency. It can be deduced that reformation of BAFs by placing a silica layer with an effective size of 0.25 mm at the bottom of reactors and lower than the air diffusers, enhanced the turbidity removal efficiency. This is because there was no turbulence caused by air bubbles in this area of BAFs. Thus, lack of turbulence condition and fine porosity of this surface area removed residuals of turbidity factors which passed through the upper layer.

Generally, among the four BAFs, turbidity removal efficiency of PCS BAF was higher than the others even in a low HRT (HRT of 39 min). Some researchers asserted that simultaneous increase of roughness and reduction of media size can increase the opportunity of trapping and removing

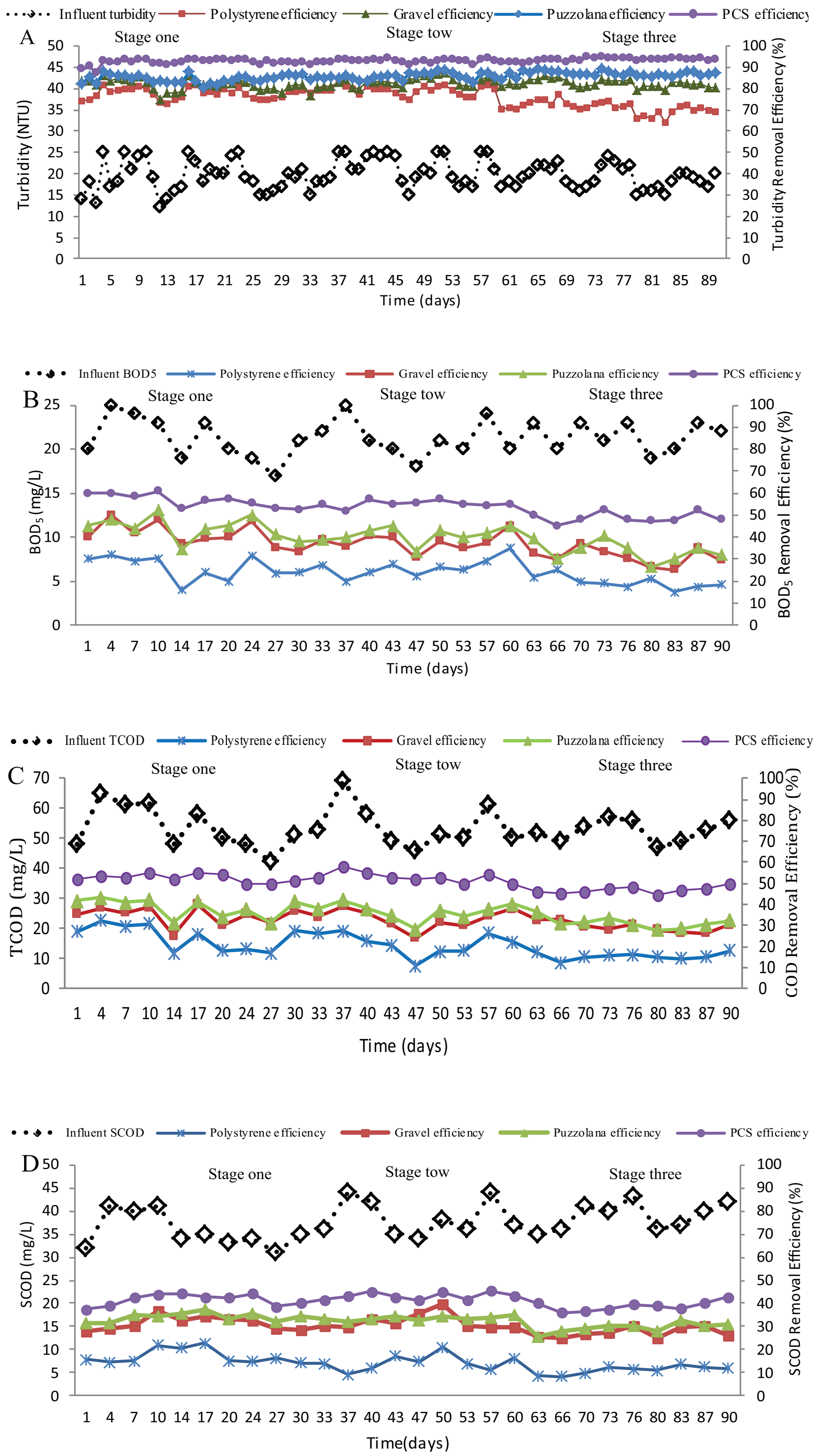


Fig. 3. Removal efficiency of the BAFs during the three stages of experiment. A:turbidity; B: $BOD_5$; C: TCOD; D: SCOD.

suspended solids (SS) [14,20]. Considering the fact that PCS surface is covered with rough and fine sand particles, it can be deduced that this characteristic is probably an important factor in trapping and removal of turbidity factors in PCS BAF.

The results of Table 2 indicate that average of $BOD_5$ in the BAFs' influent was 22 mg/L, while it was 9.5, 12.8, 13.4, and 16 mg/L in the effluents of PCS BAF, Puzzolana BAF, gravel BAF, and polystyrene BAF, respectively. Fig. 3B represents the $BOD_5$ removal efficiency condition for the BAFs in all the three stages. This figure shows that PCS BAF, Puzzolana BAF, gravel BAF, and polystyrene BAF remove more than 55, 34, 33, and 26% of $BOD_5$ in both stage one and two, respectively. But, with decrease of HRT in stage three, the removal efficiency of $BOD_5$ drops approximately to 49, 29, 28, and 18%, respectively. Fig. 3(B) demonstrates that removal efficiency of $BOD_5$ in PCS BAF is less affected by the influent concentration fluctuations, in proportion to other BAFs.

The average concentration of TCOD and SCOD influent were 53 and 36 mg/L, respectively (Table 2). However, the TCOD in the effluent decreased to 26, 33, 34.5, and 41 mg/L, as well as the SCOD decreased to about 21, 24, 25, and 31 mg/L at PCS BAF, Puzzolana BAF, gravel BAF, and polystyrene BAF, respectively. Fig. 3C shows that removal of TCOD by PCS BAF in stage one and two is approximately 52% and in stage three declines to about 47%. Fig. 3D portrays the removal efficiency of SCOD. The SCOD removal by PCS BAF in stage one and stage two was about 44%, while it was approximately 37% in stage three.

Almost in every 90 d of experiment, the removal efficiencies of TCOD and SCOD by PCS BAF were about 7–22% higher than other BAFs. High roughness of PCS surface can be mentioned as one of the reasons for high removal efficiency of TCOD by PCS BAF in which the physical trapping of pollutants, especially suspended solids and colloidal material obtain more opportunity for biological agents to biodegrade organic matters. Futhermore, the sandy rough surface will provide a proper site for the attached growth of biological agents which will improve the SCOD and TCOD removal efficiency. Another superiority of PCS is that despite its small diameter (2.5–3 mm), its porosity (54%) is higher than the other three types of media and thus its HRT in PCS BAF is higher than the other BAFs (Table 1).

### 3.2. Backwashing and hydraulic head loss

Over time and after each backwash, pores of media and silica layer of BAFs clogged, consequently, head loss happened and water level rose in the piezometric pipes. Once the piezometric pipe revealed a head loss of about 15 cm, the backwashing process was conducted for every BAF. Since most of the clogging agents accumulate in the lower parts of BAF and because setting the backwashing effluent valve at the bottom of BAF systems upgrades the removal rate of colloidal material in backwashing process [21–24]. In addition to the top effluent, a backwashing effluent valve was considered in the intermediate of silica and media layer. Fig. 4 (E-H) represents the head loss and backwashing process through the operation time for each of the BAFs. During the 90 d of operation, the number of backwashing cycle and the average interval time between backwashing process in PCS BAF was 4 times and 19.5 d, respectively. These values for Puzzolana BAF, gravel BAF, and polystyrene BAF were 8 times and 11.2 d, 9 times and 10 d, as well as 11 times and 8 days, respectively. Generally, comparison of these results indicates that in PCS BAF the number of backwashings was less than the half and the intervals between them were two times more than the other three BAFs. The findings of a review study [21] showed that the backwash intervals of 24–48 h were applied to BAF systems in secondary treatment, depending on the Organic Loading Rate (OLR), media size, density of granular media, and media type. In another study a backwashing interval of 24 h was considered for the BAF in which zeolite tailings was applied for secondary wastewater treatment [18]. Nevertheless, a BAF with an ultralight weight sludge ceramics (ULSC) media was used for advanced wastewater treatment and the system was backwashed every 3 d [17]. Consequently, the comparison between results of the current research and previous studies proves that PCS BAF requires less backwashing process. It can be deduced that the low density of PCS granules prevents media compression and thus resists the phenomena of media porosity clogging; eventually, it reduces the backwashing cycle. Moreover, high roughness of the PCS media, despite its small size, increases the capacity and effective porosity of media layer. Thus, turbidity removal in PCS media layer will occur before the foulants agents get to silica layer. So, blockage of the tiny pores of silica layer happens later. In addition, the sandy surface of PCS media which is made from natural materials provides a better situation for attached biological growth as an operant in organic matter degradation. According to BET test, specific surface area of PCS media is about 171623 $m^2/m^3$, which provides enormous surface area per unit volume in reactor for biofilm development. Increase of surface area enhances the bacterial population responsible for organic degradation through the attached growth systems. Finally, since all BAFs were quiet the same in structure, wastewater influent characteristics, start-up step, operation, and aeration system, except in the media type, it can be concluded that the PCS as a novel media in down flow BAF reactor has a very high efficiency in advanced wastewater treatment.

### 3.3. Economical analysis

In this study, all four BAFs were similar in their materials, volume of reactor, silica layer, air rate, blower pump, stainless steel net, piezometer, air flow meter, valves, and other equipment. So, the only difference in price was related to media types used in the BAFs, which is summarized in Table 3. The comparison among prices of media used in this research showed that the price of PCS media is about 140% and 111% more expensive than gravel and puzzolana, respectively; while it is about 48% cheaper than polystyrene. PCS BAF has lower number of backwash (Fig. 4E) and lower HRT (Table 2) in comparison with other cases. In this way, decreases required energy, backwashing water as well as capital cost and explains use of PCS as a suitable media in BAF systems.

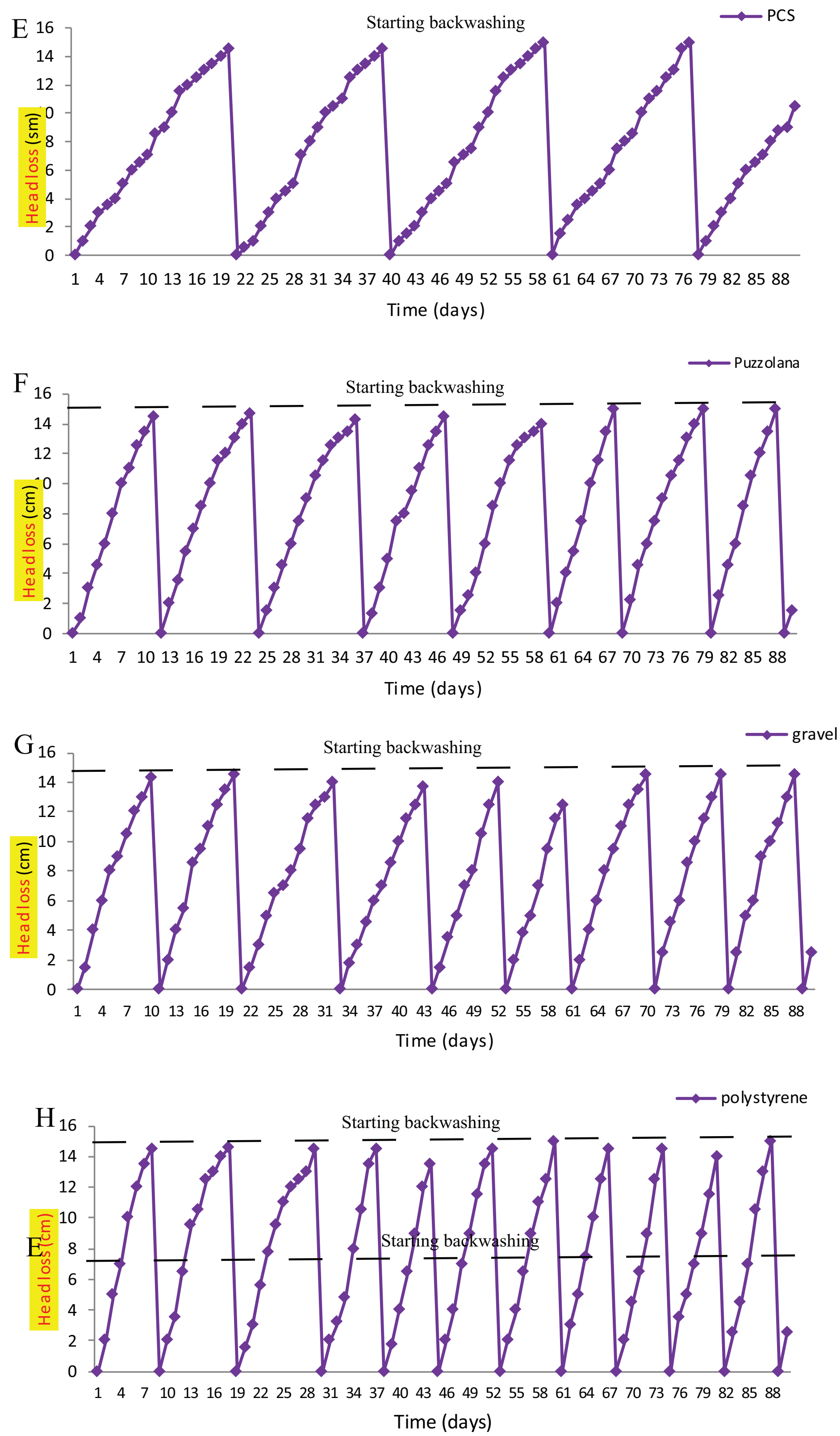


Fig. 4. Comparison of hydraulic head loss and back washing at the BAFs during the backwash intervals. E: PCS; F: Puzzolana; G: Gravel; H: Polystyrene.

Table. 3
Comparison of Medias' cost

| Media | Gravel | Puzzolana | Polystyrene | PCS |
|---|---|---|---|---|
| Media weight of BAFs | 106 | 65.7 | 47.45 | 53 |
| Price ($ per kg) | 0.2 | 0.41 | 1.3 | 0.56 |
| Total media cost ($) | 21.2 | 26.28 | 61.7 | 29.68 |

## 4. Conclusions

Results of this study showed that down flow BAF reactors with two layers; PCS media on the top and silica particles at the bottom, with the HRT of 59 to 118 min (stage one and two) can remove turbidity, $BOD_5$, TCOD, and SCOD to approximately 93, 55, 52, and 44%, respectively. So, PCS BAF reactor as an advanced municipal wastewater treatment improved the turbidity, $BOD_5$, TCOD, and SCOD of the effluent to 1.3 NTU, 9.5, 26, and 21 mg/L, respectively. Removal percentages of turbidity, $BOD_5$, TCOD, and SCOD by PCS BAF are approximately 8, 13, 15, and 10% more than Puzzolana BAF, about 8, 15, 16, and 10% more than gravel BAF, and finally about 11, 27, 30, and 23% more than polystyrene BAF, respectively. Further, applying PCS BAF improved the backwashing process to a great extent so that the time interval of each backwashing was more than 2–3 times of Puzzolana BAF, gravel BAF, and polystyrene BAF.

It can be concluded that using PCS as a novel filler in the down flow BAF type increases pollutant removal efficiency, while it reduces reactor size, sludge disposal, backwashing requirement, as well as cost.

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