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Bio-Sand filter to treat arsenic contaminated drinking water

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ABSTRACT

The global presence of arsenic (As) in drinking water has endangered the safety of human health. The present research investigated the removal of As in drinking water using bio-sand filtration (BSF). Various treatments i.e. T1 (Pinus bark), T2 (brick powder), and T3 (mixture of T1 and T2) were used to investigate the As removal from drinking water by batch mode column experiments at room temperature (15–20˚C) for 90 d. Batch experiments were conducted to check the As removal efficiency of Pinus bark and brick powder. Adsorption studies involved changing of the As and adsorbent concentrations. The BSF containing Pinus bark having depth of 5 cm showed the maximum As adsorption i.e. 95% over the time period of 80 d and adsorbed the maximum As concentration of 13.843 mg. The BSF may serve as good option for the treatment of potable water especially in the developing countries.

Keywords: Arsenic; Bio-Sand filter; Brick powder; Pinus bark; Reduction; Adsorbent; Treatment

1. Introduction

Arsenic (As) concentration in drinking water is serious threat to human health. There are many diseases linked with the As concentration above the permissible limits, i.e. reduced birth weight, oversensitivity, cardiovascular problems, damage to the nervous system, black-foot disease, inhibition of enzyme system, memory loss, paralysis, etc. As accumulates in the environment by various industrial, domestic, commercial and mineral sources [1].

The world's 33% population is effected from the water shortage [2]. A number of countries bring in more than half their food necessities as they do not have adequate water to produce more food [3]. If present trends of water utilization will not be changed then the quantity needed for a rapidly increasing world population will become twofold in the next 50 years [4,5].

Household level point of use (POU) As treatment systems is an important technology to provide relatively safe drinking water to rural populations in developing countries where centralized water supply system is not available and feasible [6,7]. POU

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treatment at the household level is easy to install and implement, affordable, improve water quality, easy maintenance and reduce health hazards [4]. Household level As treatment systems are usually based on ion exchange, adsorptive filtration, coagulation or combination of coagulation and adsorption treatment processes. All these technologies have some advantages and disadvantages [8]. The most common examples of household water treatment systems are chlorination, solar disinfection and UV irradiation [9]. But these treatment systems remained difficult to handle the problems of turbidity and microbial contamination [10].

Bio-Sand filter (BSF) is a technological advancement for the treatment of polluted water. Contaminants removed by BSF include organic matter, bacteria, viruses, protozoa, worms, and suspended particles [11]. BSF removes smell, disagreeable taste, 95.0–99.0% of organic contaminants, as well as microorganisms, worms, viruses, protozoa, and particles [12]. The use of Pinus bark in BSF has a great potential to develop cost effective As treatment for drinking water facility in rural and urban areas of developing countries including Pakistan. BSF system is the secure option for the health benefits that can be achieved [13]. BSF is new edition of the conventional slow sand filter. The BSF is small in size and modified for easy to use at households level [5]. The BSF has five separate zones: (1) inlet reservoir zone, (2) standing water zone, (3) biological zone, (4) nonbiological zone, and (5) gravel zone [14]. To treat many water sources like rainwater, groundwater, rivers, lakes or other surface water BSF filter can be used [10]. Contaminants removed by BSF include organic matter, bacteria, viruses, protozoa, worms, and particles [15].

Pinus bark is low cost and locally available material. The use of *Pinus radiata* sawdust for *Escherichia coli* removal was a useful way of reducing transfer of fecal microorganism from dairy farms to the wider environment [2]. Chemically modified *P. radiata* bark and tannins with an acidified formaldehyde solution were used for removing metal ions from aqueous solutions and copper mine acidic residual waters [16]. Abbottabad lies in semi temperate region and is naturally blessed with pine forests where key species is *Pinus roxburghii*. The use of Pinus bark in BSF is low cost and promising to develop a decentralized drinking water treatment facility. In the present study, the main focus was on the design modification for better and efficient treatment of As containing raw water by using low cost local materials i.e. Pinus bark and brick powder. The BSF in this research were the CAWST style BSF [5,15]. The focus of the design modification options was to remove the As from drinking water.

2. Materials and methods

2.1. BSF design and amendment

Treatment of As in drinking water by using BSF was carried out at COMSATS Institute of Information Technology Abbottabad, Pakistan. The treatment was done by analyzing pre and post filtration of synthetic raw water and other controlling parameters were kept constant under laboratory conditions for three months. For the treatment experiments major focus was made on the use of *P. roxburghii* (chir pine) bark as adsorbent material (biosorbent) to remove As from water. Along with this local low cost adsorbent i.e. brick powder was used to check the As treatment efficiency itself and in combination with Pinus bark. To compare and contrast the efficiency of Pinus bark and brick powder column filters were made according to the model designed by CAWST constructed by concrete according to and filled with gravel and fine sand and in them known layer on adsorbent materials in different depths were used [17,18]. For these experiments synthetic As containing raw water in known quantity was passed from each filter on daily basis [2].

2.2. BSF media preparation and construction

The filter media used in the present study was Pinus bark, brick powder, fine sand and gravel. The filter media were sieved and washed according to the standard procedure for BSF [2]. In three set of modified BSFs or treatments (T1, T2 and T3), the filter media were packed according to the order: 5 cm of under drain gravel (15 mm) at the bottom, 5 cm medium sized support gravel (6 mm), 45 cm of sand with effective size (D_{10}) of 0.19–0.22 mm, (D_{60}) of 0.66–0.90 mm and the uniformity coefficient (D_{60}/D_{10}) was 3.5–4.0 mm, as a control BSF and followed by 3 cm of top gravel layer (6–12 mm) for maintaining equal water dissipation [2,12,14].

Three BSFs or treatment system T1, T2 and T3 were made with a modification of different depths of coniferous Pinus bark biomass (CPBB), brick powder and mixture of these two medias as shown in Fig. 1(a)–(c), respectively. Different depths of filter media layers in other sets of treatments were prepared in the middleof the sand column of the BSFs. These treatments were maintained with control containing only fine sand (Fig. 1(d)). First set of BSFs consisted of two modified

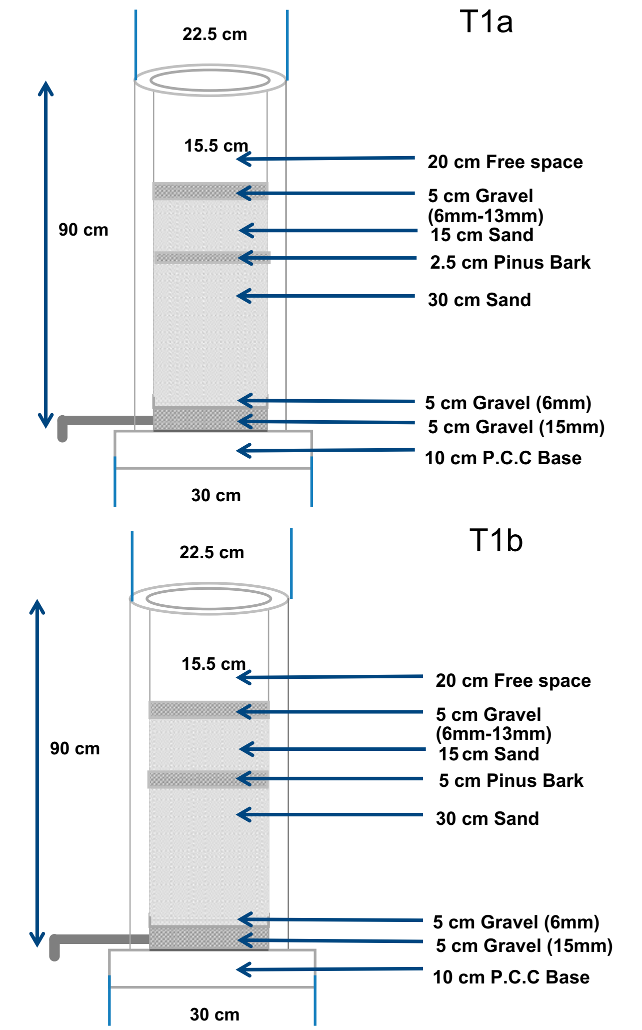

Fig. 1a. Modified BSF (T1a and T1b), containing 2.5 and 5 cm CPBB as filter media with sand column.

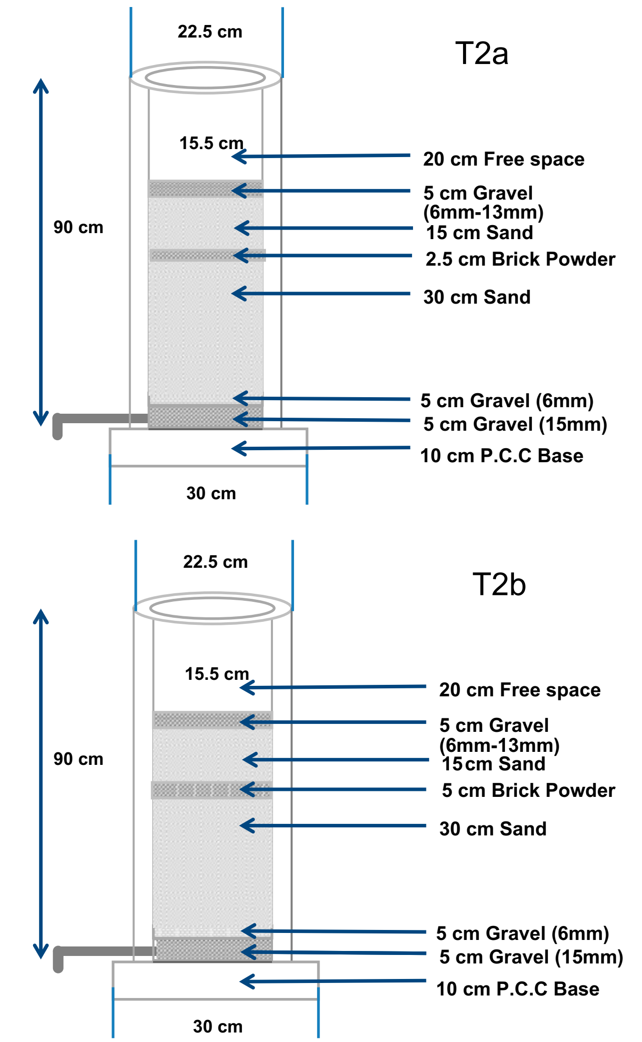

Fig. 1b. Modified BSF (T2a and T2b), containing 2.5 and 5 cm brick powder as filter media with sand column.

BSFs, T1 (T1a and T1b), containing 2.5 and 5 cm layers of Pinus bark in first and second BSF respectively. The second set of BSFs consist of two modified BSFs, T2 (T2a and T2b), containing 2.5 and 5 cm layers of brick powder. The third set of BSFs consist of two modified BSFs, T3 (T3a and T3b), containing 2.5 and 5 cm layers of mixture of Pinus and brick powder.

The gravel and sand were properly washed to remove the clay particles, organic contents and other materials according to the standard procedures [2]. CPBB or *P. roxburghii* Bark was collected from nearby pine forest then it was sun dried and cut in to the desired sizes. The Pinus bark was kept for 24 h in to small basin containing hot water for the intention to remove bark dark brown color to avoid any risk of color leaching in the treated water.

2.3. Preparation of synthetic arsenic contaminated water

Arsenic containing raw water with desired concentrations in the range from 50, 100, 150, 200, 250, 300 and 350 μg L^{-1} was prepared from arsenic stock solution that was prepared by using Arsenic trioxide (As_2O_3). Fifteen liters of the contaminated water was passed through each BSF or treatment that a normal households use on daily bases [6].

2.4. Treatment of arsenic contaminated water

Fifteen liters of contaminated water was passed through each BSF on daily basis and the initial flow rate of the poured water samples was recorded 0.45 L min^{-1} in the control (1). Water quality after

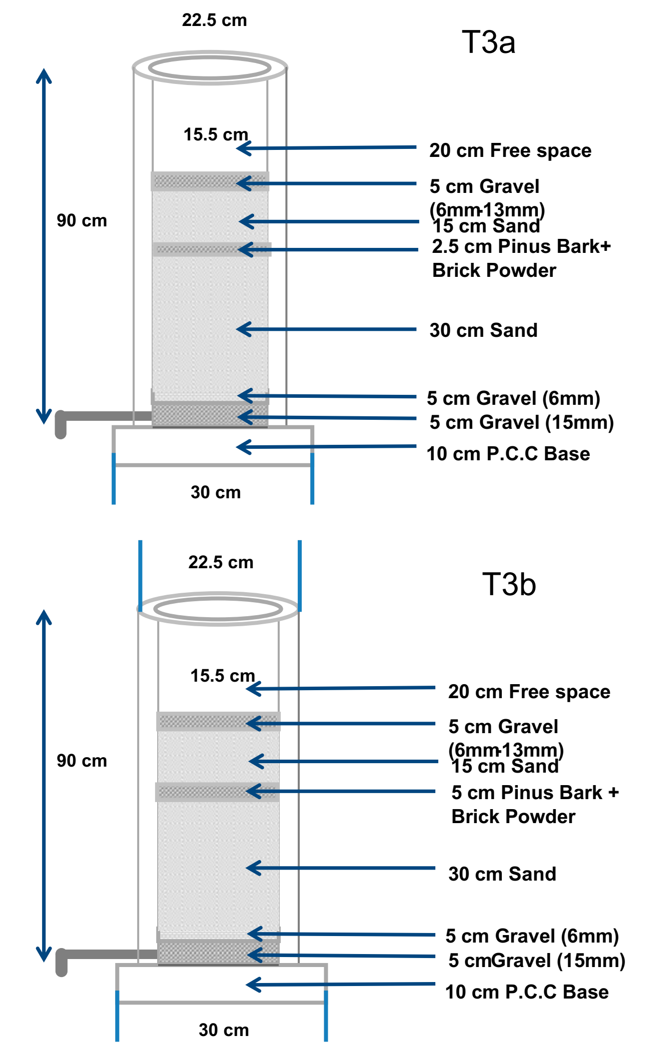

Fig. 1c. Modified BSF (T3a and T3B), containing 2.5 and 5 cm brick powder plus CPBB mixture as filter media with sand column.

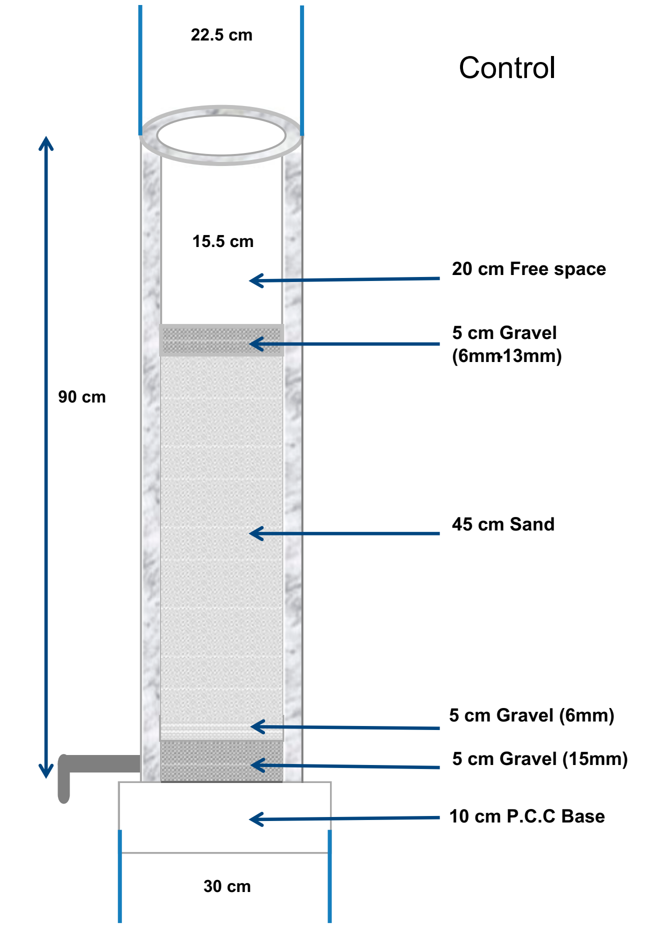

Fig. 1d. Control sand filter.

the treatment of arsenic on each run from the six treatment systems T1a, T1b, T2a, T2b, T3a and T3b was tested [18]. The treatment was continued for three months and residual concentration of arsenic in the effluent from all treatment systems or BSFs was experimentally tested on different time intervals 0, 5, 10 … 90 d. The treatment efficiency of all the BSFs was compared with control BSF [10].

2.5. Analytical methods

Arsenic in the raw and treated samples was measured by spectrophotometer at 535 nm [19]. For hydraulic flow measurement, the water level on the top of BSFs' free space was tried to maintain each time for flow measurement. In each gauging time, the mean

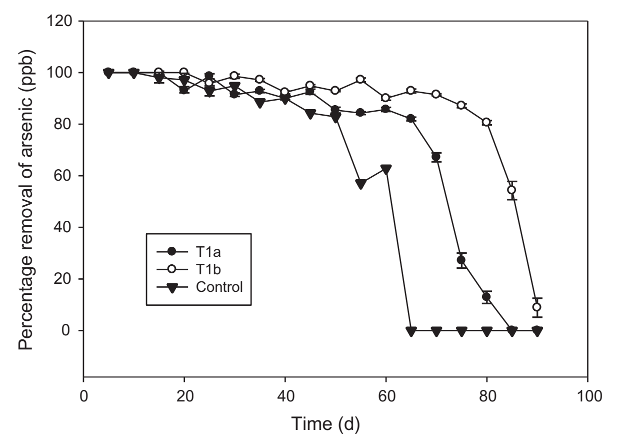

Fig. 2. Percentage removal of arsenic by the first two treatments over time period of 90 d.

water flow was measured by passing 20 L of water sample. Hydraulic flow was measured in L min^{-1}. The pH values of pre and post water samples were

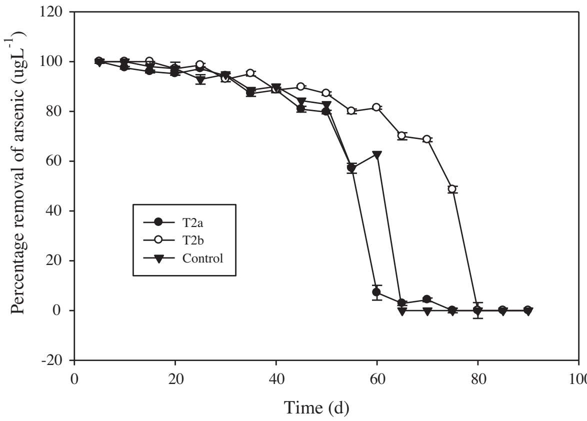

Fig. 3. Percentage As removal by the BSF containing brick powder.

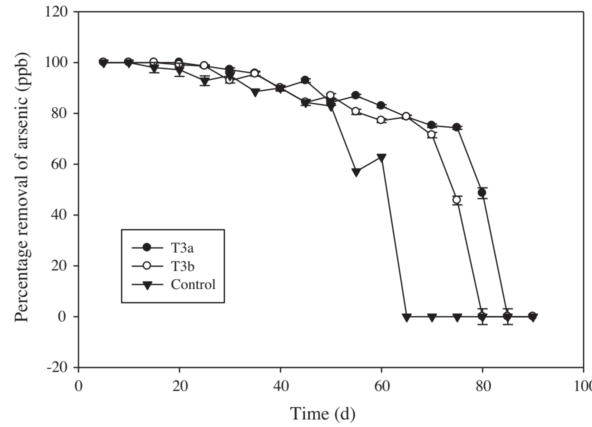

Fig. 4. As removal in BSF containing mixture of adsorbents.

determined using calibrated pH meter developed by JENWAY (3505) [5]. For samples both pre and post filtration from the BSFs Electric conductivity (microsimens per centimeter, $\mu s\, cm^{-1}$) was measured with Electric Conductivity meter or simply EC meter, developed by Hanna Instruments HI 98129 [2].

3. Results and discussion

3.1. As removal in BSF containing Pinus bark

During the 90 d time period laboratory scale controlled experiments were conducted at temperature range of 5–15˚C. Sand bed acts like mechanical device to strain out the particles in turbid water. Filter media materials used in this study i.e. CPBB, brick powder and their combination were used as natural and indigenous low cost materials to act as the adsorbent to remove arsenic from synthetic raw water. The sand column with an effective sand size of 0.5–1.0 mm would have a pore space of 0.1 mm which is efficient to remove the particle size less than 0.01 mm and the bacteria sizes less than 0.001 mm [2,20,21].

Table 1
Maximum adsorption capacity of all modified BSF treatment systems

Treatment systems	Total As given ($\mu g\, L^{-1}$)	Residual concentration of As ($\mu g\, L^{-1}$)	Total As adsorbed ($\mu g\, L^{-1}$)
T1a	15,250	3,676	11,574
T1b	15,250	1,407	13,843
T2a	15,250	6,930	8,320
T2b	15,250	3,605	11,645
T3a	15,250	2,789	12,461
T3b	15,250	3,728	11,522
Control	14,600	12,991	1,606

In treatment system 1 it is evident from Fig. 2 that T1b i.e. containing 2.5 cm Pinus bark has shown maximum arsenic removal over the time period of 80 d having treatment efficiency ranging between 80 and 90%. But after 80 d treatment efficiency decreased gradually and fall within 20–40%. It was observed that T1a and T1b removed efficiently arsenic in the range of 250–350 $\mu g\, L^{-1}$. The treatment efficiency was in order of T1b > T1a > control. Starting from day 1–45d there is little difference and fluctuation in the percentage removal efficiency. But suddenly arsenic removal in control decreases after 30d [18,22]. T1b shows the maximum As removal over time period of 85 d and treated 350 $\mu g\, L^{-1}$ of arsenic which is more that permissible value of arsenic i.e. 50 $\mu g\, L^{-1}$ according to WHO guidelines [23].

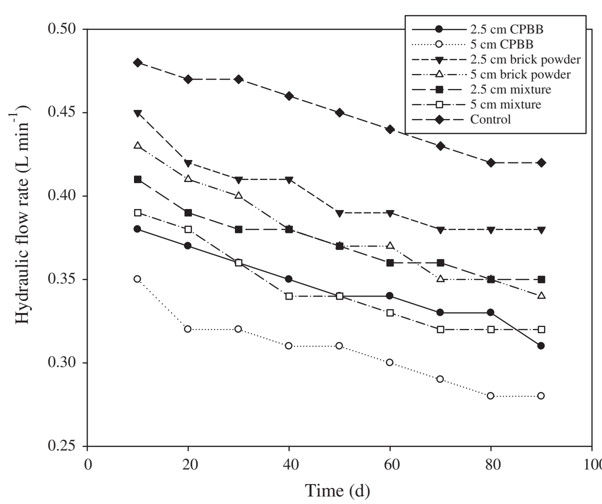

Fig. 5. Hydraulic flow rates of the six treatments during the time period of 90 d.

3.2. As removal in BSF containing brick powder

The second treatment system T2a and T2b containing 2.5 and 5 cm brick powder, respectively, as treatment medium was analyzed to check the As removal efficiency. It is evident from the Fig. 3 that T2b has the similar efficiency as compared with control i.e. both have removed arsenic between 75 and 100% up to 50 d with little fluctuations.

The sequences of the percentage removal in each treatment were recorded as:

T2b > T2a > control.

After 50 d T2b showed constant removal of 60–80% ranging from 60 to 75 d. All the systems containing brick powder show constant removal up to 200 μg L^{-1} but as dose is increased up to 350 μg L^{-1} As, a sudden fall in removal efficiency occur. It is evident from the Table 1 that T2a and T2b have effectively removed arsenic up to 70 and 75 d, respectively. The removal efficiency decreased over time period as the BSF become saturated with arsenic and other particulates.

3.3. As removal in BSF containing mixture of Pinus bark and brick powder

In third treatment system i.e. T3a and T3b containing 2.5 and 5 cm mixture (1:1) of Pinus bark and brick powder arsenic was treated in drinking water on daily basis. It is evident from the Fig. 4 that T3a and T3b have significantly removed arsenic from 80 to 100% up to 80 d. The treatment is constant up to 250 μg L^{-1}As dose but as long as concentration is increased up to 350 μg L^{-1}As the treatment systems show sudden fall from day 75 to onward. It is evident from the Table 1 that T3a and T3b treated arsenic up to 85 and 80 d respectively. The removal efficiency was more than 90%. The treatment efficiency was I order of T3b > T3a > control.

The sequence of the percentage removal in each treatment was recorded as:

T3a > T3b > control.

3.4. Dynamics in hydraulic flow rates during the BSF working

The overall hydraulic flow rates of all the six modified BSFs or treatments (T1a, T1b, T2a, T2b, T3a and T3b) had shown decreasing hydraulic flow rate over time, when 15 L were daily poured to each modified BSFs (Fig. 5). The preference of a daily 15 L charged in to each BSF was considered the optimum BSF reservoir and the lower range of daily family requirements in developing countries [5]. Hence, after each treatment, the reduction in flow rate resulted in the head loss development in the BSFs, which would cause the sand bed acting like mechanical device to strain out the particles in turbid water. For example, the sand column with an effective sand size of 0.5–1.0 mm would have a pore space of 0.1 mm which is efficient to remove the particle size less than 0.01 mm and the bacteria sizes less than 0.001 mm [23,24].

The sequences of the flow rate in each treatment were recorded as:

Control > T2a > T3a > T2b > T3b > T1a > T1b.

3.5. Changes in the electrical conductivity in BSF

Electrical conductivity (EC, μc/cm) was calculated in the effluent from each BSF on every 5th day to check the water quality. EC for all the treatments was calculated and it is evident from Fig. 6 that for all the

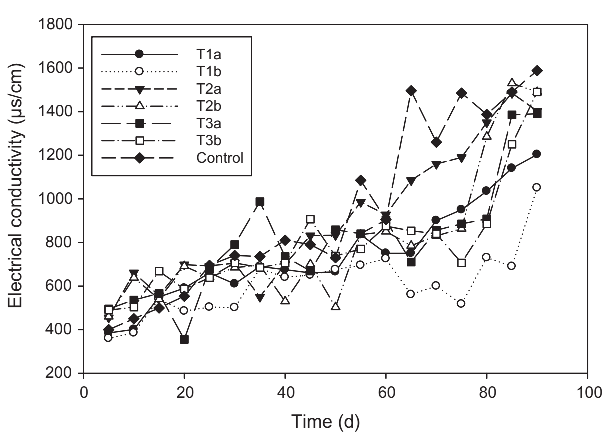

Fig. 6. EC of the six treatments during the time period of 90 d.

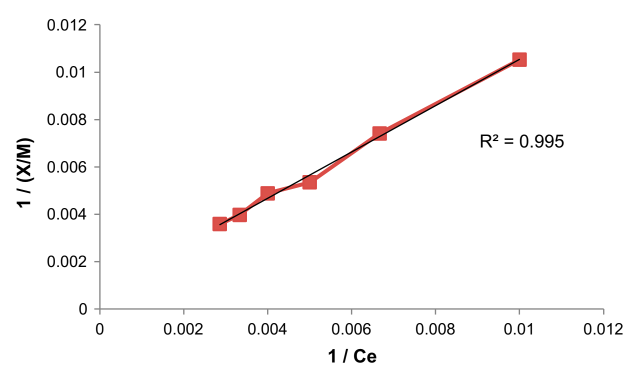

Fig. 7. Langmuir adsorption isotherms (Pinus bark 5 cm).

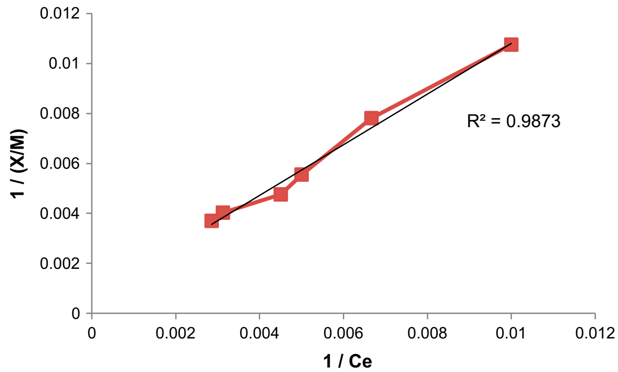

Fig. 8. Langmuir adsorption isotherms (Pinus bark 2.5 cm).

Table 2
Langmuir adsorption isotherm model constants and correlation coefficients

Langmuir adsorption isotherm			
Depth of layers	a (mg/g) or K_L	b or $q_{max.}$ (mg/g)	R^2
Pinus bark 5 cm	35	1.75	0.995
Pinus bark 2.5 cm	36	1.70	0.987

treatments EC ranged 400–1,000 µS/cm during 50 d. But after 50 d a significant fluctuation is seen in all the treatments. The control showed maximum EC between 60 and 90 d ranging from 900 to 1,500 µS/cm. All the other treatments showed overlapping behavior over the time period from all the time period. The minimum EC was observed for T1b i.e. BSF containing 5 cm Pinus bark and showed EC in the range of 400–900 µS/cm. Generally, all the treatments have shown increasing behavior in their EC. The overall effects of the modified BSFs or treatments' filtrate showed minor decrease in the values of EC over the time period between 0 and 50d which was due to the result in the adsorption of some of the charged materials present in the sand column. After the time period of 50d, it was observed that EC started increasing with fluctuations due to the reason of presences of charged ions in the effluent.

The sequences of the EC (µs/cm) in each treatment were recorded as:

Control > T2a > T3a > T2b > T3b > T1a > T1b

The sequences of the maximum adsorption of arsenic (µg L^{-1}) in each treatment system (BSF) were recorded as:

13,843 (T1b) > 12,461 (T3a) > 11,574 (T1a) > 11,645 (T2b) > 11,522 (T3b) > 8,320 (T2a) > 1,606 (control)

The current investigation on BSF using low cost adsorbents like Pinus bark and brick powder can be quite useful in developing countries which lack sophisticated equipments to deal with treatment of metal pollution of drinking water. In fact modified BSF containing Pinus bark was found quite useful in turbidity and coliform removal [2,18]. Moreover, Pinus bark has shown a tremendous potential in As removal in batch experiments [25]. The current study will open new avenues in BSF modification and pollution abatement.

3.6. Kinetics of arsenic adsorption

With respect to effective and long term arsenic removal efficiency, BSF having 5 and 2.5 cm layer of Pinus bark were selected for kinetic studies. The data were subjected to analysis using Langmuir equation and was presented graphically in Figs. 7 and 8 which confirmed the adsorption of arsenic on Pinus biomass. These linear equation based graphs confirm the adsorption mechanism.

From the Langmuir adsorption isotherm (Fig. 7), formation of unimolecular layer of adsorbate on adsorbent was verified. BSF with 5 cm layer of Pinus bark has shown more adsorption efficiency as compared with that of 2.5 cm layer of same adsorbent. The regression value in Fig. 7 also confirms the more linearity to that to second one i.e. Fig. 8.

The present study showed arsenic uptake of 99% onto 5 cm layer and 98% on 2.5 cm layer with initial adsorbate concentration of 1 mg L^{-1} using adsorbent dosages of 700 mg L^{-1}. The variability was due to mass difference of Pinus bark. Thicker layer of biomass (5 cm) offers more surface area for arsenic to be adsorbed.

The experimental data fit well with Langmuir equation. For this case, the plot of $1/(X/M)$ vs. $1/C_e$ was employed to generate the intercept value of K_f and the slope of b or q_{max}. The intercept K_L value is an indication of the adsorption capacity of the adsorbent; the slope b indicates the effect of concentration on the adsorption capacity and represents adsorption intensity. As seen from Table 2, b value was found high enough for separation. The Langmuir constants (a and b) values fit to the data. Beside this, the values of the constants explain easy separation of arsenic from the raw water and show good adsorption on Pinus bark.

4. Conclusions

The present study concluded that modified BSF with additional adsorbent of Pinus was a very good decentralized treatment option for drinking water in developing countries like Pakistan. The BSF with 5 cm depth of CPBB in treatment T1b showed >95% arsenic removal efficiencies during the assessment period as compared to the other treatments. Modified BSF containing 5 cm Pinus bark media depth has shown efficient treatment efficiency over the time period of 80 d and adsorbed the maximum arsenic concentration of 13,843 μg.

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