Breakthrough Column Studies for Iron(II) Removal from Water by Wooden Charcoal and Sand: A low cost approach

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ABSTRACT: Ground water is the major source of drinking water in rural and semi-urban areas of Assam. It contains an excessive amount of iron (1 to 10 mg/L). People living in rural and semi-urban areas of Assam uses indigenous household iron filter units – developed using community prepared wooden charcoal (CPWC) and river sand (RS) as filter media. CPWC and RS processed and respectively termed as processed wooden charcoal (PWC) and processed sand (PS). The present work evaluates adsorptive capacity of PWC and PS for dissolved iron removal through continuous mode column studies. The experiments were carried out using synthetic water containing Fe(II) at a fixed pH of 5.5 and zero dissolved oxygen levels. The adsorption breakthrough curves obtained at different bed depths indicate increase of breakthrough time with increase in bed depths, while the uptake of Fe(II) ions onto the adsorbent decreases when the linear flow rate through the bed increases. A rise in the inlet Fe(II) concentration reduces the volume treated before the packed bed gets saturated. PWC shows higher affinity for Fe(II) as compared to PS under the experimental conditions of this study. On comparison of up-scaled columns and indigenous unit models of same bed heights and flow rate, the up-scaled columns perform better than indigenous unit models and yield higher breakthrough throughputs. Among up-scaled columns, the column with PWC at top and PS at bottom yielded higher breakthrough throughput for initial Fe(II) concentration of 5 mg/L. The up-scaled columns perform reasonably well with actual groundwater containing various other ionic species and indicate its ability to remove fluoride, turbidity, sulfate and alkalinity at breakthrough point of Fe(II).

Key words: Adsorption, Iron, Wooden charcoal, Sand

INTRODUCTION

Removal of various metals from water has been subjected to severe studies in the recent years. However, most of such studies fail to provide a cost effective method (Igwe *et al.,* 2008; Gharbani, 2008; Goyal *et al.,* 2008; Shah *et al.,* 2009; Zvinowanda *et al.,* 2009; Labidi, 2008; Lori et al., 2008; Murugesan *et al.,* 2008; Nabi Bidhendi *et al.,* 2007; Rahmani *et al.,* 2009; Sahmoune *et al.,* 2009; Salim and Munekage, 2009; Shetty and Rajkumar, 2009; Singanan *et al.,* 2008). Iron is an essential mineral for human. However, its presence in groundwater – major source of potable water – above a certain level make the water unusable mainly for aesthetic considerations. Therefore, World Health Organization has set a guideline value of 0.3 mg/L of iron in drinking water (WHO, 1993) and many of the countries have adopted this value in their national drinking water standards including India. Aeration and

separation is the most widely used method for removal of iron from groundwater in public water supply systems, which is however, not so popular amongst rural and semi-urban communities lacking piped water supply. Other methods available for iron removal from groundwater are ion-exchange (Vaaramaa and Lehto, 2003), oxidation with oxidizing agents such as chlorine and potassium permanganate (Ellis *et al.,* 2000; Varner *et al.,* 1996), adsorption on activated carbon and other adsorbents (Munter *et al.,* 2005; Berbenni *et al.,* 2000; Ewa *et al.,* 2007; Oztas *et al.,* 2008; Prasenjit *et al.,* 2007) and treatment with limestone (Aziz *et al.,* 2004). Iron removal from groundwater has been a subject of intensive research for the last couple of decades in developing countries like Sri Lanka, Ghana, Burkina Faso, Argentina, South Africa, Uganda including India (Ahamad, 2005; Andersson and Johansson, 2002; Chibi, 2002). It has yielded many different designs and

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configurations of iron removal units to be used at community levels. But surprisingly none of these methods, design and configurations of iron removal units so developed has found its place in the rural and semi-urban areas either at community levels or at an individual household level probably due to high capital costs and complicated operation and maintenance requirements of these methods and units. Therefore, efforts have to be directed to look for such methods/ techniques for iron removal from the groundwater which is acceptable and easily adaptable to communities – especially for rural and semi-urban area lacking piped water supply – so as to ensure acceptable quality potable water on a sustainable basis at an affordable cost.

One of the potential strategies is to look for what is being practiced by the communities of rural and semi-urban areas to manage the high levels of iron in their groundwater. A field survey was carried out in Assam – a northeastern hilly province (area » 78438 km², population » 27 million) of India, where the groundwater contains 1-10 mg/L or more of iron (Das *et al.,* 2003; Mahanta *et al.,* 2004; Sharma *et al.,* 2005; MOWR, 2004). The rural and semi-urban population of Assam, based on their experiences of past few generations, uses indigenous household iron filter units which are fabricated using local materials such as wooden charcoal, river sand and gravel (Fig. 1). The communities using these filters believes that wooden charcoal and river sand (two of the common media used) helps in reducing the concentration of the iron from the groundwater. The wooden charcoal used in these units is prepared indigenously at community levels from woods specially procured from hilltops (not from plain lands) located in and around the communities. Indigenous household iron filter units are in use for generations, but very limited scientific studies have been carried out to understand the role of the media – the wooden charcoal and sand – used in the filter units for the removal of dissolved iron from the groundwater. Even efforts have not been made to improve the performance of these filters. Therefore, there is an obvious need to assess community prepared

wooden charcoal (CPWC) and river sand (RS) scientifically for its potential to remove dissolved iron. At the same time, it is important to preserve the overall configuration of these units as developed over past generations by the communities to ensure its adaptability even after improvement. The results of such studies is expected to enrich the-state-of-the-art knowledge of low cost treatment technology for producing potable water as well as ensuring sustainable availability of safe and hygienic drinking water at individual household levels to rural and semi-urban communities all over the globe. As a first step in this direction, the aim of the present work is to assess the Fe(II) uptake capacity of the wooden charcoal and sand through continuous mode column studies. The emphasis, therefore, is to find out the influences of bed depth, linear flow rate and concentrations of feed metal ion [i.e., Fe(II)] on the performance of Fe(II) adsorption onto adsorbent media (PWC and PS) immobilized in packed-bed columns.

MATERIALS & METHODS

The community prepared wooden charcoal (CPWC) having individual pieces of 2.5 cm × 1.5 cm × 1.5 cm to 4 cm × 2.5 cm × 1.5 cm in size range (Figure 2) was procured from Amingaon village situated at a distance of 1 km from IIT Guwahati campus on the north bank of river Brahmaputra. The procured CPWC was further processed into smaller sizes, washed with distilled water and dried at 105 °C in a drying hot air oven. The dried CPWC was sieved as per IS 2720 (1975) and particles passing through 450 μm sieve openings but retaining over 300 μm sieve openings were selected for the study which were termed as processed wooden charcoal (PWC). River sand (RS) – a local construction material was also procured from the Amingaon village market. The sand is mined from the river-beds of Kulsi and Digharu – meeting river Brahmaputra upstream approximately 50 and 35 km respectively from IIT Guwahati campus. The collected RS was then washed to remove foreign materials like floating debris, dirt, clay etc. and dried at 105 °C in the drying hot air oven. Sieve analysis of RS was carried out as per IS 2720

Fig. 1. Typical indigenous household iron filter units used in rural and semi-urban Assam.

Table 1. Properties of processed wooden charcoal (PWC) and processed sand (PS)

Properties	PWC	PS
Particle size range	425 µm – 300 µm	300 µm – 150 µm
Bulk density	290 kg/m^3	1523 kg/m^3
Moisture content	10%	0.5%
Ash/Inert content	8%	94%
BET surface area	30.083 m^2/g	0.283 m^2/g

(1975) and sand particles passing through 300 µm sieve openings but retaining over 150 µm sieve openings were selected for the study which were termed as processed sand (PS). The characteristics of PWC and PS are presented in Table 1. The scanning electron microscopy of PWC indicated presence of numerous pores while that of PS indicated absence of pores (Ahamad and Jawed, 2008).

The iron in the dissolved form [i.e., Fe(II)] is expected to change to insoluble form [i.e., Fe(III)] with change in pH. Experiments were designed to assess solubility of Fe(II) in pH range of 2 to 12. Analytical grade ferrous sulfate (FeSO$_4$.7H$_2$O) was used to prepare a Fe(II) stock solution of 200 mg/mL. The required volume of stock solution was taken in 100 mL specimen tube, added with appropriate amounts of acid (0.2N HNO$_3$) or lime solution for adjusting desired pH (Rao and Rekha, 2004) with a digital pH meter. The final volume was made up to 100 mL with distilled water to give a final Fe(II) concentration of 5 mg/L. The contents in specimen tubes were mixed thoroughly with manual shaking in an end-over-end type motion (»40-50 rpm) for 5-8 min. and then allowed to stand for 20 min. at room temperature (24±1 ºC). Fe(II) remaining in the solution was estimated as per Standard Methods (APHA, 1998) using phenanthroline method. The experiments were conducted in duplicate.

The solubility of Fe(II) in the presence of DO was assessed in a separate experiment at room temperature (24±1 ºC). 10–12 L of distilled water was taken in a plastic bucket and pH was initially adjusted to 5.5 with 0.2N HNO$_3$. Initial DO level was estimated as per Standard Methods (APHA, 1998) and then brought down to zero by adding slightly more than the stoichiometric requirement of sodium sulfite (Na$_2$SO$_3$). The required amount of stock Fe(II) solution was added and the liquid volume was made up to 15 L to achieve an initial Fe(II) concentration of 5 mg/L. The aeration was carried out with an air pump (Model: APM 414, M/S Vyubodhan Upkaran Pvt Ltd, New Delhi, India). Variation in pH was observed with increase in DO level, which was controlled with a buffer prepared using acetic acid and sodium acetate (1 mL of 0.2M acetic acid and 9 mL of 0.2M sodium acetate mixed to give 10

Fig. 2. Community prepared wooden charcoal

mL of buffer solution) (Jeffery, 1996). Samples were drawn at regular intervals for estimation of Fe(II) and DO. The experiment was conducted in duplicate.

The experimental arrangement was prepared using 10 mm internal diameter glass columns as shown in Figure 3. The adsorbing media – PWC or PS was packed up to desired bed depths in the column and was kept submerged throughout the runs to avoid air entrapment in the beds. Columns were mounted vertically and operated continuously in down flow mode using a multi-channel peristaltic pump (Model: PA-SF, M/S IKA-WERKE, Germany) at two different flow rates of 1.5 and 2.5 mL/min. The column studies were carried out at the room temperature (24±1 ºC) with Fe(II) concentration of 5 mg/L at a fixed pH of 5.5 and zero dissolved oxygen (DO). Samples from the column were collected at regular intervals till the bed exhausted or yielded effluent with 90% of initial Fe(II) concentration. All column studies were carried out in duplicate.

Efforts were made to compare the performance of up-scaled columns fabricated using PWC and PS with the models of indigenous units using CPWC and RS. Since the size of CPWC was large, PVC tubes of 10 cm internal diameter were used to fabricate up-scaled columns as well as models of indigenous units. Two combinations of layered bed were selected for the up-scaled columns: (i) 3.7 cm bed depth of PWC on top and 7.9 cm bed

depth of PS at bottom, and (ii) 7.9 cm bed depth of PS on top and 3.7 cm bed depth of PWC at bottom. Similarly, two combinations of layered bed were selected for the models of indigenous units: (i) 3.7 cm bed depth of CPWC on top and 7.9 cm bed depth of RS at bottom, and (ii) 7.9 cm bed depth of RS on top and 3.7 cm bed depth of CPWC at bottom. It gave a total bed depth of 11.6 cm for up-scaled columns and models of indigenous units. The selection of bed depths were dictated by the overall height of the PVC tube used for fabrication which was restricted to 30 cm in this study. The up-scaled columns and models of indigenous units were operated in parallel at a flow rate of 11.53 mL/min (16.6 L/d) in down flow mode with initial Fe(II) concentration of 5 mg/L, pH adjusted to 5.5 and DO level made to zero. Also up scaled columns were operated at a flow rate of 11.53 mL/min with actual groundwater samples using selected two different bed arrangements.

Mass balance of the packed-bed reactor is carried out. The variation in mass balance of the packed-bed reactor during the reaction could be illustrated by Figure 4 where u is the linear flow rate, which is the average rate of the liquid flow when the column is empty. The equation of mass balance material is: input flow = output flow + flow inside pores volume + matter adsorbed onto adsorbent material. For this system, the balance could be expressed according to the following equation

$$Q_V C_o = Q_V C + V_P \frac{dC}{dt} + m \frac{dq}{dt} \qquad (1)$$

where Q_v is the volumetric flow of the solution in the column (L/min), Q_o and C, respectively, the inlet and outlet solute concentrations (mg/L), $Q_v C_o$ the inlet flow of solute in the column (mg/min), $Q_v C$ the outlet flow of solute leaving the column (mg/min), V_p the pore volume (l) ($V_P = \frac{1}{1-\varepsilon} V_a$ where V_a is the bulk volume and ε the porosity), $V_P \frac{dC}{dt}$ the flow rate through the column bed depth (mg/min) and $m \frac{dq}{dt}$ the amount of solute adsorbed onto column media (mg/min) where m is the mass of adsorbent material and $\frac{dq}{dt}$ the adsorption rate. According to Eq. (1), the determining factors of the balance for a given bed depth of the column are the linear flow rate ($u = \frac{Q_V}{S_c}$, where S_c is the column section, m²), the initial solute concentration, the adsorption potential and the pore volume even if previous studies (Costodes et al., 2005) showed that
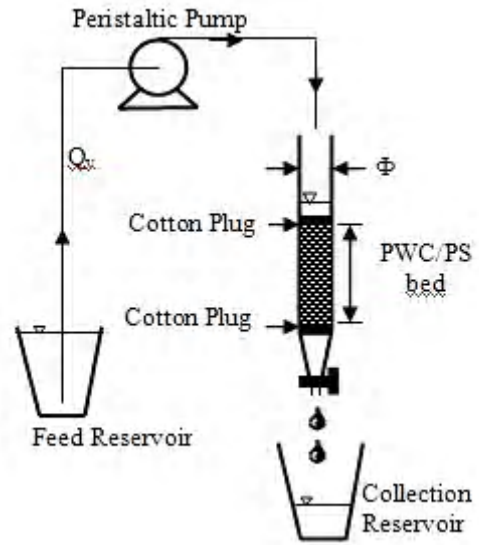

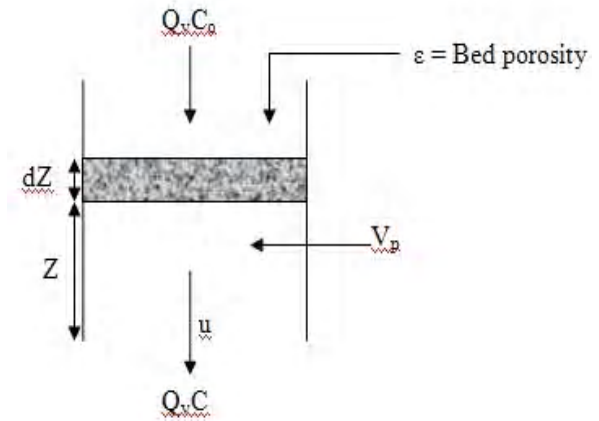**Fig. 3. Experimental columns with single medium (PWC and PS)**

Fig. 4. Schema of packed-bed reactor

the latter parameter may be neglected. Therefore, in order to optimize the adsorption process in a packed-bed column, it is necessary to examine these parameters and to estimate their influence.

A typical breakthrough profile of a column study is presented in Fig. 5. The fluid containing the metal ion flowing into the column gets through a virgin bed. The top of the adsorbent in contact with the fluid quickly adsorbs the pollutant during the first contact. Thus the fluid leaving the column is practically free of metallic ions (points P1, P2 and P3 in Fig. 5). As the volume of polluted fluid getting through the bed column increases, an adsorption zone of mass transfer (MTZ) gets defined. In this MTZ, adsorption is complete and the concentration of pollutant in the bed column varies from 100% of C_o (corresponding to total
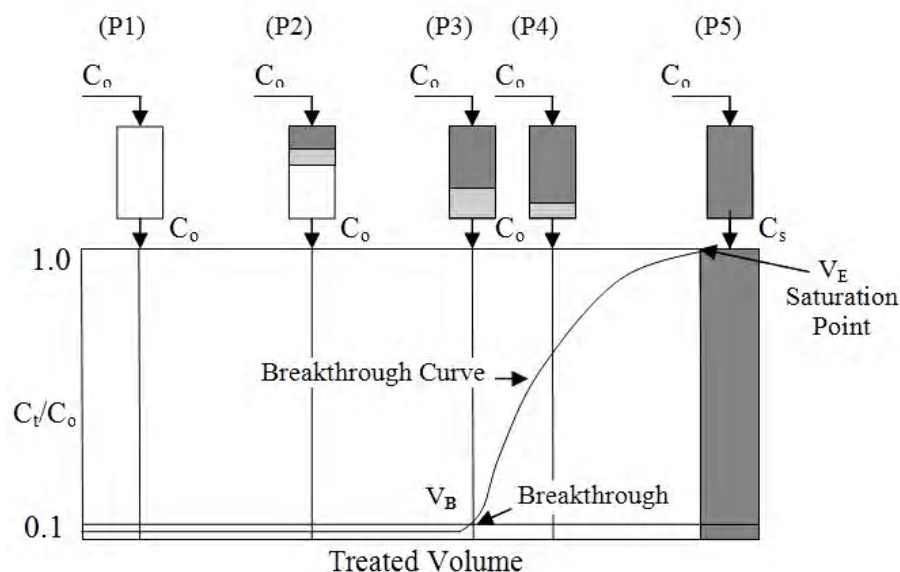
Fig. 5. Typical breakthrough profile from a column study (Source: Tchobanoglous et al., 2003).

saturation) to approximately 0% of C_o (corresponding to the virgin adsorbent). Additionally, the height of mass transfer zones (H_{MTZ}) was estimated using the relation (Tchobanologus *et al.*, 2003):

$$H_{MTZ} = Z \left(\frac{V_E - V_B}{V_E - 0.5(V_E - V_B)} \right) \quad (2)$$

where Z = height of the adsorption column, V_B = throughput volume to breakthrough and V_E = throughput volume to exhaustion. This adsorption zone then moves downwards through the bed column in relation to time until the breakthrough occurs. When this zone reaches the bottom of the bed the pollutant dissolved in the solution could not be adsorbed any longer. This moment is called "breakpoint". The plot obtained after this point gives the concentration history and is called breakthrough profile or breakthrough curve. From a practical point of view, this point allows determining the solute concentration in the effluent and the volume treated (V_B). For most adsorbent – pollutant systems, the breakthrough curve is obtained after an effluent concentration of 50% has been reached. To facilitate the calculations of the bed adsorption capacity, the breakthrough curve is often fixed at 50% (P4, Fig. 5), sometimes at 10% (P3, Figure 5) of the inlet concentration according to the target quality of the final effluent (Tchobanologus *et al.*, 2003). When the mass transfer zone leaves the bed column (P5, Fig. 5), the bed is completely saturated, adsorption in the bed does not occur and the effluent which leaves the column has the same concentration as the one that enters. The quantity of adsorbed pollutant at

breakpoint (q_B in mg/g) could be estimated for a single column from the following relation suggested by Tchobanologus et al. (2003) with known breakthrough time (t_B) using:

$$q_B = \left(\frac{x}{m} \right)_B = \frac{x_B}{m_{adsorbent}} = Q_v \left(C_o - \frac{C_B}{2} \right) \frac{t_B}{m_{adsorbent}} \quad (3)$$

where $\left(\dfrac{x}{m} \right)_B$ = breakthrough adsorption capacity (mg/g), x_B = mass of adsorbate adsorbed in the column at breakthrough (mg), $m_{adsorbent}$ = mass of adsorbent in the column (g), Q_v = flow rate (mL/min), C_o = influent adsorbate concentration (mg/L), C_B = breakthrough adsorbate concentration (mg/L) and t_B = time to breakthrough (min). The important assumptions associated with the development of Eq. (3) were: C_o taken as constant and that the effluent concentration increased linearly with time from 0 to C_B. The term

$\left(C_o - \dfrac{C_B}{2} \right)$ represented the average concentration

of the adsorbate adsorbed up to the breakthrough point.

RESULTS & DISCUSSION

The variation in Fe(II) remaining in solution with pH and DO levels is presented in Figure 6(a) and 6(b) respectively. Almost all the iron came out of the solution phase at pH > 7, whereas it remained in soluble form at
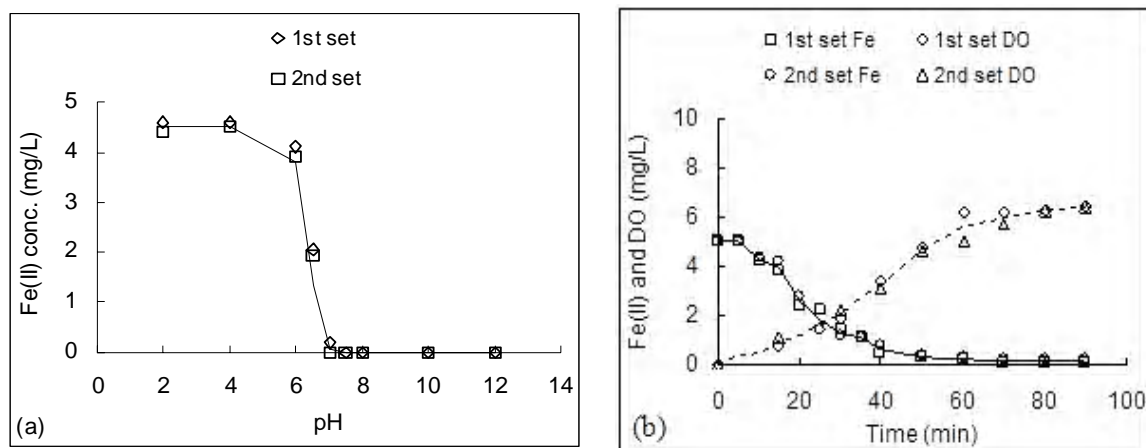
Fig. 6. Variation in Fe(II) solubility with (a) pH and (b) DO level at fixed pH 5.5.
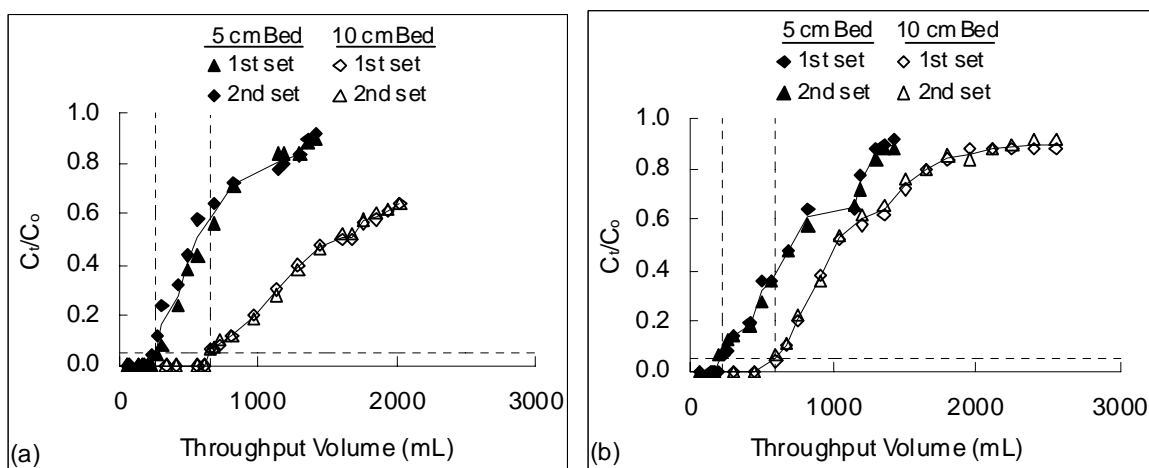**[Initial Fe(II) conc. = 5 mg/L, Temp = 29±1 ºC]**

Fig. 7. Effect of bed depth on the breakthrough curves for Fe(II) adsorption through columns of (a) PWC alone
and (b) PS alone [Q_v = 1.5 mL/min; C_o = 5 mg/L]

pH < 6. DO levels seemed to have marked effect on the solubility of Fe(II). This effect was visible at DO levels > 1 mg/L. When the DO level reached a steady value of 6 mg/L, the Fe(II) decreased to the lowest level. Therefore, further experiments were carried out at a fixed pH of 5.5 with zero DO levels to ensure availability of iron in Fe(II) form.

The results of Fe(II) adsorption onto PWC and PS are presented in the form of breakthrough curves by plotting the concentration ratio of C_t/C_o versus throughput volume. The breakthrough curves obtained for Fe(II) adsorption for two different bed depth of PWC and PS – 5 and 10 cm, at a constant linear flow rate of 1.5 mL/min are illustrated in Fig. 7 while a summary of results are presented in Table 2. Two types of column

beds were used – columns made with PWC alone and PS alone. The corresponding breakthrough curves follows nearly characteristic "S" shaped profile produced in ideal adsorption systems. The displacement of the front of adsorption with the increase in depth could be explained by mass transfer phenomena that take place in this process. When the bed depth is reduced, axial dispersion phenomena predominate in the mass transfer and reduce the diffusion of metallic ion and hence solute [Fe(II) ion] has no enough time to diffuse into the adsorbent mass. Consequently an important reduction in the volume of solution treated at the breakthrough point is observed when the bed depth in the column decreases from 10 to 5 cm (Figure 7 and Table 2). Moreover, an increase in the bed adsorption capacity (q_B) is noticed at the

breakthrough point with the increase in bed depth (Table 2). This increase in the adsorption capacity with than in the bed depth could be due to the increase in the specific surface of the adsorbent which supplies more fixation binding sites. Therefore it follows that a delayed breakthrough of the pollutant leads to an increase in the volume of solution treated. The increase in adsorption with that in bed depth was due to the increase in adsorbent doses in larger beds which provide greater service area (or adsorption sites). The breakthrough time also increases with the height of the bed. Breakthrough time is therefore the determining parameter of the process. The larger is the breakthrough time, the better are the intra-particulate diffusion phenomena and the bed adsorption capacity (Table 2).

To examine the effect of linear flow rate through the beds, the initial solute concentration and bed depth were kept constant ($C_o = 5$ mg/L, $Z = 5$ cm) while the linear flow rate varied from 1.5 to 2.5 mL/min. The breakthrough curves obtained are presented in Figure 8 while results are summarized in Table 3. Uptake of Fe(II) onto the adsorbent decreases when the linear flow rate through the bed increases. An increase in the linear flow rate reduces the volume treated until breakthrough point and therefore decreases the service time of the

bed. This is due to the decrease in contact time between Fe(II) ions and the adsorbent at higher linear flow rates. As the adsorption rate is controlled by intra-particulate diffusion, an early breakthrough has occurred leading to a low bed adsorption capacity (Table 3). These results are also in agreement with results obtained by Costodes et al. (2005). When the linear flow rate decreases; the contact time in the column increases, intra-particulate diffusion then becomes effective. Thus Fe(II) ions have more time to diffuse amidst the particles of adsorbent and a better adsorption capacity is obtained (Table 3). At a higher linear flow rate, the adsorbent gets saturated early because of a reduced contact time which leads to a lower diffusivity of the Fe(II) amidst the particles of the adsorbent (Costodes *et al.,* 2005). Therefore the throughput volume, the breakthrough time and the bed adsorption capacity are reduced.

The effect of variation in inlet Fe(II) concentrations of 5 and 10 mg/L was tested with a linear flow rate of 2.5 mL/min using bed depth of 23 and 34 cm for PWC and PS respectively. The breakthrough profiles are presented in Figure 9 while a summary is given in Table 4. A rise in inlet Fe(II) concentration yields reduced throughput volume before the packed bed got
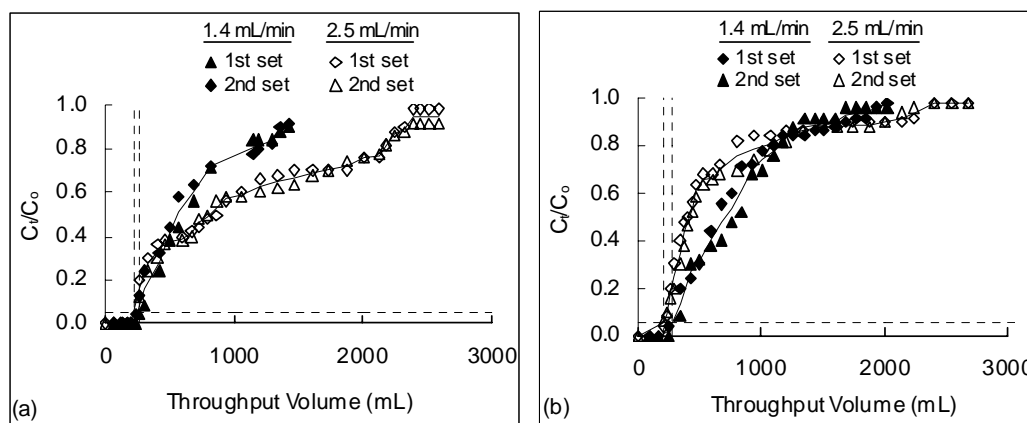

Fig. 8. Effect of variation in linear flow rates for breakthrough curves of Fe(II) adsorption through column of (a) PWC alone and (b) void space of PWC filled with PS [$Z = 5$ cm; $C_o = 5$ mg/L, $m_{c(PWC)} = 5.205$ g]

Table 2. Summary of breakthrough results for Fe(II) adsorption on columns of different bed depths.

Column Bed	Bed Depth (cm)	Adsorbent Mass (g)	Throughput Vol. V_B (mL)[a]	Breakthrough time t_B (min)[a]	H_{MTZ}[b] (cm)	Adsorption bed capacity q_B (mg/g)[c]
PWC alone	5	1.621	260	1420	6.90	0.778
	10	2.621	650	---	---	1.203
PS alone	5	6.005	220	1420	7.32	0.178
	10	11.212	600	2550	12.3	0.260

[a]Obtained from Fig. 7; [b]Height of mass transfer zone calculated using Eq. (2); [c]Calculated using Eq. (3).

Table 3. Summary of breakthrough results for Fe(II) adsorption with variation in linear flow rates.

Column bed	Flowrate Q_v (mL/min)	Throughput Vol. V_B (mL)[a]	Breakthrough time t_B (min)[a]	H_{MTZ}[b] (cm)	Adsorption bed capacity q_B (mg/g)[c]
PWC	1.4	260	186	6.9	0.778
	2.5	230	92	8.19	0.731
PWC (voids filled with PS)	1.4	280	200	7.56	0.551
	2.5	198	80	8.2	0.384

[a] Obtained from Figure 8; [b] Height of mass transfer zone calculated using Eq. (2), [c] Calculated using Eq. (3).

Table 4. Summary of breakthrough results for Fe(II) adsorption through PWC and PS beds with variation in inlet metal concentrations.

Column Bed	Inlet Conc. C_o(mg/L)	Throughput Vol. V_B (mL)[a]	Breakthrough point t_B (min)[a]	Adsorption bed capacity q_B (mg/g)[b]
PWC	5	1450	418	1.40
	10	620	179	1.20
PS	5	1490	430	0.12
	10	600	173	0.10

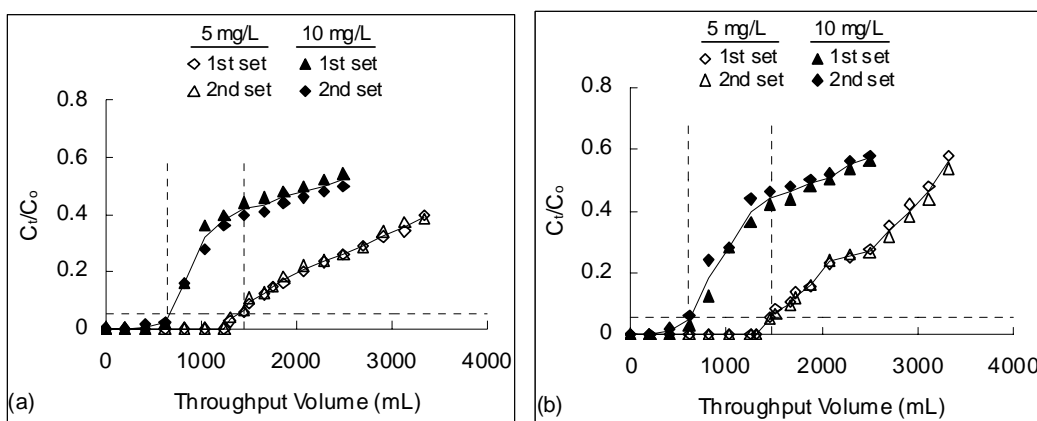[a] Obtained from Figure 9; [b] Calculated using Eq. (3)

Fig. 9. Effect of variation in inlet Fe(II) concentration on breakthrough curves through column of (a) PWC and (b) PS [Z_{PWC} = 23 cm, Z_{PS} = 34 cm, $m_{c(PWC)}$ = 5.205 g, $m_{c(PS)}$ = 58.5 g, Q_v = 2.5 mL/min]

Table 5. Performance summary of up-scaled columns and indigenous unit models

Column/Unit	Bed arrangement	Fe(II) conc. (mg/L)	Throughput Vol. V_B (L)[a]	Breakthrough time, t_B (min)[a]
Up-scaled	PWC at top & PS at bottom	5	37.00	3209
	PS at top & PWC at bottom		34.50	2992
Indigenous	CPWC at top & RS at bottom	5	23.90	2073
	RS at top & CPWC at bottom		23.00	1995

[a] Obtained from Fig. 10.

saturated. A higher metal concentration might have saturated the adsorbent more quickly, thereby decreasing the breakthrough time. The results demonstrated that an increase in inlet metal concentration has modified the adsorption rate through the bed thereby decreasing the bed adsorption capacity (Table 4) affecting the intra-particle metal diffusion process (Costodes *et al.,* 2005). Nevertheless, the saturation of the adsorbent required much more time and the breakthrough was reached before all the active sites of the adsorbent were occupied by the metal ions. The PWC column showed higher affinity for Fe(II) as compared to PS column under the experimental conditions of this study.

The breakthrough profiles obtained through up-scaled columns as well as models of indigenous unit are presented in Fig. 10 while results are summarized in Table 5. It is apparent from the results that the up-

scaled columns yielded higher volume of throughput as well as enhanced service time at the breakpoint compared to models of indigenous units indicating possibility of enhancing the performance of indigenous household iron filter units by selecting the filter media of appropriate size ranges.

The performance of up-scaled columns were evaluated with actual groundwater samples containing various other ionic species in addition to Fe(II). The breakthrough profiles are presented in Figure 11, while the summary of breakthrough throughput is presented in Table 6. It was evident that up-scaled columns were able to perform effectively with actual groundwater also and yield appeared to be reasonable and comparable in both the bed arrangements. In addition to monitoring the performance for Fe(II) removal and the breakthrough profiles, the performance of up-scaled columns were also monitored for other water quality parameters
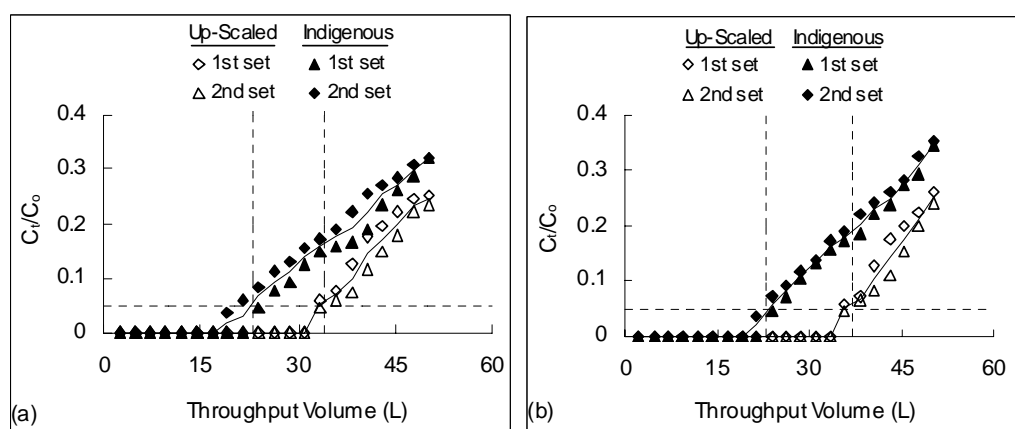

Fig. 10. Comparison of breakthrough profiles of up-scaled columns and indigenous unit models (a) PWC or CPWC at top and PS or RS at bottom (b) PS or RS at top PWC or CPWC at bottom. [C_o = 5 mg/L, Temp = 24±1 °C, m_{PWC} = m_{CPWC} = 85 g and m_{PS} = m_{RS} = 955 g]
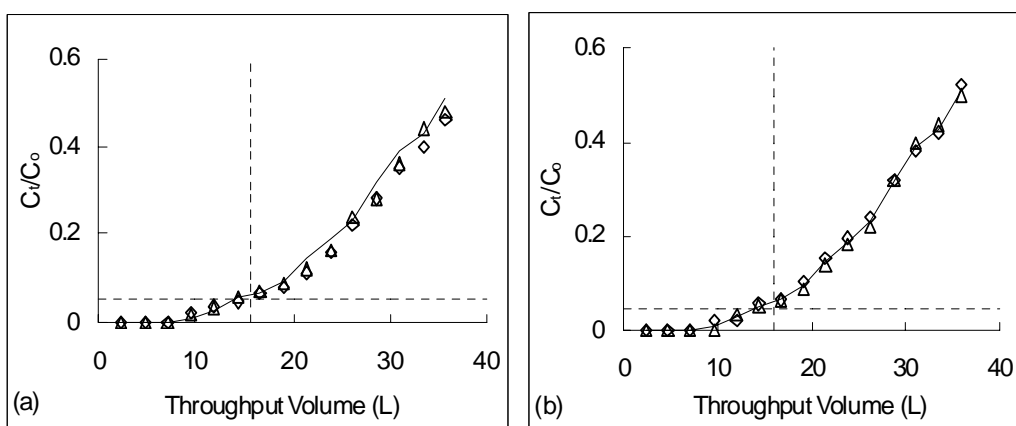

Fig. 11. Breakthrough profile of up-scaled columns: (a) PWC at top and PS at bottom (b) PS at top and PWC at bottom obtained with actual groundwater samples [C_o = 6.5 mg/L, Temp = 24±1 °C, m_{PWC} = 85 g, m_{PS} = 955 g]

Table 6. Performance summary of up-scaled columns with actual groundwater.

Bed Arrangement	Throughput volume, V_B (L)
PWC at top & PS at bottom	15.750
PS at top & PWC at bottom	16.000

Table 7. Performance of up-scaled column in terms of other water quality parameters with actual groundwater.

Water Quality Parameters	Ground-water Sample	Treated by up-scaled columns with [#]	
		PWC at top & PS at bottom	PS at top & PWC at bottom
Fe(II) (mg/L)	6.5	0.3	0.3
Flouride (mg/L)	0.47	0	0
pH	6.60	6.67	7.10
Turbidity (NTU)	25.0	0.3	1.2
Sulfate (mg/L)	15.50	3.26	3.30
Nitrate-N (mg/L)	2.6	2.6	2.6
Nitrite-N (mg/L)	0	0	0
Ammonia-N (mg/L)	3.0	1.4	1.1
Hardness (mg/L as $CaCO_3$)	210	210	200
Calcium (mg/L)	55.24	55.10	52.20
Sodium (mg/L)	33.2	33.2	33.2
Potassium (mg/L)	3.2	3.2	3.2
Alkalinity (mg/L as $CaCO_3$)	310	105	112

monitored after breakthrough with Fe(II)

at the breakthrough, which is presented in Table 7. The up-scaled columns were able to remove fluoride, turbidity, sulfate as well as alkalinity along with Fe(II).

CONCLUSION

The solubility of Fe(II) is observed to be significantly affected by the pH and DO levels. The Fe(II) came out as precipitate at pH > 7. Similarly, Fe(II) gets oxidized to Fe(III) form with increase in DO levels and came out as precipitate. The adsorption breakthrough curves obtained at different bed depths indicated increase of breakthrough time with increase in bed depths, while the uptake of Fe(II) ions by PWC and PS decrease when the linear flow rate through the bed increases. A rise in inlet Fe(II) concentration reduces the throughput volume before the packed bed gets saturated. PWC showed higher affinity for Fe(II) as compared to PS. The up-scaled columns yield higher volumes of throughput (by 50-54%) compared to models of indigenous units. It is possible to enhance the performance of indigenous household iron filter units by selecting the filter media of appropriate size ranges. The up-scaled columns performed reasonably well with actual groundwater containing various other ionic species and indicated its ability to remove fluoride, turbidity, sulfate and alkalinity at breakthrough point of Fe(II).

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