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Removal of 4-chlorophenol in sequencing batch reactor with and without granular-activated carbon

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ABSTRACT

The aim of this paper is to study the treatment of 4-chlorophenol bearing water by biological treatment in sequencing batch reactor (SBR) without any adsorbent (blank-SBR) and with an SBR loaded with granular-activated carbon (GAC–SBR) in instantaneous mode. Adsorbent dose used for GAC–SBR was found to be 16 g/L. It was observed that addition of GAC enhanced the ability of activated sludge in resisting the shock load of organics. React phase duration in blank-SBR and GAC–SBR was found to be 6 and 4 h, respectively. Removal efficiencies of blank-SBR and GAC–SBR at optimum conditions and for initial 4-chlorophenol concentrations of 100, 200, 250, and 500 mg/L were found to be 68.6 and 97%; 46.9 and 96.9%; 23.5 and 96%; and 5 and 95.9%, respectively. Kinetics of treatment process has been studied in both blank-SBR and GAC–SBR. Characterization of the sludge was done using scanning electron microscopy (SEM)/energy dispersive atomic X-ray (EDAX) analysis. Settling and filterability characteristics of the sludge have also been studied.

Keywords: Sequencing batch reactor; 4-Chlorophenol; Adsorption; Granular-activated carbon; Kinetics

1. Introduction

Chlorophenols are mainly used as preservatives, anti-mildew agents, fungicides, and disinfectants [1,2]. Chlorophenols also get formed during the chlorination of wastewaters, and are very common by-products of the breakdown of chloro-aromatics and pesticides [3]. These substances are carcinogenic in nature and they can condense to form chlorodibenzodioxins, which are extremely toxic and hazardous to the environment [4]. Phenolic compounds concentration in wastewaters emanating from phenolic resin production may be ≈400 mg/L; 50 mg/L from refineries; 12 mg/L from naphthalenic acid production; and 200 mg/L from shale dry distillation [5]. The chlorination of drinking water to sterilize river water may lead to chlorophenols formation. Chlorophenols produce a noticeable effect in drinking water even at 0.1 μg/L concentration [6]. Owing to the high toxicity of carcinogenicity of chlorophenols, they have been listed as priority environmental pollutants by the United States Environmental Protection Agency (USEPA) [7].

Annachhatre and Gheewala [8] advocated biological treatment for the complete mineralization of chlorophenols. Sequencing batch reactor (SBR) is a suspended growth biological process, which performs equalization, biological treatment, and secondary

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clarification in a single tank using a timed control sequence. In this system, wastewater is added to a "batch" reactor, treated to remove toxic and undesirable organic components, and then finally discharged [9,10].

Granular-activated carbon (GAC) is the most commonly used adsorbent in wastewater treatment and also finds application in catalysis [11]. Wilson et al. [12] showed complete biodegradation of pentachlorophenol in GAC fluidized bed reactors. Addition of adsorbents to the biological system has been reported to enhance the toxic substances removal [13]. He et al. [14] conducted two types of operation means "SBR reactor alone" and "adding zeolite powder into the SBR reactor" to treat municipal wastewater. The test results revealed that the addition of zeolite powder could improve the activity of the activated sludge. Lim et al. [15] compared the performance of two SBR added with ethylenediamine-modified rice husk and powdered activated carbon, respectively, as adsorbents for the removal of chemical oxygen demand (COD) and ammonical nitrogen from a mixture of landfill leachate and domestic wastewater at various mixing ratios. Results showed that adding modified rice husk as adsorbent in SBR could treat wastewater with more strength as compared to adding powdered activated carbon. Vinitnanthart et al. [16] observed that adding GAC to SBR improved the performance and removal efficiency of SBR against shock loadings.

Many pure culture studies have shown accumulation of toxic intermediates during biodegradation of chlorophenols because a single organism may not have the ability to completely mineralize these toxic substances. However, several studies have showed that mixed bacterial culture have the ability to use chlorophenols as their sole carbon and energy sources [17]. Sharma et al. [18] recently reported degradation of resorcinol using mixed culture in SBR. Increase in mixed liquor suspended solid (MLSS) concentration and aeration time were found to induce positive effect on resorcinol removal efficiency. Only few studies have been reported for the biodegradation of chlorophenols in SBR [19–21]. However, none of the previous researchers studied the effect of addition of adsorbent such as GAC in SBR for the removal of 4-chlorophenol. Moreover, previous researchers also did not focus on settling and filterability of the resultant slurry generated in SBR. These shortcomings of previous studies have been studied in the present study.

The aim of the present study is to study the treatment of 4-chlorophenol bearing aqueous solutions by biological treatment in SBR without any adsorbent (blank-SBR) and with an SBR loaded with granular activated carbon (GAC–SBR) in instantaneous mode. It is also aimed to study the effect of cycle time, volume exchange ratio (VER), hydraulic retention time (HRT), and GAC dosage on removal of 4-chlorophenol in SBR. Kinetics of the removal process has also been studied. Economic analysis has been performed to compare the cost of treatment in blank-SBR and GAC–SBR. The liquid–solid suspension after treatment has also been tested for its settling characteristics and filterability.

2. Materials and methods

2.1. Wastewater and activated sludge acclimatization

Wastewater of different concentration of 4-chlorophenol were prepared by adding desired amount of 4-chlorophenol to distilled water. For studies using SBR with mixed culture but without GAC (called as blank-SBR), the concentration of 4-chlorophenol was varied in the range of 50–200 mg/L. For SBR containing both mixed culture and GAC (called as GAC–SBR), the concentration of 4-chlorophenol was varied in the range of 200–1,250 mg/L. Sludge used in this study was collected from Haridwar sewage treatment plant, Haridwar, India. The sludge collected was first screened to remove coarse and bigger particles.

Acclimatization of the activated sludge with the nutrients and 4-chlorophenol was achieved in 20 days. The reactor was initially fed with easily biodegradable nutrients: $NH_4Cl = 100$ mg/L; $Na_2HPO_4.12H_2O =$ 100 mg/L; $NaCl = 50$ mg/L; $Na_2CO_{3=}150$ mg/L; and glucose = 200 mg/L without any 4-chlorophenol [22]. To maintain biomass trace elements, micro-nutrient ($Fe_2Cl_3.6H_2O$, $ZnSO_4$, $MnSO_4.H_2O$, and $CuSO_4$) were also added in lower concentrations (less than 0.2 mg/L) [23]. As the mixed culture became adapted to the environment indicated by low effluent COD, concentration of 4-chlorophenol was progressively increased and the nutrient concentration was progressively decreased. The detail of acclimatization steps are shown in Table 1.

2.2. Experimental procedure

To determine the degree of adsorption of 4-chlorophenol onto the GAC, samples of virgin GAC were tested. Varying amounts of virgin GAC were added to a series of 100 ml glass stopper flasks containing 50 ml of the wastewater containing 4-chlorophenol of different concentrations. The flasks were agitated for 12 h at 30˚C and 150 rpm, and the residual 4-chlorophenol concentration was determined.

The SBR used for the present study had an effective volume of 5 L. The air was introduced at the

Table 1
Details of acclimatization procedure

Time (d)	4-Cholorophenol concentration (mg/L)	Nutrient concentration (mg/L)					No. of cycles of 12 h each
		NH_4Cl	$Na_2HPO_4 \cdot 12H_2O$	NaCl	Na_2CO_3	Glucose	
0–4	0	100	100	50	150	200	8
4–6	50	75	75	50	100	150	4
6–10	75	50	50	50	100	100	8
10–15	100	50	50	50	50	50	10
15–20	100	0	0	0	0	0	10

bottom (inside) of the reactor with micro-bubble air diffusers and the air flow rate was controlled with a regulator. There were in all SBRs out of which one reactor was run without adsorbent (blank-SBR), the other reactor was fed with adsorbent GAC (GAC–SBR). The temperature of the mixed slurry in reactor was maintained at 30 ± 2°C with a thermostat submerged into the reactor. In addition, the DO of the reactor was monitored and controlled within a range of 2–4 mg/L by a dissolved oxygen meter. The decanting of treated wastewater was performed by peristaltic pumps.

It is well reported that instability of aerobic granules is a major technical problem encountered in operating aerobic granular sludge SBR for treating wastewater [24]. Filamentous growth which has been commonly observed in aerobic granular sludge SBR leads to poor settleability of aerobic granules and subsequent washout and disappearance of aerobic granules [25–27]. To control the filamentous growth, sludge retention time (SRT) must be controlled and MLSS concentration should be controlled within a reasonable range so as to ensure sufficiency of oxygen within the SBR [24,28]. To maintain an appropriate level of MLSS concentration within the reactor, 60 mL of sludge was wasted after every cycle which prevented the problem of sludge bulking and an excessive growth of filamentous bacteria.

In GAC–SBR, optimized amount of GAC was added at the beginning of cycle. After the completion of each cycle, the sludge was passed through a wire-net to remove GAC from the activated sludge. This is as per the methods used earlier by various researchers for the removal of adsorbents from SBR sludge [19,29]. The particles size of GAC was in the range 0.85–2.5 mm out of which about ≈70% of particles were having size ≈1 mm. Fig. 1 shows a schematic diagram of the process configuration.

The mixture of the liquid–solid suspensions in the SBR was mixed well, and the resultant slurry was tested for its settling characteristics and filterability. The sludge sedimentation tests were conducted using a 1 L graduated glass cylinder. No stirring was done during these tests. The well mixed slurry was homogenized by agitating before pouring it into the glass cylinder and it was allowed to remain under quiescent conditions. The position of the upper interface was noted after 30 min. For studying filterability of sludge from SBR, filter paper (Whatman filter paper No. 42 pore size of ca. 2.5 mm) was supported over a ceramic Buechner funnel having 0.96 cm internal diameter. The filtrate volume collected was recorded at regular intervals of time neglecting the filtrate volume obtained in the first 1 min. The operating conditions of SBR are presented in Table 2. The sludge concentration was maintained by periodic sludge wastage. SRT which measures the time for which the biomass remained in the reactor was maintained constant at 30 days in the present study.

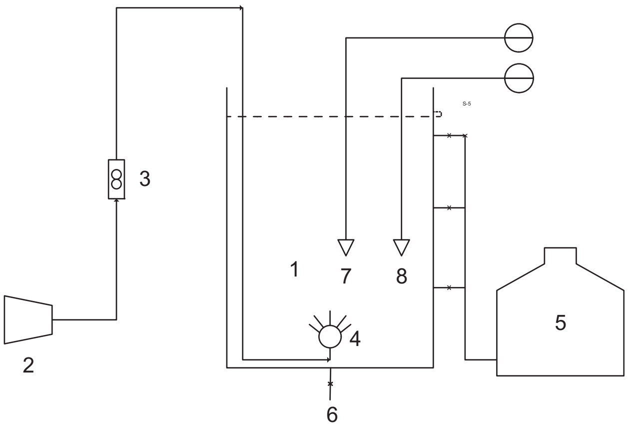


Fig. 1. Schematic illustration of the experimental system, (1) reactor; (2) air compressor; (3) air regulator; (4) air diffuser; (5) storage tank; (6) drainage valve; (7) thermostat; and (8) dissolved oxygen meter.

2.3. Analytical methods

The concentrations of 4-chlorophenol present in the solution were calculated using a double beam

Table 2
Operating conditions of blank-SBR and GAC–SBRs at steady state

Parameter	Blank-SBR	GAC–SBR
Temperature (°C)	30	30
Dissolved oxygen (mg/L)	2–4	2–4
pH	6.5–7	6.5–7
Fill phase	Instantaneous fill	Instantaneous fill
Agitator speed (rpm)	600	600
Cycle time (h)	8	6
MLSS (mg/L)	3,000–3,100	3,000–3,100
GAC dose (g/L)	0	16

UV/VIS spectrophotometer (model UV DR 5000; HACH, USA). Wavelength for maximum absorbance corresponding to 4-chlorophenol was 225 nm. Calibration curve showed a linear relationship between the absorbance and the concentration in the solution for concentrations up to 10 mg/L with the correlation coefficient value of about 0.995. Sample concentrations were sometimes diluted to below 10 mg/L to fall within the linear range. DO was checked twice every hour. MLSS and pH were checked daily.

Energy dispersive atomic X-ray (EDAX) analyzer (SEM, QUANTA, Model 200 FEG, USA) was used to study the distribution of different elements in the sludge. Firstly, the samples were eluted with milli-Q water until the electrical conductivity of the supernatant of these samples was almost equal to that of the milli-Q water. The scanning energy for the EDAX analysis ranged from 0 to 10 keV with an elapsed time of 100 s.

3. Results and discussions

3.1. Comparison of cycle time

For the blank-SBR, the residual 4-chlorophenol concentration at 6 h contact time (Fig. 2) was found to be marginally more (~1%) than that obtained after 12 h contact time (results after 7 h not shown in Fig. 2). Therefore, after 6 h contact time, a steady state approximation was accepted for blank-SBR and the react time for blank-SBR was fixed at 6 h. Similarly, GAC–SBR which was operated with 16 g/L optimized GAC dose (results discussed later) showed maximum removal at 4 h (Fig. 3); therefore, the react time for GAC–SBR was fixed to 4 h. Thus, the cycle time decreased from 6 to 4 h when GAC was used as an adsorbent in SBR.

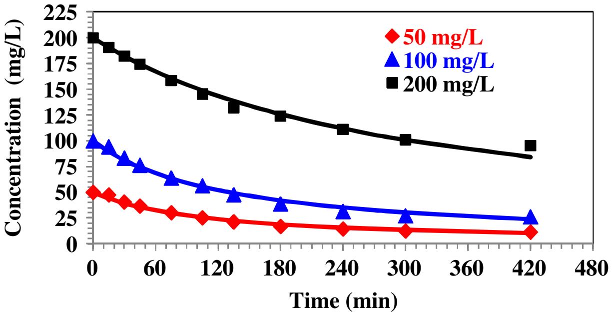


Fig. 2. Kinetics of 4-chlorophenol removal in blank-SBR for various initial 4-chlorophenol concentrations.

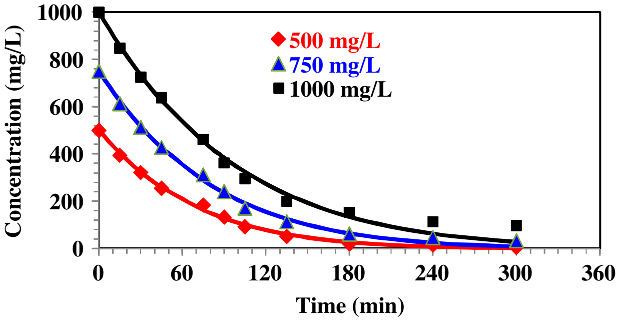


Fig. 3. Kinetics of 4-chlorophenol removal in GAC–SBR for various initial loading values.

3.2. Effect of GAC dosage in GAC–SBR

The setup of SBR was made to work in a similar way with the exception that a certain amount of GAC was added to the influents of SBR in each cycle which was completely removed from SBR after every cycle using sieves. Various amounts of GAC were added to SBR during each run and the removal efficiency was noted. The initial concentration of 4-chlorophenol used for each of these experiments was fixed at

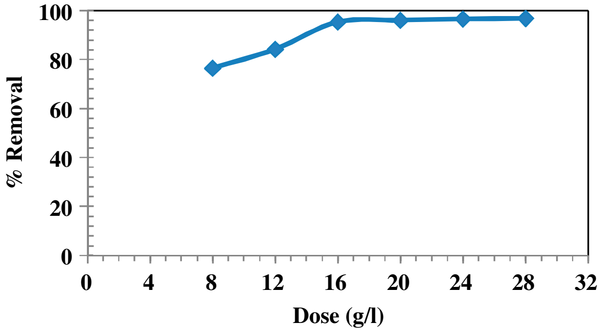


Fig. 4. Removal of 4-chlorophenol at different doses of GAC, $C_o = 200$ mg/L.

200 mg/L. It was observed that as the GAC dose increased, the removal efficiency of SBR also increased. As it can be seen from Fig. 4, this trend continues for dose up to 16 g/L of GAC and beyond this the removal efficiency of SBR became almost constant. Optimized GAC dosage of 16 g/L was taken for further studies on GAC–SBR.

3.3. Effect of VER and HRT

VER is the ration of fill volume to total working volume. It can be defined as:

$$\mathrm{VER} = \frac{V_F}{V_T} \tag{1}$$

where V_F is the fill volume (L) and V_T is the total working volume (L). HRT, which is defined as the time the wastewater takes to pass through the system, for SBRs is calculated using the formula:

$$\mathrm{HRT} = \frac{V_T}{V_F}\frac{1}{N_c} = \frac{1}{\mathrm{VER}}\frac{T_c}{24} \tag{2}$$

where N_c is number of cycles per day and T_c is the cycle time (h). Different fill volumes were used to vary the VER of two SBRs in this study. Values of VER were varied in the range of 0.2–0.7 whereas the cycle time was 8 h for blank-SBR and 6 h for GAC–SBR. The values of percentage removal of 4-chlorophenol were noted and the results are shown in Fig. 5 in terms of HRT. It may be seen in figure that the optimum HRT was 1.67 d for blank-SBR and 1.25 d for GAC–SBR. In terms of VER, these HRT values correspond to VER of 0.2 for both the SBRs.

3.4. Effect of initial 4-chlorophenol concentration

In this part of study, the effect of initial 4-chlorophenol loading on the performance of SBRs was studied. Cycle time was fixed at 8 h for blank-SBR and 6 h for GAC–SBR. VER = 0.2 was taken for both the SBRs. Results are shown in Fig. 6. It was observed that 4-chlorophenol removal efficiency in GAC–SBR was ≈80% for aqueous solution containing 4-chlorophenol concentration up to 1,250 mg/L whereas it was only 45% for 4-chlorophenol concentration of 200 mg/L in blank-SBR. Thus, GAC–SBR was able to treat water containing much higher 4-chlorophenol concentration as compared to blank-SBR. It may be seen that the removal efficiency decreases with an increase in initial 4-chlorophenol concentration in both the SBRs. This may be due to the highly toxic nature of 4-chlorophenol which inhibits growth and 4-chlorophenol degradation efficiency of micro-organisms. In GAC–SBR, removal efficiency is higher because of adsorption of 4-chlorophenol onto the GAC.

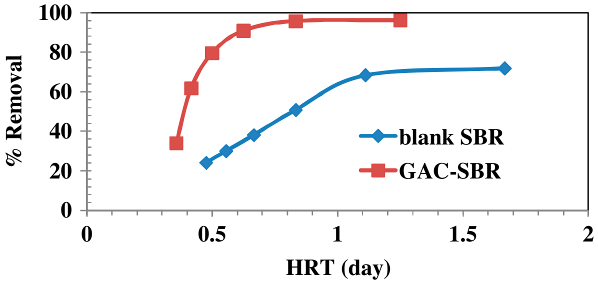


Fig. 5. Comparison of removal efficiency of 4-chlorophenol at different HRT in blank-SBR and GAC–SBR.

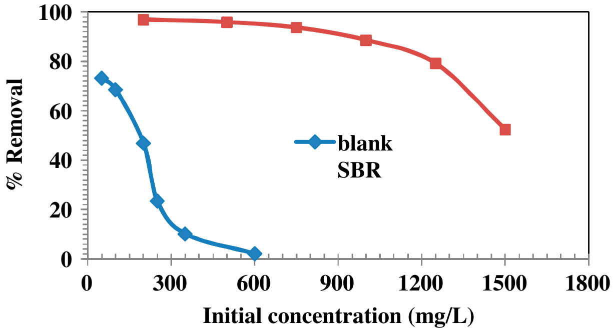


Fig. 6. Comparison of removal efficiency of 4-chlorophenol at different initial concentrations for blank-SBR and GAC–SBR, VER = 0.2.

Removal efficiencies of blank-SBR and GAC–SBR at initial 4-chlorophenol concentrations of 100, 200, 250, and 500 mg/L were found to be 68.6 and 97%; 46.9 and 96.9%; 23.5 and 96%; and 5 and 95.9%, respectively. Removal efficiencies observed in blank-SBR are due to biotic components. Difference in the removal efficiencies between GAC–SBR and blank-SBR is due to abiotic component i.e. GAC. Thus, at initial 4-chlorophenol concentrations of 100, 200, 250, and 500 mg/L, removal efficiencies due to biotic and abiotic components are 68.6 and 28.4%; 46.9 and 50%; 23.5 and 72.5%; and 5 and 90.9%, respectively. In SBR alone, cleavage of the carbon–halogen bond cleavage during the biodegradation process of chlorophenols may occur by two mechanisms. In one case, direct removal of the chlorine atom from the aromatic ring may occur by displacement with either hydroxyl groups (hydrolytically or oxygenolytically) or hydrogen atoms (reductive dechlorination). In other case, chlorine atom removal occurs via oxygenative ring cleavage [30]. However, present study shows that the mixed culture present in SBR is not able to tolerate higher concentrations of 4-chlorophenol (>200 mg/L) and the removal efficiency due to biotic components decreases at higher 4-chlorophenol concentration.

It is known that the immobilization of microbial cells onto adsorbent improves the removal efficiency [31]. The presence of GAC in SBR increases the liquid–solid surfaces, on which microbial cells, organic materials, and oxygen are adsorbed providing an enriched environment for microbial metabolism for degradation of 4-chlorophenol [31–33]. This process is referred to as simultaneous adsorption–biodegradation, in which adsorbate continuously diffuses onto the solid surface and the degraded products diffuse back into the solution phase [34]. The 4-chlorophenol removal efficiency is better in GAC–SBR as compared to SBR alone. This difference in removal efficiency gets further enhanced at high 4-chlorophenol concentrations. In GAC–SBR, adsorption might be occurring initially followed by biodegradation of 4-chlorophenol. Adsorption process gets further enhanced by the large surface area of the GAC [35].

3.5. Kinetics

When the mechanism of degradation process is unknown, kinetic data can be tested for nth-order kinetic rate equation given as:

$$-r = -\frac{dC}{dt} = kC^n \tag{3}$$

Integration of above equation, for $n \neq 1$, yields following equation:

$$C_t^{1-n} - C_o^{1-n} = (n-1)kt \tag{4}$$

For $n = 1$, following equation is obtained:

$$C_t = C_o \exp(-kt) \tag{5}$$

where C_o is the initial 4-chlorophenol concentration (mg/l) and C_t is the 4-chlorophenol concentration (mg/l) in the SBR at time, t.

The adsorption of 4-chlorophenol from aqueous solution onto GAC can be considered as a reversible process with equilibrium being established between the solution and the solid GAC phase. Assuming non-dissociating molecular adsorption of 4-chlorophenol on GAC particles with no 4-chlorophenol molecules initially present on the adsorbent, the uptake of the 4-chlorophenol molecules by GAC at any instant (t) is given as [36]:

$$q_t = q_e[1 - \exp(-kt)] \tag{6}$$

where $q_e = ((C_o - C_e)/m)$ = amount of the 4-chlorophenol adsorbed on GAC under equilibrium condition and k is the pseudo-first-order rate constant, $q_t = ((C_o - C_t)/m)$, C_e is the equilibrium 4-chlorophenol concentration (mg/l), and m is the adsorbent dose in g per liter of solution.

The kinetics of two SBRs, i.e. blank-SBR and GAC–SBR, were studied along with the kinetics of batch adsorption of 4-chlorophenol onto GAC. Various initial concentrations of 4-chlorophneol were used to observe the kinetics of blank-SBR, GAC–SBR, and batch adsorption. Figs. 2 and 3 show the plots between concentration and time for blank-SBR and GAC–SBR, respectively. Fig. 7 shows the plot between q_t vs. time. In the figure, experimental data are represented by data points whereas line represents the fit of the pseudo-first-order kinetic model. It may be seen in figure that q_t at any time t increased with an increase in C_o. This shows that the adsorbent sites are less utilized at lower concentration whereas at high concentration there is more driving force for the adsorption of 4-chlorophenol onto GAC. It may also be seen in Fig. 7 that the kinetic data is well represented by pseudo-first-order model with regression coefficients (R^2) value of 0.998, 0.993, and 0.998 for C_o = 100, 200, and 300 mg/L, respectively. The values of kinetic constants for all three systems were calculated and these values are shown in Table 3 along with the R^2 and Marquadts' percent standard deviation (MPSD) values. The kinetic data for removal of 4-chlorophenol in blank-SBR was best represented by pseudo-second-order kinetics, while in case of GAC–SBR and batch adsorption using GAC, the kinetic data were best represented by pseudo-first-order kinetics.

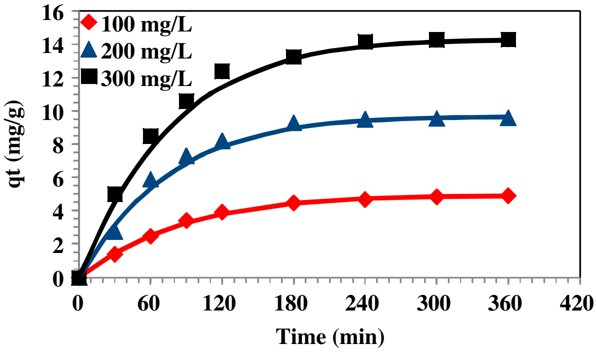


Fig. 7. Kinetics of 4-chlorophenol removal in batch adsorption for various initial loading values.

Table 3
Kinetic parameters values for the removal of 4-chlorophenol by blank-SBR, batch adsorption, and GAC–SBR

Initial concentration (mg/L)	k	n	R^2	MPSD
Blank-SBR				
50	1.84×10^{-5}	2	0.993	6.136
100	7.66×10^{-5}	2	0.993	6.030
200	1.62×10^{-5}	2	0.985	3.873
Batch adsorption				
100	0.012647	1	0.998	192.377
200	0.015168	1	0.994	278.561
300	0.01486	1	0.999	339.497
GAC–SBR				
500	0.014983	1	0.996	18.561
750	0.012847	1	0.996	19.657
1,000	0.010726	1	0.990	19.579

3.6. Economic analysis

Economic analysis requires comparison of both capital and operating costs. For the present study, both blank-SBR and GAC–SBR had same dimensions and material of construction, and same number of auxiliary equipments like diffuser, air pump, stirrer, etc. In GAC–SBR, a wire-net was used for screening the GAC so as to prevent loss of GAC from SBR. Assuming the cost of wire-net to be negligible, and the capital cost of both blank-SBR and GAC–SBR is same. Operation of SBR requires use of diffuser, air pump, stirrer, etc. Treatment time per cycle for blank-SBR and GAC–SBR were found to be 6 and 4 h, respectively. Considering the cost of electricity to be \$0.069/kWh, the electricity cost of smooth operation of blank-SBR and GAC–SBR were found to be \$0.01625/cycle and \$0.01356/cycle, respectively. However, GAC–SBR required additional GAC per cycle, therefore, total operating cost of blank-SBR and GAC–SBR was found to be \$3.25 and \$2.71, respectively, for treatment of 1 m^3 of wastewater containing 100 g/m^3 of 4-chlorophenol. Thus, use of GAC in SBR seems to be economical as compared to blank-SBR.

3.7. Studies on SBR slurry

3.7.1. Settling

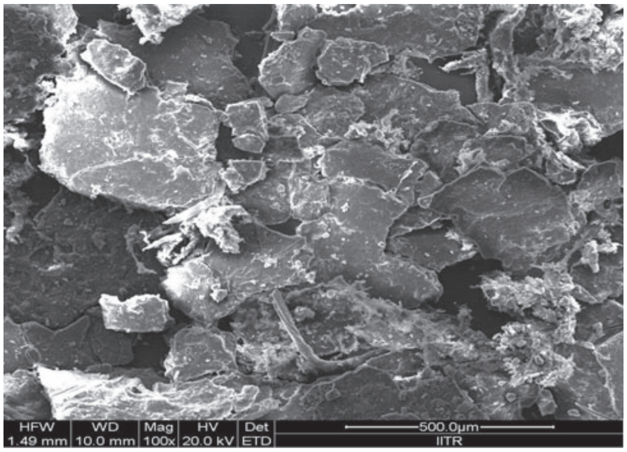
Sludge volume index (SVI), a simple parameter for characterizing sludge thickening properties, was used to quantify the settling characteristics of the sludge. SVI is the volume occupied in mL by 1 g of the sludge after 30 min of settling time. The SVI was calculated from the following relation:

$$\text{SVI (mL/g)} = \frac{(\text{Volume of settled sludge (mL/L)} \times 1,000\ (\text{mg/g}))}{\text{MLSS (mg/L)}} \tag{7}$$

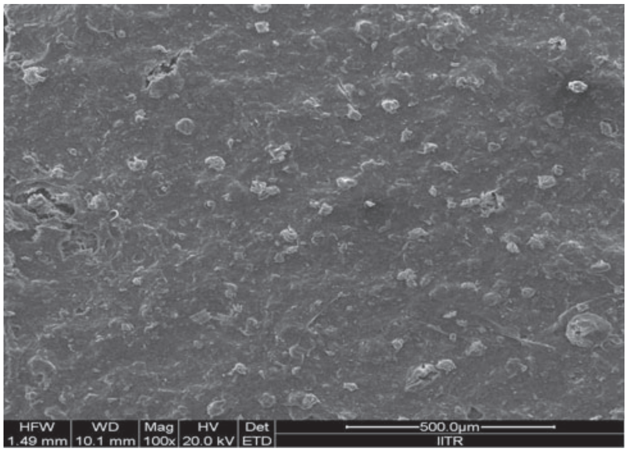
It was observed that settling of the sludge improved with time. SVI of the sludge was observed to be 38.33 and 33.33 mL/g before and after acclimatization of the sludge, respectively. Sludge having $\text{SVI} < 100$ is considered to be well settling sludge, for $100 < \text{SVI} < 200$; it is considered to be light sludge; and for $\text{SVI} > 200$, it is considered to be bulky in nature [37]. Hence for the present case, sludge was found to be well settling sludge.

3.7.2. Filterability characteristics

The following force balance equation was used for filterability calculation:



(a) Before acclimatization



(b) After acclimatization

Fig. 8. SEM of sludge before and after acclimatization.

Table 4
Performance comparison of blank-SBR and GAC–SBR

Parameter	Blank-SBR	GAC–SBR
Cycle time (h)	8	6
VER	0.2	0.2
HRT (day)	1.67	1.25
Sludge wasting rate (mL/cycle)	60	60
Removal efficiency	73% (loading = 50 mg/L)	96.9% (loading = 200 mg/L)
	68.6% (loading = 100 mg/L)	96% (loading = 500 mg/L)
	46.9% (loading = 200 mg/L)	94% (loading = 750 mg/L)

$$\frac{\Delta t}{\Delta V} = \frac{\mu}{A\Delta P}\left(\frac{\alpha C V}{A} + R_m\right) \qquad (8)$$

Here, ΔV is the filtrate volume collected in Δt time interval (m^3), α is the specific cake resistance, μ is viscosity of the filtrate (Pa s), C is the MLSS concentration in the slurry (kg/m^3), A is the filtration area (m^2), R_m is the resistance of the filter medium (m^{-1}), and P is the pressure drop across the filter (Pa) [18]. Value of α and R_m was calculated from the dt/dV vs. V plot. For MLSS concentration of $3\,kg/m^3$, viscosity of 0.959 cP and density of $1{,}025\,kg/m^3$, the values of α and R_m were found to be 3.6×1.0^{10} m/kg and $2.3 \times 1.0^{11}\,m^{-1}$, respectively. Sharma et al. [18] have reported α and R_m values of 4.53×1.0^{11} m/kg and $2.04 \times 10^8\ m^{-1}$, respectively, for resorcinol treated sludge in SBR.

3.8. Analysis of sludge

Elemental composition of sludge was determined using EDAX analyzer. Activated sludge mainly contains carbon and oxygen. EDAX spectra of nonacclimatized sludge and acclimatized sludge were analyzed. Both of these sludges were found to contain about 62% of carbon and 17% of oxygen by weight. The amounts of phosphorus and chlorine increased significantly due to acclimatization and nutrition to sludge. Also, as per the morphology obtained, there were deposits of phosphorus on the surface. Elements like sodium, potassium, magnesium, aluminum, calcium, and iron were found in traces. The scanning electron microscopy (SEM)'s of the nonacclimatized and acclimatized sludge are shown in Fig. 8. The surface texture of sludge before and after acclimatization seems to vary significantly.

4. Conclusion

It was observed that cycle time of blank-SBR decreased from 8 to 6 h when GAC was used as an adsorbent in SBR. Adsorbent dose of 16 g/L was found to be optimum for use in SBR. VER value of 0.2 was found to be best for maximizing 4-chlorophenol removal efficiency in both blank-SBR and GAC–SBR. HRT was decreased from 1.67 d for blank-SBR to 1.25 d for GAC–SBR. Hence, more water can be treated in the same time if GAC is used as an adsorbent in SBR. It was observed that with an increase in initial concentration of 4-chlorophenol, the removal efficiencies of both the SBRs decreased but GAC–SBR had comparatively more tolerance against higher loading. The comparison of two SBRs for 4-chlorophenol removal efficiencies is given in Table 4. It seems that overall use of GAC in SBR significantly improves the efficiency of SBR.

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