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Thorium biosorption by *Aspergillus fumigatus*, a filamentous fungal biomass

Kuber C. Bhainsa, Stanislaus F. D'Souza*

Nuclear Agriculture and Biotechnology Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India

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ABSTRACT

Thorium biosorption by *Aspergillus fumigatus* was carried out in a batch reactor to study the effect of initial pH and metal ion concentration, contact time, biomass dose and kinetics and equilibrium Th uptake. Thorium(IV) uptake by *A. fumigatus* was pH dependent (pH range, 2.0–6.0) and maximum sorption was observed at pH 4.0. The uptake was rapid and the biosorption process reached equilibrium within 2 h of contact times at pH 2–4 and initial Th concentration of 50 and 100 mg/L. The kinetics data fitted well to Lagergren's pseudo-second-order rate equation ($r^2 > 0.99$). A maximum initial sorption rate of 71.94 (mg/g min) and second-order rate constant of 7.82×10^{-2} (g/mg min) were observed at pH 4.0, 50 mg Th/L. The observed maximum uptake of thorium was 370 mg Th/g at equilibrium. Biosorption process could be well described by Langmuir isotherm in comparison to Freundlich and Temkin isotherms. Sodium bicarbonate was the most efficient desorbing reagent with desorption efficiency of more than 99%. Environmental scanning electron micrograph (ESEM) showed that the surface of the biomass after desorption was intact.

1. Introduction

The presence of thorium in the environment not only originates from the nuclear industry but also from other anthropogenic activities such as lignite burning in power stations, ore processing and the use of fertilizers [1,2]. Environmental problems resulting from intensified mining ore processing activities and anthropogenic activities call for the removal of radioactive elements from wastewater originating from these operations. All 12 known isotopes of thorium are radioactive and together with other unearthed not recovered radionuclides such as radium, polonium they enter into the environment, especially surface water bodies [3]. Direct toxicity of thorium is low due to its stability at ambient temperature; however thorium fine powder is self-ignitable to thorium oxide [4]. Thorium nitrate after entering into the living organisms localizes mainly in liver, spleen and marrow and it precipitates in a hydroxide form. Therefore it is very important to identify potential biosorbents for remediation of thorium from aqueous medium in order to protect the environment from this radioactive element and its daughter products.

Biosorption has been considered as a useful approach for remediation of heavy metals and radionuclides from the aqueous medium [2,5–8]. Fungal biomass holds distinct advantages over other microbial biomass with respect to industrial exploitation due to the wide range of morphological types available, which includes unicellular and filamentous forms, large-scale availability, derived products from industrial and fermentation processes, ability to grow in cheap medium and ease of harvesting. As a result, several fungal biomasses have been extensively used for biosorption of metal ions and radionuclides [9,10]. Thorium uptake too, has been reported using various fungal and bacterial biomasses, viz., *Rhizopus arrhizus*, *Penicillium* spp., *Aspergillus* spp., *Mycobacterium smegmatis*, *Citrobacter* spp. and *Pseudomonas* spp. [3,11–15]. However, considering the number of studies reported in the literature regarding uptake of metal ions, work on thorium uptake by fungal biomass are not only few but the biosorption capacity also is low. Till date, the best fungal biosorbent for Th uptake is *R. arrhizus* having an uptake capacity of 18.5% [3]. In view of these considerations we report in this study, a filamentous fungal biomass of *Aspergillus fumigatus*, having a thorium uptake capacity of 37%. Furthermore, this biomass has been reported to grow on a variety of carbon sources including glucose, sucrose, raffinose, melibiose, soya bean milk, keratin and wheat straw [16] which makes this as a suitable candidate for exploiting its bioremediation potential. The objective of this work was to characterize the uptake process in terms of influence of different parameters on biosorption of thorium which includes initial pH, contact time, equilibrium uptake, initial concentration and biomass dose. Further various kinetics and equilibrium models were applied to understand the uptake process.

* Corresponding author. Tel.: +91 22 25593632; fax: +91 22 25505151.
E-mail addresses: sfdsouza@apsara.barc.ernet.in, sfdsouza@barc.gov.in (S.F. D'Souza).

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2. Materials and methods

2.1. Organism and culture conditions

A. fumigatus (NCIM 902) was obtained from National Chemical Laboratory, Pune, India and maintained on potato dextrose agar slants. To prepare biomass for biosorption studies the fungus was grown aerobically at 25 °C on an orbital shaker (150 rpm) in a liquid media containing (g/L) KH_2PO_4, 7.0; K_2HPO_4, 2.0; $MgSO_4 \cdot 7H_2O$, 0.1; $(NH_4)_2SO_4$, 1.0; yeast extract, 0.6; and glucose, 10.0. Biomass was harvested after 48 h of growth and washed two times with distilled water. Later it was oven dried at 60 °C for 18 h, ground to fine powder, sieved through 60 mesh size (British Standard, 250 μm) and stored in desiccator until further use.

2.2. Solutions

All experimental solutions were prepared using deionized distilled water. A metal stock of 2000 mg/L was prepared by dissolving thorium nitrate pentahydrate (EMERCK), which was later diluted as required. All other chemicals used were of analytical grade.

2.3. Biosorption studies

Batch sorption experiments were carried out in 100 mL Erlenmeyer flasks containing 25 mL metal solution of desired concentration. The solution pH was adjusted as required using 1.0 M NaOH and 1.0 M HNO_3 before introducing the biomass into the solution. Biomass concentration was fixed at 1.0 g/L throughout the studies except otherwise indicated. The flasks were agitated at 150 rpm on an orbital shaker at 25 °C. Samples (0.5 mL) were collected at suitable time intervals in micro-centrifuge tubes and centrifuged at 10,000 × *g* for 3 min. Residual concentration of thorium was determined in supernatant. The kinetics of Th uptake was investigated in 250 mL Erlenmeyer flasks containing 50 mL solution of desired pH (2.0–4.0) and Th (50, 100 mg/L) concentration. Isotherm study was carried out by varying thorium concentration (50–1000 mg/L) at a fixed biomass concentration (0.5 g/L) and initial pH of 2, 3 and 4. Biomass along with the solution was incubated at room temperature on an orbital shaker and samples were collected after 24 h of incubation, which was sufficient for the system to reach equilibrium. Effect of initial metal ion concentration on Th uptake was determined in the range of 50–1000 mg Th/L at pH 4.0 and biomass concentration of 1 g/L. Varying biomass concentration in the range of 0.3–10 g/L was used at initial Th concentrations of 500–1000 mg/L to study the Th removal from the solution at different pH values. The biomass was contacted with the metal ion for 24 h through out the experiment except otherwise indicated.

2.4. Desorption of bound Th

Desorption studies were carried out by contacting 50 mg of Th-loaded (49 mg Th/g) biomass with respective eluting agent (1 g/L) and incubating in the environmental shaker at the same condition as was followed for sorption studies. The amount of Th released into the solution was monitored by collecting samples at different time intervals and analyzing the metal ion concentration in the samples.

2.5. Environmental scanning electron microscopy (ESEM)

Dry powder biomass (50 mg each) was put in control (without Th, pH 4.0) and experimental (with 50 mg Th/L, pH 4.0) flasks at 25 °C and agitated at 150 rpm for 24 h. Metal-loaded biomass was contacted with 1 M sodium bicarbonate (50 mg biomass/50 mL) in the same condition. After 24 h the biomass from the respective flasks was harvested by centrifugation at 10,000 × *g* for 10. This was followed by washing of the biomass twice with water (pH 4.0) and harvesting as described in biosorption studies. The resulting wet pellets were dried at 60 °C till constant weight and powdered. The surface structure of these biomass samples were examined using environmental scanning electron microscopy (ESEM, FEI QUANTA-200) at 20 keV.

2.6. Analysis of thorium and calculation of metal ion uptake

Thorium concentration in the supernatants was analyzed using Arsenazo III reagent [13]. Uptake of thorium (q, mg/g) was calculated using the formula $q = (C_o - C_f) \times V/W$ where C_o is the initial thorium concentration (mg/L); C_f, the residual thorium concentration (mg/L), V, volume of solution and W, the dry weight (g) of the biomass used. The uptake (q) is expressed as mg Th/g in terms of gram dry weight throughout the work. This method can detect tetravalent thorium and hence the study would be considered as uptake of Th(IV).

2.7. Statistical analysis

All the experiments were performed in triplicates and the data represents average of the values obtained. Variation of the values was always found to be less than 5%. The statistical analysis for linear regression and modeling of rate equation and isotherms was carried out by using Microsoft Excel 2000.

3. Results and discussion

3.1. Effect of pH on Th uptake

Effect of pH on Th uptake was investigated in the range of pH 2.0–6.0 at 100 mg Th/L. Thorium uptake was measured after 24 h of incubation. Thorium uptake was significantly affected by change in pH and maximum thorium uptake by the biomass was observed at pH 4.0 (Fig. 1). The uptake was 67.7 mg/g corresponding to 68% removal of initial metal ion present. Increasing or decreasing the pH on either side of the peak resulted in decline of Th uptake. Very poor uptake, 5.3 mg/g was observed at pH 6.0 unlike pH 2.0 at which the uptake was 20.3 mg/g. However, changing the initial pH to 3 increased the Th uptake to 45.6 mg Th/g. Similar improvement in uptake was also observed at pH 5 with an uptake capacity of 43 mg Th/g biomass. This indicates that interaction of the biomass with Th was favorable in the range of pH 3.0–5.0 with a maximum uptake being exhibited at pH 4.0. Controls, without the biomass were run along with the experimental set. The influence of pH

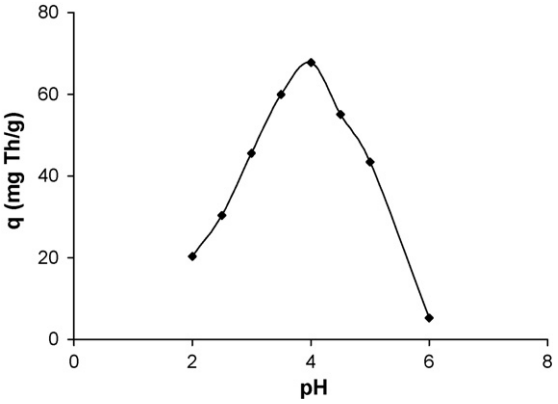

Fig. 1. Effect of initial pH on thorium uptake by *Aspergillus fumigatus* biomass.

on thorium uptake was similar to the thorium biosorption being reported for other biomass such as *Pseudomonas*, *R. arrhizus*, and *M. smegmatis* [3,12,14].

Solution pH has a very important role in determining the speciation of the metal ion and status of binding sites present on the biomass [17]. Often, determination of biosorptive uptake as a function of pH becomes difficult because of increasing tendency of the metal ion undergoing hydrolysis with decreasing hydrogen ion concentration [12]. In case of thorium it becomes even more complicated due to significant decrease in its solubility with increasing pH of the solution. Besides the main hydrolysis products Th also exists in the form of colloidal $Th(OH)_4(aq)$. At pH 2.0, thorium solubility is very high with Th present in the form of Th^{4+} as a soluble species. However, change of pH to 3.0 initiates formation of colloidal particles, $Th(OH)_4(aq)$. With further increase in pH, the hydrolysis of thorium yields major ionic species such as $Th(OH)^{3+}$, $Th(OH)_2{}^{2+}$, $Th_2(OH)_2{}^{6+}$, $Th(OH)^{3+}$, and $Th_6(OH)_{15}{}^{9+}$ with Th^{4+} showing significant decrease [18]. The hydrolysis of metal ion has been found to increase with rise in atomic number [19].

Thorium uptake at equilibrium was found to be less at pH 2.0 compared to pH 4.0. This may be due to low affinity of the biomass binding to Th^{4+}, which is the major ionic species present at pH 2.0. The predominant hydrolyzed species such as $Th(OH)_2{}^{2+}$, $Th_2(OH)_2{}^{6+}$ at pH 4.0 favor the biosorption process, being more efficiently biosorbed than Th^{4+} [20].

3.2. Kinetics of thorium uptake

The effect of varying initial pH on kinetics of Th uptake at two different initial concentration, 50 and 100 mg Th/L was studied and the kinetics of uptake has been represented as plot of q (mg Th/g) versus contact time, t (min) in Fig. 2a and b, respectively. The general trend of kinetics of Th uptake indicated biphasic nature of the process at all concentrations and pH investigated. The initial rapid uptake occurred within 10 min of contact time, which later slowed down to reach the equilibrium after 2 h of contact time. The equilibrium uptake was highest, 31 and 70 mg Th/g at pH 4.0 for initial concentration of 50 and 100 mg Th/L, respectively. The uptake value declined to 15 and 24 mg Th/g at pH 2.0. Although different equilibrium uptake was observed at different initial pH of the solution, the uptake by the fungal biomass completed 70% of its equilibrium uptake within 5 min of contact time at all pH (100 mg Th/L) studied. The maximum equilibrium Th removal was 66 and 68% at pH 4.0 for initial concentration of 50 and 100 mg Th/L, respectively. The initial rapid of thorium uptake occurring in first few minutes accounted for almost 70% of the equilibrium uptake, typical of a biosorption processes. This rapid uptake was similar to the uptake of radionuclides reported for microbial and plant biomass [5,14,21]. The faster biosorptive uptake has significant practical implication in bioreactor operation where the processes would require less operational time [22].

3.2.1. Lagergren's pseudo-first and pseudo-second-order kinetics

The results of Th uptake obtained at different contact times were applied to first and second-order Lagergren's equations. The pseudo-first-order reaction of Lagergren [23] for sorption can be expressed as

$$\frac{dq}{dt} = k_1(q_{eq} - q) \quad (1)$$

where q_{eq} and q are the amount of metal biosorbed per unit weight (mg/g dry weight) of biosorbent at equilibrium and at any time t (min), respectively, and k_1 is the rate constant of pseudo-first-order sorption (min^{-1}). The integrated form of the above equation after

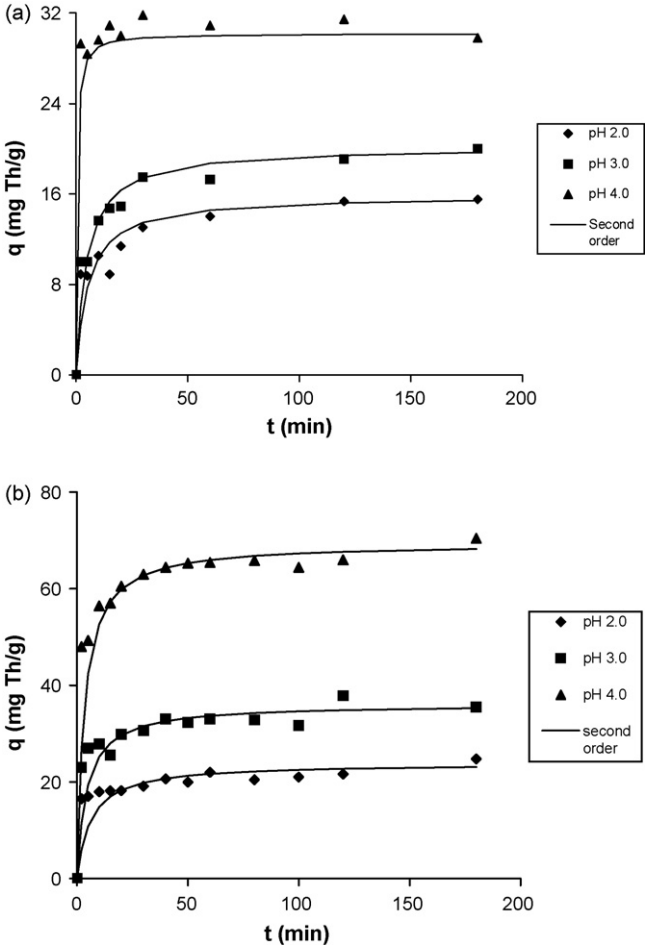

Fig. 2. (a) Effect of pH on kinetics of thorium biosorption at initial concentration, 50 mg Th/L and (b) effect of pH on kinetics of thorium biosorption at initial concentration, 100 mg Th/L.

applying the boundary conditions, for $t = 0$, $q = 0$, becomes

$$\log(q_{eq} - q) = \log(q_{eq}) - \left(\frac{k_1}{2.303}\right) t \quad (2)$$

The value of the rate constant (k_1) of pseudo-first-order sorption reaction obtained by plotting of $\log(q_{eq} - q)$ versus t is given in Table 1a. Thorium uptake at 50 mg/L and pH 2.0 showed best fitting ($r^2 = 0.9375$) to Lagergren's first-order kinetics compared to other pH and metal concentration however, the uptake at pH 4.0 did not fit to the kinetics ($r^2 = 0.045$). The first order rate constant at 50 mg/L showed no particular trend while increasing the pH from pH 2 to pH 4. On the other hand the r^2 value at 100 mg/L varied between 0.7742 and 0.8078 and the first order rate constant increased from 1.52×10^{-2} min^{-1} to 2.07×10^{-2} min^{-1} while the pH was increased from 2 to 4. The low r^2 values indicate that the uptake data cannot be explained by pseudo-first-order kinetics [24].

Table 1a
Lagergren's pseudo-first-order kinetics rate constant for thorium biosorption.

	pH	k (min^{-1})	r^2
50 mg/L	2	1.64×10^{-2}	0.938
	3	8.52×10^{-3}	0.851
	4	1.61×10^{-3}	0.045
100 mg/L	2	1.52×10^{-2}	0.774
	3	1.82×10^{-2}	0.875
	4	2.07×10^{-2}	0.808

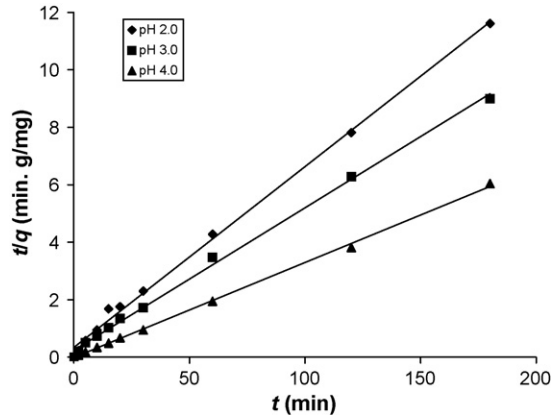

Fig. 3. Lagergren's pseudo-second-order kinetics of thorium biosorption at 50 mg Th/L, pH 2.0–4.0.

The pseudo-second-order rate of Lagergren [25] can be expressed as

$$\frac{dq}{dt} = k_2(q_{eq} - q)^2 \quad (3)$$

where k_2 (g mg^{-1} min^{-1}) is the rate constant of pseudo-second-order sorption. The integrated linear form of Eq. (3) can be represented as

$$\frac{t}{q} = \frac{1}{(k_2 q_{eq}^2)} + \left(\frac{1}{q_{eq}}\right) t \quad (4)$$

The pseudo-second-order rate constant (k_2) and q_{eq} can be calculated from the intercept and slope of the linear plot of t/q versus t.

The initial rate of uptake h (mg/g min) can be represented as

$$h = k_2 q_{eq}^2 \quad (5)$$

The kinetic data were fitted to Lagergren's pseudo-second-order rate equation and plots of t/q versus t were obtained for both 50 and 100 mg Th/L (Figs. 3 and 4). The equilibrium uptake, initial sorption rate and pseudo-second-order rate constant were calculated from slope and intercept of the Lagergren's pseudo-second-order plot and are tabulated in Table 1b. All these parameters were affected by change in initial pH and initial concentration of the solution. The equilibrium uptake (q) increased with increasing pH both, at 50 and 100 mg/L. The initial sorption rate (h) increased from 2.98 mg/g min at pH 2.0 to 71.94 mg/g min at pH 4 (50 mg Th/L). Similarly, the initial sorption rate (h) changed from 3.90 (mg/g min) to 21.78 (g/mg min) at 100 mg Th/L while the pH was increased from 2.0 to 4.0. All r^2 values obtained from the plots were found to be above 0.95.

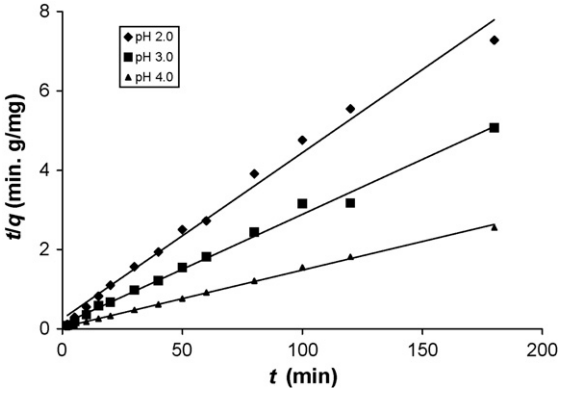

Fig. 4. Lagergren's pseudo-second-order kinetics of thorium biosorption at 100 mg Th/L, pH 2.0–4.0.

Table 1b
Lagergren's pseudo-second-order rate constant at different pH for thorium biosorption.

	pH	q_e (mg/g)	h (mg/g min)	k_2 (g/mg min)	r^2
50 mg/L	2	15.87	2.98	1.18×10^{-2}	0.997
	3	20.16	4.28	1.05×10^{-2}	0.998
	4	30.21	71.94	7.82×10^{-2}	0.999
100 mg/L	2	23.86	3.90	6.85×10^{-3}	0.989
	3	36.10	8.33	6.39×10^{-3}	0.993
	4	69.44	21.79	4.52×10^{-3}	0.998

Data obtained from the kinetic of uptake when modeled with pseudo-second-order equation showed excellent fitting (Figs. 3 and 4) and the kinetic rate constant and r^2 values are >0.99 (Table 1b). This suggests that the kinetics of Th uptake followed Lagergren's pseudo-second-order equation. This was further confirmed by calculating the q_e based on pseudo-second-order reaction that showed very good fit between the experimental data and the predicted curve obtained by modeling the uptake value (Fig. 2a and b). Similar kinetic trend have been reported for uptake of metal ions by microbial biomass in earlier studies [26–28]. The result indicates that thorium uptake follows a pseudo-second-order reaction model, which agrees with chemisorption as the rate-limiting step [28].

3.3. Biosorption isotherm

Thorium uptake by the fungal biomass was modeled by both Langmuir and Freundlich type isotherms. Langmuir model assumes uniform energies of adsorption with no transmigration of adsorbate in the plane of the surface. Hence this model is valid for the monolayer adsorption onto a surface, containing a finite number of identical sites [29]. The Langmuir isotherm is represented by the following equation:

$$q_e = Q_0 b C_e / (1 + b C_e) \quad (6)$$

where C_e is the equilibrium concentration (mg/L) and q_e is the amount adsorbed per specified amount of adsorbent (mg/g), Q_0 is the amount of adsorbate required to form a monolayer (known as 'maximum loading capacity'). The linear form of Langmuir isotherm can be represented as

$$\frac{C_e}{q_e} = \left(\frac{1}{Q_0}\right) C_e + \left(\frac{1}{Q_0 b}\right) \quad (7)$$

The affinity constant b, of Langmuir isotherm related to the energy of adsorption can be utilized to find out if the biosorption process is favorable at a certain concentration. This is achieved by deriving a dimension less separation factor, R_L, represented as

$$R_L = \frac{1}{1 + b C_o} \quad (8)$$

where C_o is the initial concentration of Th in the solution.

Freundlich model describes monolayer adsorption with lateral interaction between sorbed species on the surface. According to this model:

$$q_e = K_F C_e^{1/n} \quad (9)$$

or

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (10)$$

where all the terms have usual significance as above and $1/n$ and K_F refer to the intensity of adsorption and Freundlich constants,

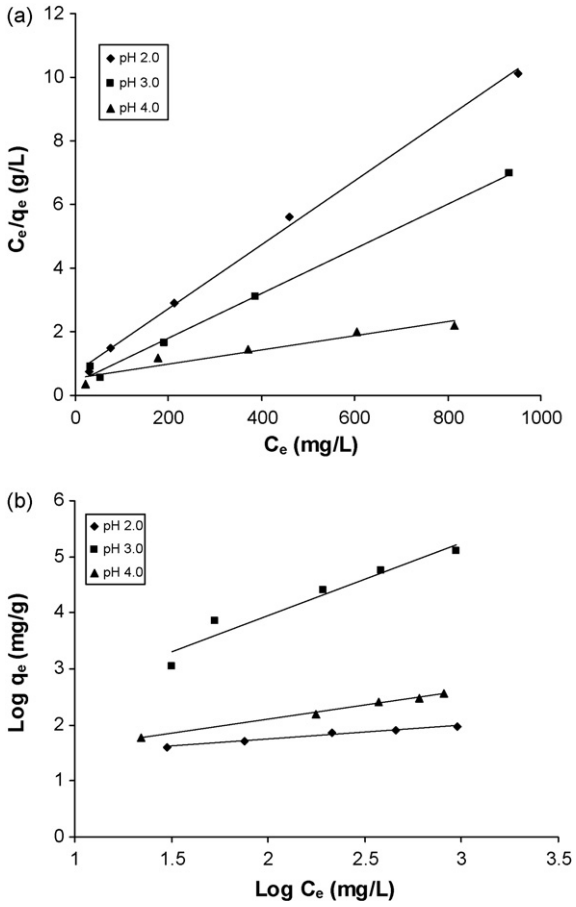

Fig. 5. (a) Linearised Langmuir biosorption isotherm of Th uptake at varying initial pH and (b) linearised Freundlich biosorption isotherm of Th uptake at varying initial pH.

respectively. Thus a plot of $\log q_e$ versus $\log C_e$ should be a straight line with the slope of $1/n$ and intercept of $\log K_F$.

Temkin isotherm model assumes that the heat of adsorption of all the molecules in the layer decreases linearly rather than in a logarithmic manner, as implied in the Freundlich isotherm. Temkin isotherm model is given by the equation [30]:

$$q_e = RT/b \ln(AC_e) \quad (11)$$

$$q_e = B \ln A + B \ln C_e \quad (12)$$

Table 2
Isotherm constant parameters for thorium biosorption by *Aspergillus fumigatus*.

Isotherm type	Thorium biosorption at initial pH		
	2	3	4
Langmuir constants			
Q_0 (mg/g)	99	143	455
b (L/mg)	0.014	0.018	0.004
r^2	0.997	0.995	0.933
Freundlich constants			
K_F (L/g)	17.10	21.82	12.27
n	3.922	0.766	1.984
r^2	0.980	0.939	0.993
Temkin isotherm			
A (L/g)	2.71	2.61	1.45
B	16.10	24.90	81.66
r^2	0.989	0.785	0.915

Table 3
Biosorption of thorium by fungal biomasses.

Fungal biomasses	Biosorption capacity (mg Th/g biomass)	References
Aspergillus niger	22	[3]
Aspergillus terus	60	[3]
A. fumigatus	370	This work
Penicillium chrysogenum	142	[3]
Rhizopus arrhizus	185	[3]
Saccharomyces cerevisiae	119	[11]

where $B = (RT)/b$, R is the universal gas constant (8.314 J/mol K), T is absolute temperature in K, C_e is the residual equilibrium concentration (mg/L) and q_e is the amount adsorbed per specified amount of adsorbent (mg/g) at equilibrium.

The plots obtained by modeling the uptake data using straight-line form of Langmuir and Freundlich have been presented in Fig. 5a and b. The isotherm parameters have been calculated from the respective slopes and intercepts and are presented in Table 3.

The uptake process could be well described by Langmuir, Freundlich and Temkin isotherm as shown by the r^2 values at varying initial pH (Table 2). The maximum loading capacity (Q_0) calculated from Langmuir plot at initial pH of 2, 3 and 4 were 99, 143 and 455 mg Th/g biosorbent, respectively, whereas the observed values were 94, 134 and 370 mg Th/g biomass, respectively. The data clearly shows lesser uptake at pH 2 compared to pH 4.0. This again could be attributed to favorable binding of bivalent $Th(OH)_2^{2+}$ onto the biomass together with lower solubility of Th at higher pH. The maximum loading capacity at pH 2.0 was similar to the thorium uptake capacity (90 mg Th/g biosorbent) reported for *R. arrhizus* [19]. However, the biosorption capacity observed at pH 4.0 was two times higher than the biosorption capacity shown by *R. arrhizus*

Table 4
Desorption of bound thorium using different desorption solution.

Desorption reagent	Amount of Th desorbed[a] (expressed as percent of sorbed[b] metal)
1 M HCl	87
1 M H_2SO_4	80
1 M HNO_3	79
1 M $NaHCO_3$	99
1 M Na_2CO_3	97
0.1 M EDTA	91

[a] 50 mg of Th-loaded (49 mg Th/g) biomass was contacted with 50 mL of the respective desorption reagent and incubating in the environmental shaker at 150 rpm, 25 °C.
[b] Thorium-loaded biomass, 100% value is 49 mg Th/g.

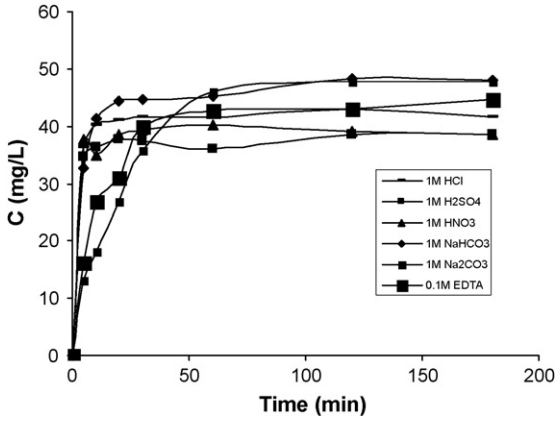

Fig. 6. Desorption kinetics of Th (150 rpm, 25 °C).

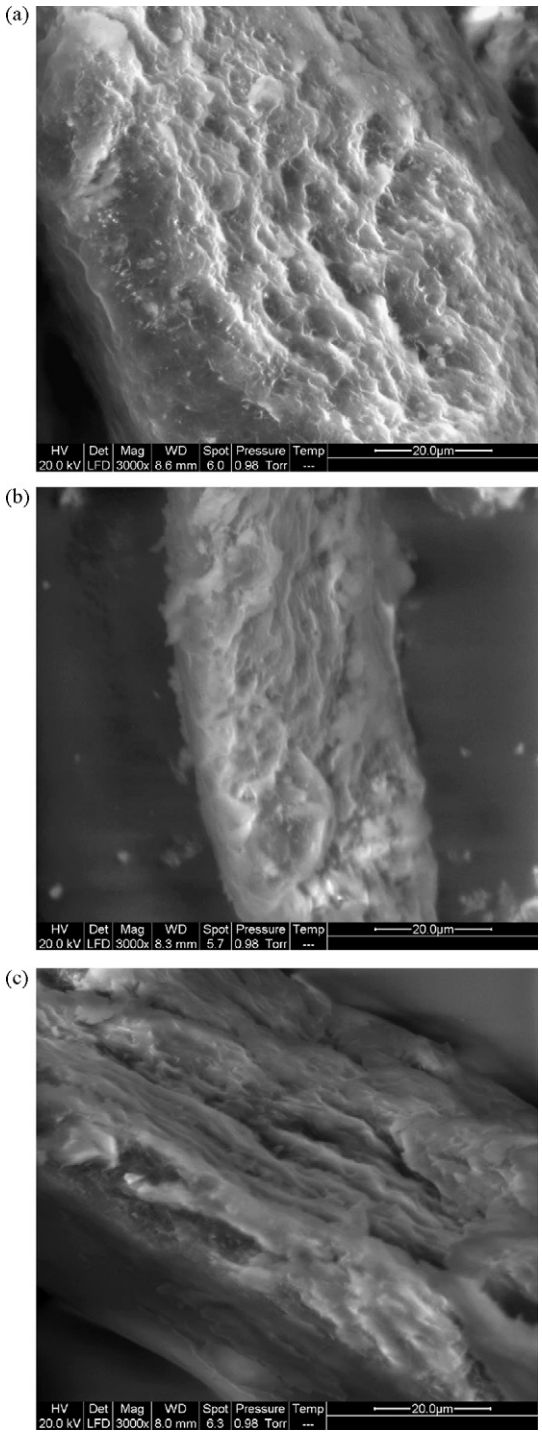

Fig. 7. Environmental scanning electron micrograph (ESEM) of biomass before and after desorption. (a) Typical micrograph of *A. fumigatus*, (b) micrograph of Th-loaded *A. fumigatus* and (c) micrograph of *A. fumigatus* after desorption with 1 M $NaHCO_3$.

[3], the best known fungal biosorbent known for thorium so far. The observed Q_0, 370 mg Th/g (corresponding to 455 mg/g calculated value) in this study is the highest for thorium biosorption by any fungal biomass reported in the literature until now (Table 3). The data also suggests that, the thorium uptake exhibited by this biomass surpasses the economic threshold value proposed (>15%) for a biosorbent to be practically applicable [31].

When $0 < R_L < 1$, the sorption process is considered as favorable. Based on Eq. (8) the R_L values obtained at initial pH of 2, 3 and 4 at 50 mg Th/L were 0.59, 0.53 and 0.83, respectively. Similarly the values obtained at highest initial concentration studied, i.e., 1000 mg Th/L were 0.07, 0.05 and 0.2, respectively. Since all the R_L values are less than 1, the thorium biosorption process is favorable in the pH and concentration range included in this study.

The values of Freundlich isotherm constant (K) and n at all initial pH indicated high Th biosorption capacity and favorable uptake by the fungal biomass.

3.4. Desorption of bound Th

Desorption of the bound metal ion is an important aspect for application of the biosorbent in a biosorption process. In view of this, various desorbing reagents were used to assess their desorption efficiency. Among all, mineral acids were least effective in removing the bound Th from the biomass (Table 4). The best-eluting agent were 1 M Na_2CO_3 and 1 M $NaHCO_3$ showing 97 and 99% desorption, respectively. EDTA even at 0.1 M concentration eluted 91% of the bound Th. In our previous study we had observed maximum desorption efficiency of 93% using 1 M $CaCO_3$ [14].

Though, biosorption kinetics is being investigated for many biosorption systems, desorption kinetics is rarely reported. However, for the biosorbent to be applied successfully, desorption kinetics is equally important. In view of this kinetics of desorption, i.e., release of metal ion into the solution was investigated and the data has been presented in Fig. 6. The desorption process was fast and more than 80% bound Th were released into the medium within 10 min of contact time using 1 M $NaHCO_3$. However, maximum desorption of 99% was achieved only after 2 h of contact time. Though 1 M sodium carbonate showed equally good equilibrium desorption (97%) in terms of kinetics it was slower in comparison to 1 M $NaHCO_3$. Other reagents were poor both in terms of overall efficiency as well as kinetics of desorption. Hence, present results suggest that bound Th could be successfully released using 1 M sodium bicarbonate allowing the biomass to be used in subsequent cycle of biosorption.

3.5. ESEM study

The surface structure of biomass before Th uptake (Fig. 7a) showed many small grooves which become less prominent after uptake (Fig. 7b). After desorption of the bound Th (Fig. 7c) by sodium bicarbonate the surface structure was found to be similar to the biomass before uptake. This indicates the successful desorption of the bound thorium had very little affect and thus repeated sorption and desorption of Th onto the biomass possible.

4. Conclusions

Thorium uptake by *A. fumigatus* biomass was dependent on initial pH and optimum pH favoring the process was found to be pH 4.0. The process was rapid and followed Lagergren's pseudo-second-order kinetics indicating it operates through chemisorption mechanism. Equilibrium thorium uptake capacity was found to be 370 mg Th/g biosorbent, highest so far for any fungal biomass in relation to thorium biosorption. The equilibrium uptake could be well described by Langmuir isotherm. Thorium biosorbed onto the biomass could be desorbed efficiently using 1 M sodium bicarbonate. The surface of the biomass was stable after desorption as showed by ESEM study. The overall performance of the biomass suggests that it can serve as a useful biosorbent for thorium removal from aqueous solution.

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