Chapter 5  Screening of algae for biosorption of uranium
5.1. Materials

5.1.1. Collection of biomass

The algal biomass after collection was washed thoroughly with tap water. This was followed by washing three times with the deionised water and finally by glass distilled water in order to get a clean biomass that is free from silt, sand, diatoms and other epiphytic organisms. Biomass after cleaning was dried at an ambient temperature of 25 ± 2 ºC. Biomass was powdered using mortar and pestle to get a uniform particle size. The particle size that could pass through the sieve of 500 µm but was retained by the 250 µm sieve size was used for the experiments.

5.1.2. Chemicals:

\( \text{UO}_2(\text{NO}_3)_2.6\text{H}_2\text{O} \) (Merck, Germany) was used to prepare the uranium solution. The pH of the uranium solution was adjusted to required values by using \( \text{Na}_2\text{CO}_3 \) or \( \text{HNO}_3 \).

5.2. Methods:

Except otherwise indicated, for all the sorption experiments 50 mg of dry biomass was introduced to 50 ml of uranium solution in 150 ml conical flasks in a temperature controlled environmental shaker (30 ± 2 ºC) at 150 rpm. All experiments were performed using the biomass having a uniform particle size of 250-500 µm. Estimation of uranium (VI) was done by Arsenazo (III) method (Savvin, 1961). Briefly 0.5 ml sample was mixed with 0.1 ml of oxalic acid (4%) and 0.1 ml of Arsenazo (III) (0.05%) and diluted with hydrochloric acid (4 M) to a total volume of
2.5 ml before analyzing at a wavelength of 650 nm. The data presented in the result represents the average of the triplicate readings ± standard error. The statistical analysis was done for Analysis of variance (One way ANOVA and Tukey’s significance test) OriginPro 7.5 software. The values having $P<0.05$ were considered as significantly different. For each of the experiments, solutions without biomass were used as controls.

The biosorption equilibrium of uranium per unit algal biomass (mg of U/g dry weight of algal biomass) was calculated using following expression

$$q_e = \frac{[C_0 - C] \times V}{W} \quad (5.1)$$

where ‘$C_0$’ and ‘$C$’ are the concentration of uranium (mg/l) in the solution before and after the biosorption respectively. ‘$V$’ is the volume of uranium solution used in liters and ‘$W$’ is the amount of biomass used in grams.

### 5.2.1. Screening of algae for Uranium biosorption.

The screening of all of algae was done at pH 2.5 and 7.5. Initial concentration of the uranium solution was 100 mg/l. The estimation of the uranium left out in the solution was done after 3 hours of contact time. Amount of uranium sorbed was calculated using the equation 5.1. The algae showing more than 40% uranium removal in this study were selected for further studies.

### 5.2.2. Effect of pH on uranium sorption.

The effect of pH on the biosorption of uranium was studied for the algae that were short listed based on the results of screening data, using an initial uranium concentration of 100 mg/l. The residual uranium concentration was estimated from the samples withdrawn after 3 hours. The range of pH studied was 1.5 to 7.5.
5.2.3. Effect of contact time on uranium biosorption.

Effect of contact time was investigated at an initial uranium concentration of 100 mg/l. Periodically, 0.5 ml of sample was withdrawn, centrifuged at 10,000 rpm for 10 minutes, and the dissolved uranium concentration was estimated. Sorption kinetics was investigated at two pH values for each of the short listed algae, one being the optimum pH for the sorption process, and, other one the extreme pH (2.5 or 7.5) where the alga has showed good sorption potential in screening studies.

5.2.4. Metal loading capacity of short listed algal samples.

Maximum uranium loading capacity for each of the short listed algae was determined by repeatedly contacting the biomass with freshly prepared uranium solution. Briefly, 100 ml, 100 mg/l Uranium solution was brought in contact with algae. After the equilibrium was achieved, $C_f$ and $q_e$ were calculated. The biomass were filtered and again brought in contact with freshly prepared 100 mg/l uranium solution. Again the $C_f$ and $q_e$ were calculated after achieving the equilibrium. The process was repeated till the biomass did not show further removal of uranium.

5.3. Results and discussions

5.3.1. Screening of algae for Uranium biosorption

The objective behind the screening of a large number of algae was to shortlist those algae that can remove uranium from aqueous medium at pH 2.5 and/or 7.5. There are either no or very rare reports on the biosorbents of uranium performing efficiently under such conditions. Different functional groups present on the biomass remain in ionized form at or near their pK values (Davis et al., 2003; Kalin et al., 2005). Thus as the number and diversity of functional groups present on the biomass surface
increases, the sorption of metal ions by the same biomass at different pH values can be expected. Algae have a complex cell wall as compared to bacteria and fungi, to the extent that within the algae group we need to differentiate three evolutionary pathways, green algae, brown algae, and red algae (Romera et al., 2006).

There are studies reporting the use of algae for the bioremediation of heavy metals, however there are only few reports on the possible use of algae for the sorption of uranium (Vieira and Volesky, 2000). In an exhaustive screening, 63 different algae (23 from division Chlorophyta, 12 from Phaeophyta, 25 from Rhodophyta, and 3 from Cyanophyta) from marine water, fresh water and brackish water habitats, belonging to four different divisions were screened for the sorption of uranium at pH 2.5 and 7.5. The percent removal of uranium at pH 2.5 and 7.5 by the algae was calculated and data was presented in Table 5.1.

**Table 5.1. Percent removal of uranium at pH 2.5 and 7.5 by different algae collected from different habitats** (M.W. = Marine water, F.W. = Fresh water, E.W. = Estuarine water), (V = 50 ml, W = 50 mg, Temperature = 30 ± 2 ºC, Contact time = 3 hrs).

<table>
<thead>
<tr>
<th>Number</th>
<th>Name of the algae</th>
<th>Habitat</th>
<th>% Removal at pH 2.5</th>
<th>% Removal at pH 7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td><em>Bryopsis pennata</em></td>
<td>M.W.</td>
<td>2.4 ± 0.5</td>
<td>2.5 ± 0.4</td>
</tr>
<tr>
<td>2.</td>
<td><em>Caulerpa peltata</em></td>
<td>M.W.</td>
<td>9.5 ± 1.2</td>
<td>8.1 ± 1</td>
</tr>
<tr>
<td>3.</td>
<td><em>Caulerpa sertularioides</em></td>
<td>M.W.</td>
<td>3.4 ± 0.6</td>
<td>3.4 ± 0.7</td>
</tr>
<tr>
<td>4.</td>
<td><em>Caulerpa taxifolia</em></td>
<td>M.W.</td>
<td>8.7 ± 0.6</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>5.</td>
<td><em>Chara wallichi</em></td>
<td>F.W.</td>
<td>5.2 ± 1</td>
<td>0.0 ± 0.0</td>
</tr>
</tbody>
</table>
6. *Chlorella vulgaris*  
   F.W. 7.3 ± 1.2 40 ± 2
7. *Cladophora colabensis*  
   B.W. 11.3 ± 3 16.9 ± 3
8. *Cladophora attenuata*  
   M.W. 3.2 ± 2 16.9 ± 2
9. *Cladophoropsis zollingeri*  
   M.W. 5.4 ± 1.2 8.0 ± 1.9
10. *Enteromorpha prolifera*  
    M.W. 6.6 ± 2.3 9.2 ± 1.2
11. *Enteromorpha kylini*  
    M.W. 4.6 ± 0.6 8.3 ± 1.5
12. *Hydrodictyon reticulatum*  
    F.W. 7.8 ± 1.4 0.0 ± 0.0
13. *Monostroma oxyspermum*  
    M.W. 16.9 ± 1.9 1.9 ± 0.2
14. *Nitella hyalina*  
    F.W. 0.0 ± 0.0 6.4 ± 1.2
15. *Pithophora polymorpha*  
    F.W. 0.7 ± 0.1 4.0 ± 0.7
16. *Pseudobryopsis mucronata*  
    M.W. 2.6 ± 0.3 4.6 ± 0.8
17. *Rhizoclonium kochianum*  
    M.W. 47.2 ± 1.6 11.45 ± 0.7
18. *Spirogyra crassa*  
    F.W. 38.4 ± 1.3 30.5 ± 1.5
19. *Spongomorpha indica*  
    M.W. 9.0 ± 1.3 5.3 ± 1
20. *Tetrasporidium javanicum*  
    F.W. 0.0 ± 0.0 0.0 ± 0.0
21. *Ulva fasciata*  
    M.W. 0.35 ± 0.0 10.1 ± 0.2
22. *Ulva lactuca*  
    M.W. 6.0 ± 0.5 16.1 ± 0.6
23. *Valoniopsis pachynema*  
    M.W. 12.4 ± 0.4 16.1 ± 0.5
24. *Zygnema cylindrosporum*  
    F.W. 3.16 ± 0.2 0.28 ± 0.0

**Division Phaeophyta**

25. *Dictyota bartayresiana*  
    M.W. 0.0 ± 0.0 2.0 ± 0.3
26. *Dictyopteris woodwardii*  
    M.W. 7.0 ± 1.2 5.7 ± 0.8
27. *Padina tetrastromatica*  
    M.W. 62 ± 2.1 5.5 ± 0.9
| 28. | Sargassum crassifolium | M.W. | 6.0 ± 0.8 | 0.3 ± 0.1 |
| 29. | Sargassum swartzii | M.W. | 1.5 ± 0.1 | 17.9 ± 2.1 |
| 30. | Sargassum tenerrimum | M.W. | 62.7 ± 2.5 | 35 ± 0.1 |
| 31. | Sargassum wightii | M.W. | 0.0 ± 0.0 | 13.4 ± 2.3 |
| 32. | Sphacelaria furcigera | M.W. | 4.9 ± 1.1 | 11.2 ± 2.1 |
| 33. | Spatoglossum asperum | M.W. | 60 ± 0.2 | 90 ± 3.1 |
| 34. | Stoechospermum marginatum | M.W. | 0.31 ± 0.0 | 18.8 ± 2.1 |
| 35. | Giffordia mitchellae | M.W. | 3.9 ± 0.7 | 5 ± 1.5 |

**Division Rhodophyta**

<p>| 36. | Acanthophora delilei | M.W. | 17.2 ± 1.6 | 3.7 ± 0.6 |
| 37. | Amphiroa anceps | M.W. | 3.2 ± 0.1 | 17 ± 1.2 |
| 38. | Bostrychia radicans | M.W. | 2.8 ± 0.3 | 3.4 ± 0.5 |
| 39. | Caloglossa leprieurii | M.W. | 4.2 ± 1.3 | 13.7 ± 1.5 |
| 40. | Compsopogon coeruleus | F.W. | 8.0 ± 1.5 | 3.6 ± 0.6 |
| 41. | Catenella repens | E.W. | 49.5 ± 3 | 6.6 ± 1.2 |
| 42. | Centroceras clavulatum | M.W. | 3.1 ± 0.8 | 0.3 ± 0.1 |
| 43. | Ceramium rubrum | M.W. | 0.0 ± 0.0 | 0.3 ± 0.1 |
| 44. | Dasya iyengarii | M.W. | 0.0 ± 0.0 | 0.3 ± 0.0 |
| 45. | Gelidium micropterum | M.W. | 5.6 ± 0.9 | 8.9 ± 1 |
| 46. | Gelidium pusillum | M.W. | 0.4 ± 0.1 | 4.8 ± 0.8 |
| 47. | Gracilaria corticata | M.W. | 1.5 ± 0.1 | 11.5 ± 1.3 |
| 48. | Gracilaria foliifera | M.W. | 5.2 ± 0.9 | 2.5 ± 1.3 |
| 49. | Grateloupia lithophila | M.W. | 0.0 ± 0.0 | 3.8 ± 0.9 |</p>
<table>
<thead>
<tr>
<th></th>
<th>Species</th>
<th>Category</th>
<th>M.W.</th>
<th>F.W.</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.</td>
<td>Hypnea musciformis</td>
<td>M.W.</td>
<td>7 ± 2</td>
<td>10.6 ± 3</td>
</tr>
<tr>
<td>51.</td>
<td>Hypnea valentiae</td>
<td>M.W.</td>
<td>1 ± 0.5</td>
<td>10.6 ± 1.6</td>
</tr>
<tr>
<td>52.</td>
<td>Jania rubens</td>
<td>M.W.</td>
<td>30.8 ± 3.2</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>53.</td>
<td>Laurencia pedricularioides</td>
<td>M.W.</td>
<td>5.6 ± 1.2</td>
<td>5.3 ± 1.1</td>
</tr>
<tr>
<td>54.</td>
<td>Porphyra vietnamensis</td>
<td>M.W.</td>
<td>2.7 ± 0.5</td>
<td>10.8 ± 0.9</td>
</tr>
<tr>
<td>55.</td>
<td>Rhodymenia palmetta</td>
<td>M.W.</td>
<td>4.9 ± 0.8</td>
<td>4.1 ± 0.6</td>
</tr>
<tr>
<td>56.</td>
<td>Jania rubens</td>
<td>M.W.</td>
<td>30.8 ± 3.2</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>57.</td>
<td>Sarconema filiforme</td>
<td>M.W.</td>
<td>6.7 ± 2.3</td>
<td>3 ± 0.6</td>
</tr>
<tr>
<td>58.</td>
<td>Sirodotia cirrhosa</td>
<td>F.W.</td>
<td>1 ± 0.5</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>59.</td>
<td>Solieria robusta</td>
<td>M.W.</td>
<td>10.9 ± 3.5</td>
<td>1.3 ± 0.9</td>
</tr>
<tr>
<td>60.</td>
<td>Spyridia filamentosa</td>
<td>M.W.</td>
<td>1.7 ± 1.2</td>
<td>4.0 ± 1.5</td>
</tr>
</tbody>
</table>

**Division Cyanophyta**

<table>
<thead>
<tr>
<th></th>
<th>Species</th>
<th>Category</th>
<th>M.W.</th>
<th>F.W.</th>
</tr>
</thead>
<tbody>
<tr>
<td>61.</td>
<td>Scytonema bohneri</td>
<td>F.W.</td>
<td>0.4 ± 0.1</td>
<td>6.8 ± 2.3</td>
</tr>
<tr>
<td>62.</td>
<td>Lyngbya majascula</td>
<td>M.W.</td>
<td>3.4 ± 1.6</td>
<td>15 ± 2.5</td>
</tr>
<tr>
<td>63.</td>
<td>Nostoc linckia</td>
<td>F.W.</td>
<td>0.7 ± 0.3</td>
<td>0.0 ± 0.0</td>
</tr>
</tbody>
</table>

The algae showing a percent removal of uranium ≥ 40% at pH 2.5 and/or 7.5 were *Chlorella vulgaris* (Chlorophyta), *Padina tetrastromatica*, *Sargassum tenerrimum* and *Spatoglossum asperum* (Phaeophyta), and, *Catenella repens* (Rhodophyta). The % removal of uranium at pH 2.5 and 7.5 for *C. vulgaris* was 7.3 ± 1.2 and 40 ± 2, for *P. tetrastromatica* was 62 ± 2.1 and 5.5 ± 0.9, for *S. tenerrimum* was 62.7 ± 2.5 and 35 ± 0.1, for *S. asperum* was 2.1 ± 0.2 and 79.7 ± 3.1, and for *C. repens* was 49.5 ± 3
and 6.6 ± 1.2, respectively. These five algae were shortlisted and selected for the subsequent studies.

5.3.2. Effect of pH on uranium sorption.

The effect of pH on biosorption of uranium by *C. vulgaris*, *P. tetrastromatica*, *S. tenerrimum*, *S. asperum*, and *C. repens* was investigated in order to find out the optimum pH for the sorption process, and to elucidate the performance of biomasses across the pH range 1.5 to 7.5. A plot of pH versus $C_f$ was plotted (Fig. 5.1).

**Fig. 5.1. Effect of pH on the biosorption of uranium by** *C. vulgaris*, *P. tetrastromatica*, *S. tenerrimum*, *S. asperum*, and *C. repens*. *(V = 50 ml, W = 50 mg, Temperature = 30 ± 2 °C, Contact time = 3 hrs).*

![Graph showing pH vs. concentration of uranium](image)

pH optima for the sorption process was 4.5 while using *C. vulgaris*, *P. tetrastromatica*, *S. tenerrimum*, and *C. repens* as sorbents. However, the pH optimum for *S. asperum* was found to be across the pH range of 4.5 to 5.5. At pH 4.5 the initial uranium concentration of 100 mg/l was reduced to 14.5 mg/l by Chlorella, 6.67 mg/l.
by *P. tetrastromatica*, 4.2 mg/l by *S. tenerrimum*, 1.7 mg/l by *S. asperum* and to 10 mg/l by *C. repens*. A similar kind of trend was followed for the sorption of uranium by all the biomass. A decreased biosorption at low pH values like 1.5 and 2.5 was observed for all the biomass. As the pH was increased, biosorption also increased, and reached the maximum around pH 4.5. Concomitant increase in pH above 4.5 resulted in decrease of biosorption. The reason suggested for the decreased biosorption at low pH like 1.5 and 2.5 could be because at this pH there is a high concentration of H$^+$ and H$_3$O$^+$, which compete with other ions (uranyl) for the binding sites on the surface of the biomass (Sar and D’Souza, 2002). The reason for increased biosorption at pH 4.5 could be due to the presence of ligands like carboxyl, amino, and phosphate on the surface of biomass, which have $pK$ values in the range of 3 to 5 (Kalin *et al*., 2005). Decrease in the uptake of uranium at higher pH could be due to the formation of uranyl carbonate complexes, as the initial pH of the solution was adjusted with Na$_2$CO$_3$, and also, atmospheric CO$_2$ plays a role in the formation of uranyl carbonate complexes above pH 6 (Krestou and Panias, 2004). At higher pH values the aqueous carbonate competes with surface binding sites (present on the surface of biomasses) for uranyl ions and reduces the availability of uranium for biosorption (Wazne *et al*., 2006). Also at higher pH, formation of solid schoepite (4UO$_3$.9H$_2$O) takes place, which decreases the dissolved uranium concentration in solution, and consequently leads to the reduced sorption of uranium onto the biomass (Saxena *et al*., 2006). For all the subsequent experiments, in addition to the pH optima, *C. vulgaris* and *S. asperum* were investigated at pH 7.5, and *P. tetrastromatica*, *S. tenerrimum*, and *C. repens* were also investigated at pH 2.5.
5.3.3. Effect of contact time on uranium biosorption

The aim of this study was to find out the time taken to achieve the equilibrium state. For all the five algae studied, the initial stage of sorption was rapid, followed by a slow stage. The plot of $q_e$ versus time is shown in Fig. 5.2-5.6

**Fig. 5.2. Effect of contact time on the sorption of uranium by *C. vulgaris*.** ($V = 50$ ml, $W = 50$ mg, Temperature = 30 ± 2 °C).
Fig. 5.3. Effect of contact time on the sorption of uranium by *P. tetrastromatica*. 

\( V = 50 \text{ ml}, W = 50 \text{ mg}, \text{Temperature} = 30 \pm 2 ^\circ \text{C} \).

![Graph](image)

Fig. 5.4. Effect of contact time on the sorption of uranium by *S. tenerrimum*. \( V = 50 \text{ ml}, W = 50 \text{ mg}, \text{Temperature} = 30 \pm 2 ^\circ \text{C} \).

![Graph](image)
Fig. 5.5. Effect of contact time on the sorption of uranium by *S. asperum*. (V = 50 ml, W = 50 mg, Temperature = 30 ± 2 °C).

Fig. 5.6. Effect of contact time on the sorption of uranium by *C. repens*. (V = 50 ml, W = 50 mg, Temperature = 30 ± 2 °C).
These figures also indicated that sorption took place in two stages, first one was rapid surface adsorption and the second one was a slow intracellular diffusion. The higher rate of biosorption in initial stage of biosorption could be due to electrostatic interactions, between metal ions and surface ligands on the algal biomasses. These binding sites present on surface of the biomasses start binding to uranyl ions as soon as they come in contact with each other (Mungasavalli et al., 2007; Zafar et al., 2007). The metal removal was rapid, with more than 50% of total biosorption taking place in initial 30 minutes of contact time. The $q_e$ for C. vulgaris was 97.6 ± 3 and 44.5 ± 4 mg/g at pH 4.5 and 7.5 respectively. Similarly, for S. asperum $q_e$ was 98.4 ± 1.02 and 84.9 ± 0.8 mg/g at pH 5.5 and 7.5 respectively. For P. tetrastromatica, S. tenerrimum, and C. repens, $q_e$ of 59.9 ± 1.9 and 94.5 ± 0.7; 65 ± 1.9 and 91.5 ± 0.49; and, 67.2 ± 0.46 and 93.7 ± 0.25 mg/g could be achieved at pH 2.5 and 4.5 respectively. Time taken to achieve equilibrium for the sorption process was 120 min while using C. vulgaris, at pH 4.5 and 7.5; 120 and 180 min for S. asperum at pH 5.5 and 7.5 respectively; 60 min for P. tetrastromatica at pH 2.5 and 4.5; 60 and 45 min for S. tenerrimum at pH 2.5 and 4.5 respectively; and 45 min for C. repens at pH 2.5 and 4.5. Rapid sorption is considered as a good characteristic of a biosorbent, as it allows short solution-sorbent contact time, and also allows the use of shallow contact beds of sorbent materials in column applications (Volesky, 1990). For all the subsequent studies it was ensured that enough time for contact of biomass with uranyl solution was provided. Therefore, for all of the subsequent studies data for 3 hours has been presented. After the equilibrium was achieved, $q_e$ remained constant (studied for 24 hours, data not shown).
5.3.4. Metal loading capacity of short listed algae

Maximum metal loading capacity for *C. vulgaris*, *P. tetrastomatica*, *S. tenerrimum*, *S. asperum*, and *C. repens* was investigated. The results are shown in Table 5.2.

**Table 5.2.** Maximum metal loading capacities of different algae at corresponding residual uranium concentration values.

<table>
<thead>
<tr>
<th>Algae</th>
<th>pH</th>
<th>(q_{\text{max}}) (mg/g)</th>
<th>(C_r) (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Chlorella vulgaris</em></td>
<td>4.5</td>
<td>375 ± 10</td>
<td>400 ± 8</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>130 ± 7</td>
<td>600 ± 12</td>
</tr>
<tr>
<td><em>Padina tetrastromatica</em></td>
<td>2.5</td>
<td>180 ± 5</td>
<td>410 ± 15</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>450 ± 7</td>
<td>375 ± 8</td>
</tr>
<tr>
<td><em>Sargassum tenerrimum</em></td>
<td>2.5</td>
<td>200 ± 8</td>
<td>400 ± 6</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>500 ± 6</td>
<td>350 ± 8</td>
</tr>
<tr>
<td><em>Spatoglossum asperum</em></td>
<td>5.5</td>
<td>625 ± 10</td>
<td>300 ± 8</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>200 ± 10</td>
<td>400 ± 10</td>
</tr>
<tr>
<td><em>Catenella repens</em></td>
<td>2.5</td>
<td>225 ± 5</td>
<td>380 ± 7</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>280 ± 6</td>
<td>530 ± 5</td>
</tr>
</tbody>
</table>

A metal loading capacity of greater than 15% of biomass and dry weight has been defined as an economic threshold for practical application of biosorption (Kalin *et al.*, 2005). The maximum metal loading capacity achieved in percent values was, 37 and 13 for *C. vulgaris* at pH 4.5 and 7.5 respectively; 18 and 45 for *P. tetrastromatica* at pH 2.5 and 4.5 respectively; 20 and 50 for *S. tenerrimum* at pH 2.5 and 4.5 respectively; 62 and 20 for *S. asperum* at pH 5.5 and 7.5 respectively; and, 22 and 28 for *C. repens* at pH 2.5 and 4.5 respectively. The corresponding residual concentration of uranium at which the maximum metal loading capacity was attained is also given in the table 2. Except *C. vulgaris* at pH 7.5, all the biomasses have shown a good metal loading capacity. Using the same biomass, a significant difference in \(q_e\) at two different pH values was observed. The difference in \(q_e\) at two
pH values could be because, the different functional groups (carboxylates, hydroxyl, sulphate, phosphate etc) present on surface of the biomass, ionize at pH around their pK values (Bayramoglu et al., 2006; Davis et al., 2003). Thus, the functional groups, which are in ionized form at one pH, may not be ionized at other pH. Therefore at two different pH values, number of binding sites available for the sorption of uranium would not be same.

Yang and Volesky (1999) reported *Sargassum fluitans* a brown alga having a uranium loading capacity of 15% at pH 2.6. Kalin et al., (2005), while reviewing the use of algae and microbes, for the removal of uranium from mining waste waters, reported the uranium loading capacity of 0.28% for *C. vulgaris* at pH 3.5, 0.42% for *Rhizopus arrhizus* at pH 3.5, and 0.2% for *Penicillium* spp. at pH 3.5. As compared with the existing biosorbents, the findings of our investigations indicate a possible use of *C. vulgaris, P. tetrastromatica, S. tenerrimum, S. asperum, and C. repens* for efficient and cost effective treatment method for uranium removal from aqueous wastes having a variable pH.

5.4. Conclusions

The search for ideal biosorbents for uranium has been an active field of research. A number of biosorbents for uranium have already been reported, but to the best of our knowledge none has proved to be an efficient biosorbent at low, neutral or near neutral pH values. This work shortlists five different algae amongst the 63 screened for uranium sorption, and, describes their potential for uranium sorption with respect to the following points
• The natural occurrence of these algae in sea water, brackish water, and, due to their photosynthetic property makes them easily available and a cheap source of biosorbent material.

• The removal of uranium by algae was fast, with more than 50% of the total biosorption taking place in 30 min.

• An efficient metal loading capacity (>15 %) at pH 2.5 (in addition to the loading capacity at optimum pH of the sorption process) was achieved while using *P. tetrastromatica*, *C. repens*, and *S. tenerrimum*. We were the first to report the possible sorption of uranium at a low pH of 2.5, using a sorbent biological origin (Bhat *et al.*, 2008).

• *S. asperum* could remove uranium efficiently at pH 7.5. For the best of our knowledge, this is also the first report of efficient uranium sorption at pH 7.5 using any kind of biological sorbent.

As discussed earlier in the sections 2.3.1, 2.3.2, and 5.3.1, that the biosorbents reported by various researchers have the limitations to perform efficiently at pH 2.5 and/or 7.5. The algae shortlisted in this study (*C. vulgaris*, *P. tetrastromatica*, *S. tenerrimum*, *S. asperum*, and *C. repens*) could efficiently remove the uranium at pH 2.5 and/or 7.5. Thus, may help in overcoming the limitations of existing biosorbents and may also help in the removal of uranium from aqueous medium having a varying pH (2.5 to 7.5).

*S. asperum* showed the highest metal loading capacity (62.5%) as compared to other studied algae. Hence this alga was selected for further studies on the biosorption of uranium.