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Phycoremediation for Leather Industrial Effluent - Treatment and Recycling Using Green Microalgae and its Consortia

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A R T I C L E  I N F O

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A B S T R A C T

The leather industry represents an important economic sector in many countries especially in India. On the other hand, it generates large amounts of wastewater containing ammonium ion, sulphides, surfactants, acids, dyes, sulfonated oils, and organic substances including natural or synthetic tannins agents. However, treatments of these effluents using physical and chemical methods are quite expensive technology. Most leather industries construct a number of shallow evaporation ponds or Central Effluent Treatment Plant (CETP) to manage the effluent despite there is still a considerable amount of pollution load to be dealt. Hence the present work is focused on biological treatment to reduce the pollutants of tannery effluents through microalgal treatment process taken from the leather industries central treatment plant, Madhavaram, Chennai District, Tamil Nadu, India. The effluent samples were characterized before and after the treatment by measurements of Physico – chemical properties. In our findings we observed that the consortium of Microalgal species such as Chlorella vulgaris LS120 and Scenedesmus obliquus LS121 at various concentrations effectively reduces the TDS, COD and BOD levels of effluents as confirmed by the Physico – Chemical measurements at regular interval of 7 days for a period of 21 days. The concentration of algal consortium and effluent 250: 250 was found to effectively reduce TDS, BOD and COD levels when compared to individuals. Hence this green remediation technology avoids use of chemicals and the whole process of effluent treatment is simplified and eco – friendly.

Introduction

In India tanning industry occupies an important position in export earnings. Tanneries are a very important industry in Tamil Nadu. The total production capacity is expected to increase 2 or 3 times in the proceeding or coming years in order to achieve 10% global market share (Subramanian and Sastry, 1999). A wide variety of both organic and inorganic pollutants are present in effluents from tanneries, paper and pulp mills, steel industries, sugar factories, fertilizers, dyeing and textile units etc., (Amin, 1990). Phycoremediation is the use of macroalgae or microalgae for the removal or biortransformation of pollutants, including nutrients and xenobiotics, from wastewater and CO₂ from waste air (Olguin, 2003). Microalgae have received more attention in recent years, especially in tropical and subtropical regions, as an alternative biosystem for wastewater treatment (Fallowfield and Garrett, 1985; de la Noue et al., 1992). Algal systems have traditionally been employed as a tertiary treatment process (de la Noue et al., 1985; Oswald, 1988) and have recently proposed as a potential secondary treatment system (Tam and Wong, 1989). Algal systems are further credited by their potential biomass production as sources of fine chemicals or animal feed (Borowitzka and Borowitzka, 1988). Regardless of the operating system or the level of wastewater treatment concerned, the success of an algal system relies on the ability to take up inorganic nutrients such as N and P from the wastewater and assimilate them for their growth. Microalgae offer a low-cost and effective approach to remove excess nutrients and other contaminants in tertiary wastewater treatment, while producing potentially valuable biomass, because of a high capacity for inorganic nutrient uptake (Bolan et al., 2004; Muñoz and Guieysse, 2006).

Bionanotechnology can easily merge with other technologies and modify, endorse or clarify any existing scientific concept which is why it so called a platform technology (Shmidt, 2007). The use of nanomaterials to biorremediate and disinfect wastewater is gaining popularity (Mohan and pitman, 2007). In a study by Zhang et al. (2008), Scenedesmus sp. showed high removal efficiency for inorganic nutrients from artificial and real domestic secondary effluents. In addition, microalgae play an important role during the tertiary treatment of domestic wastewater in maturation ponds or the treatment of small- to middle-scale municipal wastewater in facultative or aerobic ponds (Aziz and Ng, 1993; Mara and Pearson, 1986; Oswald, 1995). Using microalgae in continuous treatment processes would be of great advantage, because most industries are in direct exigency for implementing cost-effective continuous treatment
processes. Algal species are relatively easy to grow, adapt and manipulate within a laboratory setting and appear to be ideal organisms for use in remediation studies (Dresback et al., 2001). Hence the present work is focused on biological treatment to reduce the pollutants of tannery effluents through micro algal treatment process taken from the leather industries.

Materials and Methods
Isolation and culturing of microalgae
Chlorella vulgaris LS120 and Scenedesmus obliquus LS121 was isolated using serial dilution, standard plating, colony isolation and culture techniques. The algal genus was identified with the help of standard monographs and recent available literature (Philipose, 1967).

Molecular Characterization
Molecular Characterization and species determination was further confirmed by sequencing a ribosomal RNA region comprising 18s Small Subunit (SSU) sequences from the isolated strains. Small Sub Unit (SSU) 18S rDNA was amplified by PCR with the oligonucleotide primers.

**Euk328f:** 5’-ACCTGGTTGATCCTGCAG-3’ (Moon-vander Staay et al., 2000)
**Chlo02R:** 5’-CTTCGAGCCCCAACTTT C-3’ (Zhu et al., 2005)

Ribosomal RNA gene sequences of the selected strains were searched against GenBank using Basic Local Alignment Search Tool (BLAST) (Altschul et al., 1997). Phylogenetic analysis was conducted by using maximum likelihood tool in MEGA software, version 5.05 (Tamura and Dudley, 2007).

Source of raw wastewater
The wastewater used in the present investigation was obtained from a tannery processing raw skins into semi finished leather. The steps involved in the process are soaking, liming, pickling and tanning. The wastewater from soaking and pickling operations were collected in a separate drain. The coarse solids such as fleshing, trimmings and hair are screened through a metal screen of aperture 5mm. The screened effluent was collected in a tank.

Experimental Design
Chlorella vulgaris LS120, Scenedesmus obliquus LS121 were grown in appropriate medium (Kanz and Bold, 1969) along with the consortiums of these algae by altering pH slightly. On reaching the exponential phase the culture was transferred with the different concentrations of the effluent in the ratio of 100:400, 200:300, 250:250, 300:200 and 400:100 respectively.

Physico-chemical analysis of the wastewater
The wastewater samples were analysed for pH, BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), total organic carbon and total dissolved solids, in accordance with standard methods of analysis of wastewater (American Public Health Association, 2000).

Statistical Analysis
Values of all data are expressed as mean ± SD. The one-tailed paired Student’s t-test was used to determine statistical significance between the untreated and treated parameters at P < 0.05. All analyses were carried out in triplicate.

Results
Among the physico-chemical parameters studied in leather industrial effluents treatment TDS, TSS, BOD, COD, Nitrogen, Phosphorus, Magnesium, Chloride, Sulphate, Sulphide, Nitrate, Nitrite, Calcium, Sodium, Potassium and Trace metals such as Copper, Manganese, Chromium showed reduced concentrations significantly shown in Table 1; whereas pH and dissolved oxygen showed increased concentration after the treatment with microalgae and its consortium. The high level tolerance of various pollutants and large surface area offered by the tiny cells make microalgae highly suitable for effluent treatment.

DNA extraction from the isolated strains was done by Qiagen plant DNA easy kit and confirmed the presence of bands through agarose gel electrophoresis. The nuclear encoded 18s rRNA genes were amplified by polymerase chain reaction (PCR) using EUK 328 and Chlo02R primer. There were approximately 990 nucleotides gene sequences obtained from the selected strains and the chromatograms were corrected manually to remove the mismatched and primer sequence by using chromas software. The strain LS121 and LS120 showed 99% identical to S. obliquus (AF183452) and C. vulgaris (FR751196) respectively. The sequences obtained have been submitted to the NCBI database and the accession numbers were represented in the Table 2.

The tree (Fig 1) shows a maximum likelihood Phylogenetic analysis depicting the relatedness of the isolates 18s ribosomal region with the selected sequences from the public database. The strains presented a good correlation between morphological and genetic assignment. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site. The analysis involved 9 nucleotide sequences. All positions containing gaps and missing data were eliminated. There were a total of 784 positions in the final dataset. Evolutionary analyses were conducted in MEGA5.

Before Treatment with algae, the raw effluents were analyzed for bacterial growth in Nutrient basal agar medium. About minimal colony growth was observed and complete elimination of fecal streptococci and pathogens were recorded. In the present study it was observed that the selected microalgae with its consortium treated effluents showed the reduction of various physico-chemical parameters and also some of heavy metals.

The complete breakdown of organic and inorganic matter should be the desired outcome to avoid persistence of potentially hazardous compounds in the environment (Bumpus, 1987). The breakdown of organic matter which directly leads to the reduction of total dissolved solids in the treated effluents. The present study reveals the significant reduction in the total dissolved solids of the effluents treated with the microalgae and its consortium. The equal concentration of algae and effluent system shows the highest reduction of TDS in all the treatment flasks. About 24.96%, 46.25%, and 65.09% of reduction in Chlorella vulgaris LS120 treated effluents on 7th, 14th and 21st days respectively whereas Scenedesmus obliquus LS121 shows 13.59%, 43.78% and 58.56% reduction. Above all 28.35%, 49.51% and 67.34% significant reduction in the total dissolved solids of the treated effluents with the microalgae and its consortium. The equal concentration of algae and effluent system shows the highest reduction of TDS in all the treatment flasks. About 24.96%, 46.25%, and 65.09% of reduction in Chlorella vulgaris LS120 treated effluents on 7th, 14th and 21st days respectively whereas Scenedesmus obliquus LS121 shows 13.59%, 43.78% and 58.56% reduction. Above all 28.35%, 49.51% and 67.34% reduction were recorded in the consortium of these algae. Hence this study has demonstrated the successful reduction of TDS by using algal cultures to remove nutrients from industrial effluents (Fig 2).
Table 1: Physico Chemical Analysis of Raw Effluent, CETP, Treated Effluent and Microalgae Treated Effluent

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>RAW EFFLUENT</th>
<th>TREATED EFFLUENT (CETP)</th>
<th>TREATED EFFLUENT WITH MICROALGAE LS 120</th>
<th>LS 121</th>
<th>LS 120+LS 121 (consortium)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.21</td>
<td>7.42</td>
<td>8.45</td>
<td>8.65</td>
<td>8.32</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>184</td>
<td>92</td>
<td>89.3</td>
<td>113</td>
<td>93.3</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>3280</td>
<td>3272</td>
<td>1145</td>
<td>1352</td>
<td>1072</td>
</tr>
<tr>
<td>Chlorides (mg/L)</td>
<td>1000</td>
<td>950</td>
<td>926</td>
<td>926</td>
<td>924</td>
</tr>
<tr>
<td>Sulphate (mg/L)</td>
<td>907</td>
<td>998</td>
<td>150</td>
<td>170.6</td>
<td>141.7</td>
</tr>
<tr>
<td>Oil &amp; Grease</td>
<td>4.4</td>
<td>3.2</td>
<td>2.19</td>
<td>2.29</td>
<td>2.2</td>
</tr>
<tr>
<td>BOD (mg/L)</td>
<td>450</td>
<td>125</td>
<td>43.6</td>
<td>53.6</td>
<td>41.3</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>1440</td>
<td>440</td>
<td>99</td>
<td>92</td>
<td>89.6</td>
</tr>
<tr>
<td>Phosphate (mg/L)</td>
<td>0.67</td>
<td>0.25</td>
<td>0.22</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>Ammonical nitrogen (mg/L)</td>
<td>203</td>
<td>48</td>
<td>39</td>
<td>34.6</td>
<td>32</td>
</tr>
<tr>
<td>Percent Sodium</td>
<td>72</td>
<td>66</td>
<td>46</td>
<td>45</td>
<td>43</td>
</tr>
<tr>
<td>Total Chromium (mg/L)</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Hexavalent Chromium(mg/L)</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Sulphide (mg/L)</td>
<td>17.6</td>
<td>6.4</td>
<td>4.03</td>
<td>4.66</td>
<td>3.70</td>
</tr>
</tbody>
</table>

CETP – Common Effluent Treatment Plant

Table 2: Accession number, Length and Closest Relative strains of Isolated strains

<table>
<thead>
<tr>
<th>Microalgal strain</th>
<th>Accession number</th>
<th>Length (nt)</th>
<th>Closest Relative</th>
<th>% Similarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. obliquus LS 121</td>
<td>KC912857</td>
<td>834</td>
<td>S. obliquus (AF183452)</td>
<td>99</td>
</tr>
<tr>
<td>C. vulgaris LS 120</td>
<td>KC912856</td>
<td>849</td>
<td>C. vulgaris (FR751196)</td>
<td>99</td>
</tr>
</tbody>
</table>

S – Scenedesmes, C- Chlorella, nt – Nucleotides

Table 3: Oil and Grease of Treated Effluent in different concentrations

<table>
<thead>
<tr>
<th>CONCENTRATIONS</th>
<th>Chlorella vulgaris LS120</th>
<th>Scenedesmes obliquus LS121</th>
<th>Consortium LS120+LS121</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae : Effluent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mL</td>
<td>7</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>100:400</td>
<td>3.9±0.05</td>
<td>3.4±0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.29±0.03</td>
<td>2.30±0.03</td>
</tr>
<tr>
<td>200:300</td>
<td></td>
<td>4.1±0.04</td>
<td>3.8±0.04</td>
</tr>
<tr>
<td>250:250</td>
<td></td>
<td>3.4±0.05</td>
<td>2.19±0.04</td>
</tr>
<tr>
<td>300:200</td>
<td></td>
<td>3.1±0.05</td>
<td>2.1±0.05</td>
</tr>
<tr>
<td>400:100</td>
<td></td>
<td>3.8±0.05</td>
<td>2.1±0.05</td>
</tr>
</tbody>
</table>
Figure 1: Phylogenetic Tree analysis of isolated strains of LS120 and LS121

- LS 120
  - Chlorella vulgaris YSL016 (FR751196)
  - Chlorella vulgaris (AB237642)
  - Chlorella vulgaris YSR023 (FR751202)
  - Chlorella vulgaris isolate YSW04 (GU732417)
  - Chlorella variabilis OK1-ZK (AB437257)
  - Chlorella variabilis (AB236862)
- Scenedesmus obliquus YSR17 (HM103383)
- Scenedesmus obliquus YSR02 28S (GU732426)
- Scenedesmus obliquus YSR01 (GU732419)
- Scenedesmus obliquus YSR05 (GU732426)
- LS 121
- Scenedesmus obliquus(AF183482)

Figure 2: Total Dissolved Solids of Treated Effluent in different concentration

<table>
<thead>
<tr>
<th>Days</th>
<th>LS 120</th>
<th>LS 121</th>
<th>LS 120 + LS 121</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
</tr>
<tr>
<td>14</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
<tr>
<td>21</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
</tbody>
</table>

**Total Dissolved Solids (TDS)**

- Concentrations:
  - 100:400
  - 200:300
  - 250:250
  - 300:200
  - 400:100
The consistent reduction in the BOD and COD levels were recorded in the algae treated effluents. The highest reduction of COD and BOD level was recorded in *Chlorella vulgaris* LS120 and *Scenedesmus obliquus* LS121 to about 93% and 90%. The consortium of these microalgae showed 94% and 92% of reduction in the COD and BOD level of the treated effluents (Fig 3 & 4).

Initial pH of the raw effluent was 6.2, increased steadily to 8.83 in 21 days (Fig 5) after the addition of *C. vulgaris* LS120, reached 8.65, in *S. obliquus* LS121 8.42. However, after gradual increase, pH was maintained at around 8.8, 8.6 and 8.4. Even after 25 days the effluent, pH was stable and was well within the discharge limits; this study has showed that Phycoremediation technology has a wider scope in pH regulation, apart from nutrient removal capabilities. Thus, the buffering capacity of the microalgae remained, even during the addition of effluent, suggesting the potential of these microalgae and its consortium in continuous treatment of the effluent.

The complete breakdown of an organic matter was observed in this study, treated effluents shows consistent reductions in Chloride, Sulphate, Phosphate, Ammonium and Sodium salts. The use of algae in effluent treatment could prove beneficial in different ways since they bring about the oxygenation and mineralization in addition to serving as a food source for many aquatic species.

Oil and grease are not stable in water as a homogenous mixture. Present on the surface, they will stick to it rather than remaining suspended in the water. Oils are comprised of materials such as phenolic type or aromatic compound. Biological treatment is generally effective in degrading dissolved oils and other types of stabilized emulsions which cannot be destabilized by chemical coagulants. However, a biological system is only effective on highly dilute oil-contaminated wastewaters because mineral-based oils are absorbed by the microorganisms faster than they can be metabolized. It has been reported that biological organisms are efficient in oxidizing dispersed or emulsified oil, but large amounts of free oil. In our present study we have recorded the significant reduction in oil and grease in the raw effluent (Table 3).

**Discussions**

In this study, *Chlorella vulgaris*, *Scenedesmus obliquus* and its consortia has been shown to possess excellent nutrient scavenging capability. Being treated alone in the effluents the consortium showed very high rate on utilization of nutrients. The inorganic compounds normally used by microalgae are CO$_2$ and bicarbonate (Borowitzka, 1998), the latter requiring the enzyme carbonic anhydrase to convert it to CO$_2$.

Total dissolved solids content of the effluent decreased upon treatment, which is due to the utilisation of various nutrients by *Chlorella vulgaris*, *Scenedesmus obliquus* and its consortia. The quantification might project reduced reduction levels because there could be a conversion of the total suspended solids already present in the effluent into dissolved materials for algal uptake and assimilation.

Nitrogen is another crucial parameter and is becoming increasingly important in wastewater management because nitrogen can have many effects on the environment (Sørensen and Jorgensen, 1993). Nitrogen can exist in different forms because of various oxidation states, and it can readily change from one form to another depending on the oxidation state present at the time. In the environment, living organisms can accomplish changes from one oxidation state to another.

The principal forms of nitrogen are organic nitrogen, ammonia (NH$_3$ or NH$_4^+$), nitrite (NO$_2^-$) and nitrate (NO$_3^-$). The presence of nitrogen in wastewater during discharge can be undesirable because it has ecological impacts and can affect public health. Ammonia is extremely toxic and also an oxygen-consuming compound, which can deplete the dissolved oxygen in water. Although nitrate itself is not toxic, its conversion to nitrate is a concern in the domain of public health.

Nitrite is a potential public health hazard (Sedlak, 1991) and, in the body, can oxidize iron (II) and form methaemoglobin, which binds oxygen less effectively than normal haemoglobin. All forms of nitrogen are taken up as a nutrient by the microalgae, although the most common nitrogen compounds assimilated by microalgae are ammonium (NH$_3$) and nitrate (NH$_4^+$) (Oliver and Ganf, 2000). In our study, *C. vulgaris* was able to reduce all forms of nitrogen substantially and ammonia and nitrate levels, in particular, were drastically reduced. Ammonia may also be stripped off into the air as a result of the increased pH values often found in algal cultures (Nunez et al., 2001).

Phosphate removal by selected microalgae and its consortium during Phycoremediation is due to the utilisation of phosphorus for growth. The phosphorus, which is used in the algal cells mainly for production of phospholipids, adenosine triphosphates (ATP) and nucleic acids, gets assimilated as inorganic orthophosphate, preferably as H$_2$PO$_4^-$ or HPO$_4^{2-}$ and the uptake process is active, *i.e.* it requires energy (Becker, 1994). The chemical stripping of phosphorus may be regarded as an advantageous side-effect of the algal growth, with enhanced phosphorus removal as a result. The investigation revealed that the phosphate removal efficiency of these microalgae and its consortium was nearly 95% in both the wastewater and ETP solid treatment processes. These phosphates were removed by photosynthetic assimilation and calcium phosphate precipitation because of high pH levels caused by intense algal photosynthetic activity (Hammouda et al., 1994). Moreover, microalgae are able to assimilate phosphorus in excess, which is stored in the cells as polyphosphate granules and magnesium and potassium are co-transported along with phosphate (Bitton, 1990).

During Phycoremediation using all these algae is a drastic reduction in magnesium levels and moderate decrease in potassium levels was observed. Although sodium levels did not show appreciable change, there was a significant reduction in calcium concentrations. This is aided by the carbonate ions, which not only decrease the crystallinity of calcium phosphates and promote the formation of amorphous calcium phosphates but also compete with phosphates in precipitating with calcium to form calcite (CaCO$_3$) at pH values above eight (Arvin, 1983). However, sodium levels were reduced due to the tendency of the microalgae for bioaccumulation. In addition, *C. vulgaris*, *S. obliquus* and *N. oculata* induced progressive reduction in both BOD and COD values of the effluent and this could be attributed to the high algal growth rate and intense photosynthetic activity (Colak and Kaya, 1988). Many studies have demonstrated the success of using algal cultures to remove nutrients from waste waters rich.
Figure 3: Chemical Oxygen Demand (COD) of Treated Effluent in different concentrations

Figure 4: Biological Oxygen Demand (BOD) of Treated Effluent in different concentrations
Figure 5: pH of Treated Effluent in different concentrations

**pH LS120**

- Concentrations:
  - 100:400
  - 200:300
  - 250:250
  - 300:200
  - 400:100

**pH LS121**

- Concentrations:
  - 100:400
  - 200:300
  - 250:250
  - 300:200
  - 400:100

**pH LS120 + LS121**

- Concentrations:
  - 100:400
  - 200:300
  - 250:250
  - 300:200
  - 400:100
in nitrogenous and phosphorus compounds (de la Noue and Proulx, 1988). There was a drastic reduction in the BOD and COD content of effluent treated with microalgae. As stated by Nandan et al., in 1990, microbial methods are being increasingly used for the reduction of BOD and COD. More than 95% reduction of BOD has already been reported by Manoharan and Subramaniam, (1993) in ossein effluents and paper mill effluents by using Oscillatoria psuedogeminita var granulata. Similar results have been reported by Govindan (1983, 1984) using algal culture. He reported that there was considerable reduction of BOD & COD in soya, paper tannery, sugar and dairy mill effluents after treatment. A significant colour reduction was observed on 7th, 14th and 21st day of the treatment. On treating with Chlorella vulgaris, Scenedesmes obliquus and Nannochloropsis oculata the acidic pH level in the tannery effluents was changed to neutral in the 14th day and on the 21st day it was changed to alkaline. Gomoyo et al., 1972 have reported that increased pH leads to oxidative discoloration of effluents. The use of algae in wastewater treatment could prove beneficial in different ways since they bring about oxygenation and mineralization in addition to serving as a food source for some aquatic species (El nabarawy and Welter, 1984).

Conclusion
It is apparent that the current methods used in effluent treatment plants are unable to treat the wastes they receive and so discharge toxic and persistent pollutants into rivers and estuaries. To stop pollution and to prevent metal-toxicity there is a clear need for an overall waste treatment strategy that would help for the elimination of priority pollutants at source. This can be achieved by indigenous microorganisms found in various stressed habitats which can be used as indicators of pollution and to resist, process, metabolize and detoxify metals in polluted waste water. The results of this study was promising but further systemic field level, large scale experiments are needed before commercialization and industrial scaling-up, further studies are to be carried out for implementation at an industrial scale as well as for effective utilisation of biomass. The use of Bionanotechnology in the future is expected to expand into numerous industrial applications and help decrease production cost by reducing energy consumption, attenuate environmental pollution and increase the remediation efficiency in developed countries.

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References


