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Sustainable Algal Technologies for Detoxifying and Valorizing

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Tannery Wastewater

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Abstract

The urgent need to treat the vast quantities of wastewater generated by the leather industry arises from an impending global crisis i.e. within the next fifty years, the availability of safe surface and groundwater resources is projected to become one of the world’s most critical concerns. Although it is ironic that both the establishment and operation of conventional wastewater treatment plants are prohibitively expensive, the Common Effluent Treatment Plant (CETP) in Kolkata demonstrates that bioremediation offers a viable alternative in ameliorating the harmful effect of the wastewater in addition to utilize it for creating value. The spontaneous growth of algae observed in operational modules of CETP, Kolkata prompted an investigation into the limiting factors controlling algal proliferation. Microalgae are widely recognized as efficient biosorbents and bioaccumulators of environmental contaminants. They enable integrated bioremediation by effectively removing pollutants from diverse wastewater streams while generating biomass with significant potential for sustainable applications. Their potential as a sustainable biosorption solution is attributable to low-cost cultivation, reduced energy requirements, and simplified biomass separation, which collectively confer operational and economic advantages over conventional treatment technologies. Furthermore, microalgal species can be genetically or physiologically enhanced for improved

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photosynthesis, carbon assimilation, bioproduct synthesis, and heavy metal removal. This study evaluates the biosorption potential of the filamentous cyanobacterium Pseudanabaena limnetica in removing heavy metals from tannery wastewater, including chromium. Recovering the extracted metals from the algal biomass could further establish resource recovery as a feasible and value adding option.

Keywords: Bioremediation; common effluent treatment plant; environmental management; heavy metals; microalgae; Pseudanabaena limnetica; tannery wastewater.

1. Introduction

Despite the abundance of available water, humans can only use 0.3% of it. The remaining 99.7% is found in the oceans, ice caps, soils, and suspended in the atmosphere (Oves 2018). Nearly 475 million km3 of freshwater resources are available around the world in the form of groundwater or surface water, which humans primarily consume (Shiklomanov 1997) in different domestic, agricultural and industrial sectors.

Accelerated urbanization in recent decades due to population expansion, and economic growth has led to an increase in wastewater generation, 80% of which is returned to environment untreated. By 2030, 40% of the world’s population is predicted to lack access to fresh water. The leather industry ranks among the most waterdemanding sectors worldwide. India ranks 13th on the list

of countries with extremely high-water risk (Ebcifa, Judith Betsy and Stephen Sampath Kumar 2022). Processing requires 40 litres of pure water for every kilogramme of raw hides or skins. With the growing threat of freshwater scarcity expected to intensify over the next fifty years, treating and reusing the large volumes of wastewater from leather manufacturing has become a critical priority, both for India and the global community (Das, Das, et al., Algae Development in Tannery Wastewater Treatment Tanks 2021).

Kolkata is manufacturing and export hub accounting for approximately 50% of the total leather and leather goods exports in India. Government of West Bengal implemented Calcutta Leather Complex (CLC) with a

Common Effluent Treatment Plant (CETP) based on a concept report of CLRI Chennai under the UNIDO- assisted National Leather Development Programme. Fortunately, the concerned area where the CETP is located is part of the East Kolkata Wetlands (EKW), distinguished as one of the largest urban wastewater-fed aquaculture systems in the world. The generational knowledge of more than 100 years to turn wastes into wealth has made East Kolkata Wetlands to earn its Ramsar designation. The CETP situated at CLC, Bantala is the working solution of dealing the huge amount of tannery waste coming from more than 500 tanneries in Kolkata. Eight modules of CETP daily handle about 16.3 cusecs tannery effluents, most of which is discharged out of CETP after sequential amelioration of all the physical, chemical and biological wastes from the effluent.

Das and team (2021) recorded the occurrence of seven algal species in the treatment tanks of CETPs at CLC. A filamentous, mat-forming species, Pseudanabaena limnetica, was observed in the Aeration Tank. It is one of the three species of Cyanophyceae that efficiently ameliorate different toxicants in the tannery wastewaters along with other algal species such as one species under Chlorophyceae, two under Euglenophyceae and single species of Bacillariophyceae found to grow in different treatment tanks of CETP.

Pseudanabaena limnetica, a non-heterocystous cyanobacterium widely distributed in eutrophic brackish and freshwater systems, particularly in tropical and subtropical regions (Komárek 2003) and is capable of atmospheric nitrogen fixation. Its growth is strongly regulated by inorganic phosphorus availability, especially phosphate, which acts as a key limiting nutrient (Pomati and Neilan 2004). The species frequently dominates shallow, hypertrophic, and polymictic water bodies due to its adaptation to low light, high turbulence, and unstable stratification (Mischke 2003) (Casé, et al. 2008). High abundances have been reported in gravel-pit lakes and other stressed shallow systems, where it contributes to extreme primary productivity and bloom formation, reflecting its tolerance to nutrient enrichment, sediment resuspension, and episodic meteorological disturbances (Rojo and Cobelas 1994) (Casé, et al. 2008).

This study evaluates the biosorption potential of the filamentous cyanobacterium Pseudanabaena limnetica for the removal of heavy metals from tannery wastewater, with particular emphasis on chromium, a major contaminant originating from leather-processing operations. Owing to its filamentous morphology, high surface-area-to-volume ratio, and the presence of functional groups on the cell surface, P. limnetica is expected to effectively bind and sequester metal ions from complex effluents. Further research may explore the feasibility of recovering the adsorbed metals from the algal biomass, thereby transforming waste treatment into a resource recovery strategy. Such an approach not only enhances the sustainability of tannery wastewater management but also adds economic value by enabling the reuse of recovered metals and the potential downstream utilization of metal-loaded or regenerated biomass.

2. Methodology:

Monthly sampling is performed at CETP. Algal samples collected from the treatment tank (Aeration Tank). The concentrations of copper (Cu), zinc (Zn), lead (Pb), chromium (Cr), manganese (Mn), and iron (Fe) were

determined using an Atomic Absorption Spectrophotometer. Measurements were carried out in flame absorption mode under default operating conditions with element-specific hollow cathode lamps. Instrument calibration and sensitivity checks were performed using recommended standard. All chemicals and reagents employed were of analytical reagent grade. Metal extraction from tannery effluent samples was performed by nitric acid (HNO_3) digestion following Standard Methods (Eaton, et al. 1995), and the digested samples were subsequently stored under refrigeration until further analysis.

3. Result & Discussion

The algal matrix of Pseudanabaena limnetica demonstrated the capacity to accumulate significant quantities of heavy metals, including up to 2.8 g/kg of Fe, 12.4 g/kg of Cr, and 67.8 mg/kg of Pb along with significant amount of other heavy metals like like Cu, Zn, and Mn (Fig. 1).

The algal matrix exhibited a strong capacity for heavy metal accumulation, demonstrating effective biosorption

of both major and trace metals from the tannery wastewater system. Among the metals analyzed, Fe and Cr showed particularly high levels of accumulation, reaching concentrations of up to 2.8 g kg^{-1} and 12.4 g kg^{-1}, respectively, in the algal biomass. Pb was also retained in appreciable amounts, with concentrations up to 67.8 mg kg^{-1}. In addition, notable accumulation of other heavy metals, including Mn, Cu, and Zn was observed, indicating the broad-spectrum metal-binding capability of the algal matrix.

Seasonal variation significantly influenced metal accumulation patterns. Mn concentrations in the biomass were recorded high during the pre-monsoon period, decreased during the monsoon, and again increased to in the post-monsoon season, marking an average annual concentration of 1.37 g kg^{-1}. A similar seasonal trend was evident for Fe and Zn as well. Pb concentrations showed relatively minor seasonal variation. Cr accumulation

remained consistently high across all seasons, increasing from 9.64 g kg^{-1} in the pre-monsoon to 10.96 g kg^{-1} during the monsoon and reaching a peak value of 15.64 g kg^{-1} in the post-monsoon season. Trace metals also exhibited seasonal fluctuations. Cu concentrations were comparatively as lower as 21.9 mg kg^{-1} but stable during the pre-monsoon and monsoon periods, followed by an increase in the post-monsoon season. Zn accumulation ranged from 165 mg kg^{-1} to 99 mg kg^{-1} in all seasons.

Overall, the results highlight the efficiency of the algal matrix in sequestering high concentrations of Cr and Fe, along with measurable amounts of other heavy metals, across varying seasonal conditions. The elevated postmonsoon accumulation for most metals suggests enhanced biosorption under conditions of increased pollutant loading and favourable environmental parameters, underscoring the potential of this algal system for sustainable heavy metal remediation and resource recovery.

4. Conclusion

Numerous studies highlight the high adsorption capacity, low cost, and absence of secondary pollution associated with algal systems, underscoring their potential for

wastewater purification, metal recovery, and sustainable treatment technologies (Dwivedi 2012).

Although the capital investment and operational costs associated with conventional wastewater treatment plants are often prohibitively high, observations from the Common Effluent Treatment Plant (CETP) in Kolkata demonstrate that bioremediation represents a viable and cost-effective alternative for mitigating the adverse impacts of industrial wastewater while simultaneously enabling value generation. The spontaneous proliferation of algal biomass within operational units of the CETP highlights the intrinsic capacity of native algal communities to thrive under wastewater conditions without external inoculation or intensive energy inputs.

Under adequate light availability, algal metabolism fundamentally alters the treatment dynamics by producing oxygen through photosynthesis rather than consuming it, thereby reducing the energy demand typically associated with mechanical aeration. Concurrently, algae assimilate carbon dioxide, effectively coupling wastewater treatment with biological carbon sequestration. This dual functionality not only enhances pollutant removal efficiency but also introduces the potential for generating carbon credits as an added economic incentive. Collectively, these findings underscore the potential of algalbased bioremediation systems to transform conventional wastewater treatment from a cost-intensive, end-of-pipe process into an integrated, low-energy, and valuegenerating environmental management strategy.

Microalgae are emerging as key components of integrated bioremediation, effectively removing pollutants from various wastewaters while producing valuable biomass. Their expanding role in biorefineries enables the generation of high-value products such as biofuels and pharmaceuticals, strengthening biorefinery potential. Integrated into circular bioeconomy models, microalgal systems support resource recovery, waste reduction, and environmental sustainability as evidenced by the clear, colourless and odourless effluent released daily from the CETP, Kolkata, endorses a quiet yet powerful testament to the transformation of industrial waste into environmentally compliant water.

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