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Highlights

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Ecological and Economic Worth of Microalgae in Urban Lakes

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Abstract

Microalgae are primary producers in aquatic ecosystems, which aid in the ecological processes of primary production, biogeochemical cycling, nutrient cycling, etc. The biochemical composition of microalgae includes high protein, fat, and carbohydrate, which constitute a vital raw material in the biofuel, pharmaceutical, and nutraceutical industries for the manufacture of biofuel, food, supplements, animal feedstock, medicine, bioplastics, and fertilizer. However, selecting appropriate strains for an economically viable production process is challenging, necessitating an exploration of commercially viable algal strains. The composition and assemblage of algal species reflect the ecological health of aquatic ecosystems and are utilized as bioindicators of aquatic environments, revealing their physical and chemical health. The present study determines the diversity and composition of microalgal species in lakes in the Hebbal-Nagavara Valley, Bangalore. The study documents microalgae belonging to Cyanophyta, Chlorophyta, Euglenozoa, Bacillariophyta, Charophyta, Ochrophyta, and Glaucophyta, with Chlorophyta being the dominant group. Dominance (D) varied from 0.25 to 0.55, with a maximum at Narsipura 2 Lake and a low at Kogilu Lake, whereas the Shannon diversity index ranged from 0.69 to 1.60. All physicochemical and microalgal data were subjected to cluster analysis to categorize the lakes according to their environmental status based on the level of contamination. Therefore, alterations in the physical and chemical properties of waterbodies are immediately reflected in the composition of the biotic community within the ecosystem. Microalgae-based biomonitoring is a very effective and cost-effective technique for determining the degree of pollution in water based on species assemblages.

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Keywords: Microalgae, Lakes, Diversity Index, Water Pollution, Bioindicator.

1. Introduction

The structure and functioning of aquatic ecosystems are being altered due to anthropogenic activities, evident from the deteriorating physicochemical conditions, sustained inflow of nutrients through untreated wastewater, eutrophication, declining vegetation cover in the catchment, increased grazing pressure, etc. (Ramachandra *et al.*, 2020). Microalgae, being the primary producers or autotrophs, are crucial for aquatic ecosystem stability, and the composition of species indicates the ecological health of waterbodies as an ecological indicator. Hence, microalgae are a dependable tool for assessing the ecological status and water quality of wetlands (Crossetti & Bicudo, 2005). Algae are unicellular or multicellular, eukaryotic or prokaryotic (Asulabha *et al.*, 2022). In nature, microalgae are abundant and omnipresent, requiring different nutrients and temperatures. Algae can survive in a wide range of habitats, including freshwater, marine, hypersaline conditions, etc., and species vary in size, shape, colour, behaviour, and habitat (Khalil *et al.*, 2021). Freshwater microalgal groups include Chlorophyta, Cyanobacteria, Rhodophyta, Euglenoids, Eustigmatophyta, Chrysophyta, Haptophyta, Synurophyta, Bacillariophyta, Pyrrhophyta, Cryptophyta, and Phaeophyta (Wehr *et al.*, 2015).

Microalgae, the primary producers in aquatic ecosystems, play a crucial role in the aquatic food chain in transferring materials and energy. Microalgal population density, diversity, and composition vary depending on the ecological health of aquatic ecosystems and hence aid as crucial water quality indicators (Zhang *et al.*, 2021). Investigations of algal assemblages offer a sensitive, valuable, and quantitative representation of ecological changes (Paerl *et al.*, 2003) and aid in pollution monitoring because of their large population, quick pace of development, affordable cost, easy maintenance, and ability to respond quickly to low pollution levels. Algae are valuable indicators of the extent of water quality degradation and its short-term effects, as the prevalence of blue-green algae indicates eutrophic conditions in water bodies. In contrast, the dominance of green algae and diatoms indicates oligotrophic conditions (Khan *et al.*, 2011).

Sustained discharge of untreated industrial effluent, domestic sewage, agriculture, and urban runoff alters the chemical integrity of aquatic ecosystems, as evidenced by water quality degradation and the composition of algal species. Water quality parameters Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved oxygen (DO), Potential of Hydrogen (pH), nitrogenous compounds, cations, and anions indicate physicochemical elements influencing phytoplankton species assemblages (Mohammed & Mahran, 2022).

Microalgae, which are sensitive to water quality variations, help understand the extent of water contamination and aid in economically monitoring and managing ecosystems. Changes in the climate due to global warming with escalating greenhouse gas (GHG) footprint have necessitated an exploration of ecologically feasible, economically viable, and environmentally sound energy options to address the challenges of dwindling stock of fossil fuels and the need for mitigating GHG footprint. Bio-based feedstocks, such as microalgal biomass, have emerged as a viable alternative due to higher photosynthetic efficiency, lipid accumulation, shorter cycling time, and efficient carbon sequestration apart from the scope of a viable alternative to fossil fuels. Selecting an appropriate algal strain based on unique characteristics, including cellular contents, growth behaviour, and metabolic pathways, is crucial for biorefinery processes and products (Sarma *et al.*, 2021). The current study through biomonitoring investigates (i) the diversity and the economic worth of microalgae in Hebbal-Nagavara Valley lakes, and (ii) explores the scope of third-generation feedstock for a sustainable and cost-effective biorefinery.

2. Materials and Methods

2.1 Study Area: Lakes in Hebbal-Nagavara Valley of Greater Bangalore

Greater Bangalore (latitudes 12°49'5' N and 13°08'32" N, longitudes 77°27'29" E and 77°47'2" E), located at 920 meters above sea level, has three watersheds: Koramangala-Challaghatta, Hebbal-Nagavara, and Vrishabhavathi. Due to the undulating topography of the Bangalore landscape, several tanks were built in the early 18th century to meet water requirements for irrigation and domestic purposes, apart from fishing and washing. The open-source GIS software QGIS[3] was used for spatial analyses, and Figure 1 depicts the distribution of monitored lakes in the Hebbal-Nagavara Valley, Greater Bangalore.

2.2 Sample Collection and Analyses

Field investigations were carried out during 2018–2020, and water samples were collected in disinfected water sampling containers at inlets and outlets of lakes in the Hebbal-Nagavara Valley. Physicochemical parameters such as water temperature, dissolved oxygen, pH, total dissolved solids, electrical conductivity, turbidity, chloride, total hardness, calcium, magnesium, total alkalinity, chemical oxygen demand, biochemical oxygen demand, nitrate, and orthophosphate were estimated using the standard protocol (APHA, 2012).

Microalgae were collected by filtering 50 liters of lake surface water with a plankton net. Microalgae samples were fixed in a 4 per cent Lugol iodine solution and concentrated at 50 mL. The samples were labelled and preserved

[3]https://qgis.org

Figure 1: The Map Depicts the Urban Lakes in The Hebbal-Nagavara Valley, Bangalore.

Source: Authors'Compilation

in plastic bottles before being taken to the laboratory for taxonomic study. Microalgae samples were identified and counted using standard keys using an optical microscope (Olympus) (Desikachary, 1959; Prescott, 1970; Guiry & Guiry, 2023).

2.3 Statistical Analysis

PAST software[4] was used to compute microalgae diversity, diversity indices (such as the Shannon-Weaner diversity index, Simpson diversity index), Dominance index, Pielou Evenness index, and cluster analysis.

3. Results and Discussion

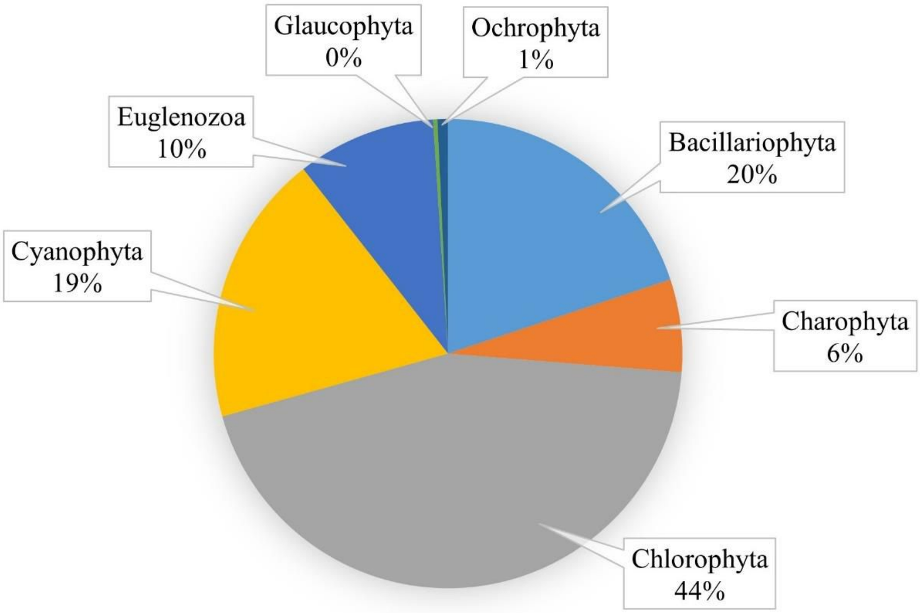
3.1 Microalgal Composition in Urban Lakes

The study documents microalgal species belonging to groups like Cyanophyta (19 per cent), Chlorophyta (44 per cent), Euglenozoa (10 per cent), Bacillariophyta (20 per cent), Charophyta (6 per cent), Ochrophyta (1 per cent), and Glaucophyta (<0 per cent).

Figure 2 illustrates that the Chlorophyceae group is more diverse (44 per cent) than the Bacillariophyceae group (20 per cent). This density may be due to the highly enriched

[4]https://past.en.lo4d.com/windows

Figure 2: The Taxonomic Compositions of Microalgal Communities in Urban Lakes



Source: Authors'Compilation

organic waste load and nutrients providing favorable conditions for their growth. The diversity of the Chlorophyceae group in these lakes could also be attributed to carbon inputs due to anthropogenic activities involving the discharge of untreated sewage and the dumping of solid waste. The optimal water temperature for the growth of Cyanobacteria and Chlorophyta is around 18–25 °C (Liu et al., 2011). Phytoplankton can adjust their light conditions by altering their light-harvesting pigments, such as Chlorophyll a (Chl a) (Arrigo *et al.*, 2010).

3.2 Microalgal Diversity in Lakes

Figure 3 depicts the multiple diversity indices computed for monitored lakes in the Hebbal-Nagavara valley, with the Shannon Wiener (H') index ranging from 0.69 to 1.60. Dominance (D) ranged from 0.25 to 0.55, with a maximum at Narsipura 2 Lake and a minimum at Kogilu Lake. Species evenness index (J') ranged from 0.63 to 1. Simpson index (1-D) values were highest (0.75) in Kogilu Lake and lowest (0.45) in Narsipura 2 Lake.

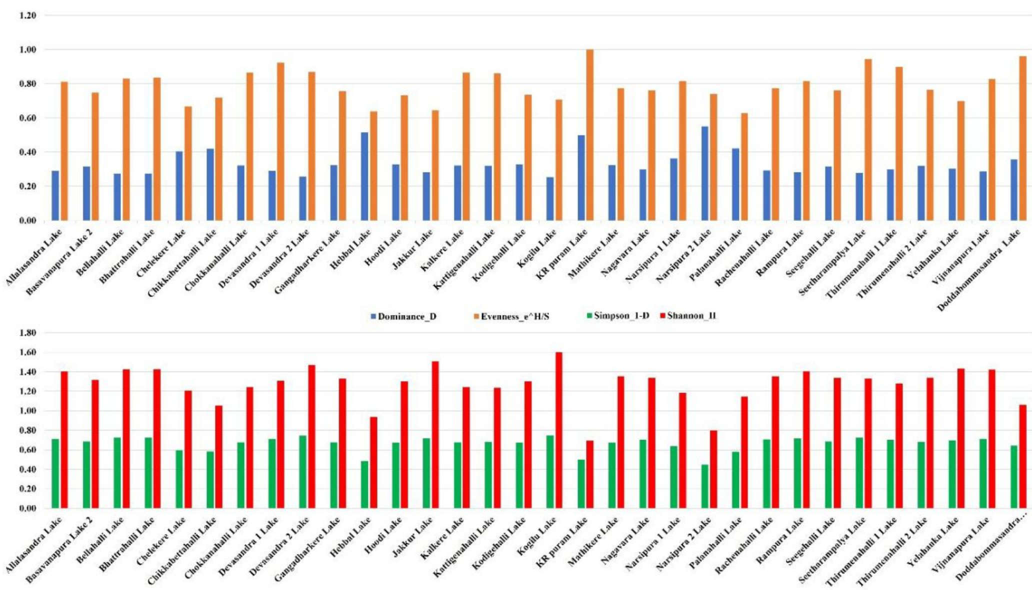
The index of diversity (H') and evenness index

(J') indicate the degree of pollution in water. H' values range from 0 to 1, indicating highly polluted water; the values range from 1 to 3, indicating not critically polluted water; and the values > 3 indicate clean water. Meanwhile, J' values range from 0 to 0.3, indicating highly polluted water. Lastly, J' values range from 0.3 to 0.5, indicating not critically polluted water, and 0.5 to 0.8, indicating clean water (Li *et al.*, 2019). The present study suggests lakes are contaminated due to the sustained inflow of untreated sewage water (Figure 3).

3.3 Relationships between Lakes, Water Quality Data, and Microalgal Species

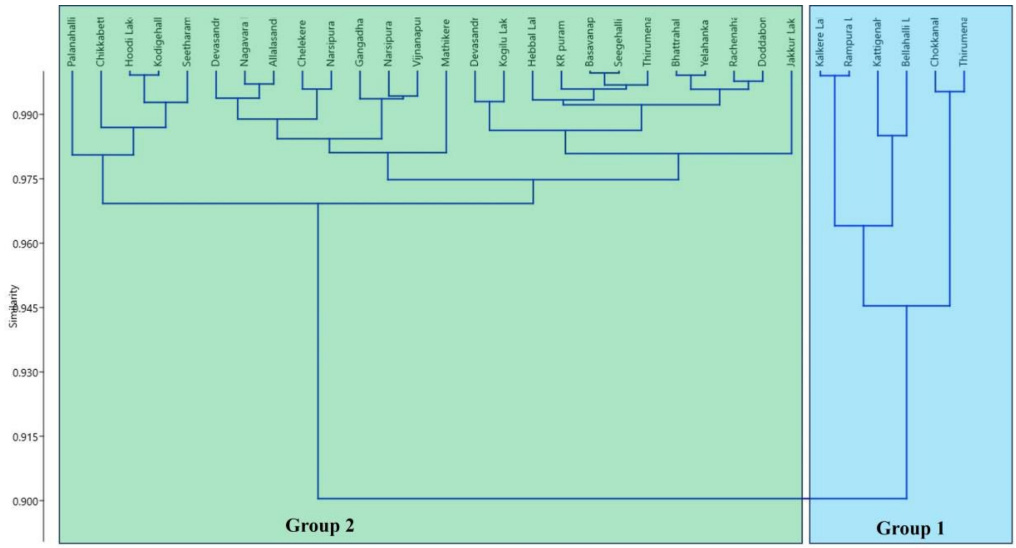
Cluster analysis (CA) is a multivariate statistical technique that provides intuitive similarity relationships between lakes, considering microalgal species with water quality data. The data classifies 32 freshwater lakes based on (i) microalgal groups, like Bacillariophyta, Charophyta, Chlorophyta, Cyanobacteria, Euglenozoa, Glaucophyta, and Ochrophyta, and (ii) physicochemical status. The results showed that Group 1 (G1) is more polluted with higher ionic and nutrient contents and has less phytoplankton diversity, which includes Bellahalli Lake, Chokkanahalli Lake, Kalkere Lake, Kattigenahalli Lake, Rampura Lake, and Thirumenahalli 2 Lakes (Figure 4). Changes in the algal community can be attributed to environmental stressors, notably nutrient

Figure 3: The Diversity Indices of Microalgae in Different Hebbal-Nagavara Valley Lakes



Source: Authors' Compilation

Figure 4: Microalgal Groupings Based on Physical and Chemical Status



Source: Authors'Compilation

pollution, leading to lower oxygen concentrations, which affect other organisms in the aquatic food chain (Johnstone *et al.*, 2006; Camargo & Alonso, 2006). Conductivity, COD, and BOD are crucial variables, indicating variation in water chemistry and nutrient levels, which determine algal species assemblages. COD and BOD are commonly used organic pollution indicators in water bodies, and the amount or type of organic matter significantly affects microalgal community structure (Kim *et al.*, 2021).

3.4 Commercial Importance of Microalgae

A biorefinery is a process that turns a single biomass into many products. Microalgae are light-driven cell factories, generating bioactive substances from primary metabolites (carbohydrates, lipids, and proteins) and secondary metabolites (carotenoids, pigments, sterols, and vitamins) at different development phases (Kiran & Venkata Mohan, 2021), which constitute vital feedstock for the pharmaceutical, cosmetic, and nutritional sectors. Microalgae can cure cancer, hypertension, diabetes, neurological illnesses, and autoimmune disorders, besides being beneficial for the heart, brain, and immunity (Udayan *et al.*, 2023).

Microalgae, contrary to higher plants and animals, constitute a vital source of necessary enzymes to synthesise PUFA (Docosahexaenoic acid, Eicosapentaenoic acid, ã-Linolenic acid, and Arachidonic acid), which are essential in food chain (Spolaore *et al.*, 2006; Pulz & Gross, 2004). Compared to chemical fertilisers, biofertilisers are more economical and environmentally benign since they may increase soil fertility, improve nutrient availability, encourage sustainable plant development, and lessen the harmful effects of excessive chemical inputs on the environment. It has been reported that the well-known genera Nostoc and Anabaena may fix up to 20–25 kg N/ha. During the rainy season, they are applied to rice crops as biofertiliser (Kumar *et al.*, 2022).

The burgeoning population and escalating energy demand have necessitated exploring viable energy alternatives to mitigate fossil fuel dependence through algal biofuel from the third-generation feedstock, such as microalgae, which has emerged as a viable renewable fuel option. Compared to other terrestrial plants, microalgae have higher photosynthetic efficiency with biomass output containing relatively higher protein, carbohydrate, and lipid content, making microalgae a viable feedstock for biofuel, and value-added products (Table 1).

Table 1: Valuable Products from Microalgae

Microalgae	Valuable products	Reference
Chlorella vulgaris	Biodiesel	Moradi & Saidi,2022
Spirulina maxima	Biodiesel	Rahman *et al.*,2017
Spirulina platensis	Bioethanol and Biomethane	Rempel *et al.*,2019
Chlorella vulgaris	Bioethanol	Condor *et al.*,2022
Chlamydomonas reinhardtii	Bioethanol	Nguyen *et al.*,2009
Chlorococum sp.	Bioethanol	Harun *et al.*,2010
Chlamydomonas reinhardtii	Microalgal biochar	Torri *et al.*,2011
Chlorella vulgaris	Microalgal biochar	Yuan *et al.*,2015
Haematococcus pluvialis	Astaxanthin and Lutein	Molino *et al.*,2018
Acutodesmus dimorphus, Spirulina platensis, Chlorella vulgaris, Scenedesmus dimorphus, Anabaena azolla, and Nostoc sp.	Bio-fertilizers	Ammar *et al.*,2022

Source: Authors' compilation

Microalgae paves the way for third-generation biofuels with high photosynthetic efficiency, a low land requirement, and the potential to replace traditional liquid fossil fuels with sustainable alternatives. Microalgae with a basic cellular structure and shorter life cycles (approximately 1–10 days) would synthesize significant amounts of lipids per dry-weight biomass (40–86 per cent) and use less water than terrestrial crops. They also grow well in wastewater and do not require pesticides, herbicides, or fertilizers to thrive. They can be produced under controlled conditions in specially built bioreactors or grown in brackish or saltwater on non-arable soil. Additionally, microalgae are utilized to create highly valuable, commercially profitable products with extra utility and help with carbon sequestration and bioremediation (Verma *et al.*, 2010; Rodolfi *et al.*, 2009). Three distinct methods exist for growing microalgae: autotrophic, mixotrophic, and heterotrophic cultures (Sharma *et al.*, 2022). Compared to autotrophic and heterotrophic modes of culture, the mixotrophic mode of microalgal cultivation is an effective way to yield a greater amount of lipids (Zhan *et al.*, 2017).

The biochemical conversion of microalgal biomass through anaerobic digestion provides biogas; alcoholic fermentation would yield bioethanol, and photobiological hydrogen production (Sivaramakrishnan *et al.*, 2022). The market prices for microalgae-based biodiesel, glycerine, and algal meal were 0.73 USD/L, 320–500 USD/ton, and 1200–1800 USD/ton, respectively (Subhadra and Edwards, 2011). The MBSP (minimum biodiesel selling price) is estimated to be $2.17/L, and to be competitive, the price needs to be at or below the average petroleum diesel price of $1.09/L. The feasibility of the process is significantly influenced by factors such as oil content, nitrogen content in waste effluents, and extraction and esterification efficiencies (Zewdie and Ali, 2022).

Microalgae biomass is being utilized in cattle feed formulations as a valuable source of triglycerides, vitamins, pigments, and essential amino acids (Ahmad *et al.*, 2022) and in aquaculture for partial feed replacement, oxygen generation, and wastewater treatment (Han *et al.*, 2019). Algal biochars, rich in nutrients and ion exchange capacity, are useful as agricultural soil amendments and adsorbents in wastewater treatment for removing pollutants. Biofuels such as bioethanol, biodiesel, biocrude oil, pyrolytic bio-oil, biomethane, biohydrogen, and bio-jet fuel may be manufactured from microalgal biomass. However, there are challenges for commercial application, and an integrated biorefinery strategy, together with the selection of appropriate strains, the development of biomass pre-concentrating processes, and the use of wet microalgal biomass might improve both economic viability and environmental sustainability (Khan *et al.*, 2023).

An economic analysis of photobiological

hydrogen generation from *Chlamydomonas reinhardtii* indicates a selling price of \$0.57/kg to \$13.53/kg for algae-produced hydrogen (Amos, 2004). An estimated 5000 tonnes of chlorella are grown worldwide each year (García *et al.*, 2017), and about12,000 tonnes per year of dried whole algae, Spirulina (at the cost of \$30/kg) is produced per year with 70 per cent of the production by the South Asian countries - China, India, and Taiwan.

Microalgae from lakes have a significant economic value, evidenced by the accounting of ecosystem services. The provisioning service offered by microalgae from Karnataka, India, wetlands were valued at 110467 Rs/ha/year, considering the prospects of biofuel, protein, and glycerol production (Ramachandra *et al.*, 2021). Microalgae, with high protein content, omega-3 fatty acids, vitamins, and antioxidants, is evolving as the major industry with increasing consumer interest due to its nutritional benefits. The Microalgae Market Outlook (2023-2033) predicts a valuation of US\$ 11.8 billion in 2023 and \$25.4 billion by 2033, with an 8% compound annual growth rate (CAGR) during this forecast period (https://www.futuremarketinsights.com/reports/microalgae-market). The global food and beverage microalgae market, valued at \$125 million in 2023, is expected to grow at a 7 per cent annual rate between 2023 and 2033, reaching \$247.4 million by 2033. This growth is driven by the growing use as food additives due to microalgal ability to enhance taste, texture, flavor, aroma, and nutritional values[5] . Microalgae have emerged as a viable third-generation feedstock for sustainable biorefineries, reducing costs and aiding in effective bioremediation with their ability to uptake nutrients (Sarma *et al.*, 2021).

The strategic approach to benefiting the national economy is through the algal bio-economy and establishing research centers, exploring viable strains, educating start-up businesses, and developing financing instruments for projects and research. Microalgal research institutes focusing on application research, technology advancement, product development, process improvement, publications, and patent commercialization would herald the sustainable energy path.

4. Conclusion

Microalgae are a valuable source of triglycerides, vitamins, pigments, and essential amino acids and are widely used as an important biological resource in various sectors, including the food sector, the manufacturing of biofuels, wastewater treatment, cosmetics, and medicines. Unplanned anthropogenic activities have been impacting aquatic ecosystems, evidenced by the erosion of the physicochemical characteristics and microalgae composition of

[5]https://www.futuremarketinsights.com/reports/microalgae-food-and-beverage-sector

the lakes in the Hebbal-Nagavara Valley, Bangalore city. The current investigation documents microalgal species of the groups Cyanophyta, Chlorophyta, Euglenozoa, Bacillariophyta, Charophyta, Ochrophyta, Glaucophyta, and Chlorophyta, which constitute a dominant group. The diversity indices showed the extent of lake pollution. Cluster analysis of 32 lakes in Hebbal-Nagavara Valley showed that Group-1 lakes are more polluted with less phytoplankton diversity than Group-2 lakes, necessitating urgent restoration and conservation measures to prevent further eutrophication. Microalgae based biorefineries are emerging as a viable industry for manufacturing biofuels and value-added goods such as protein, pigment, and antioxidants, which support the livelihood of local people at disaggregated levels. Lakes, rich in microalgal biomass, generate valuable bioproducts and offer environmental benefits like bioremediation and nutrient cycling. These microalgae may be separated and farmed on a vast scale, providing long-term, environmentally favourable options as the world seeks sustainable solutions. The city should implement restoration programs and initiate conservation measures involving local stakeholders in and around the lakes.

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