Macrophytes' function in bio-geochemical cycling and aquatic ecosystem maintenance of homeostasis

Dr. Parvindar Kaur Chhabda[1]; Dr. Shyam Maurya[2]; Veena Kumar[3]

Received: 07 February 2025; Revised: 15 March 2025; Accepted: 02 April 2025; Published: 20 May 2025

Abstract

The Homeostasis of Phosphorus (HP) in subterranean macrophytes (MP) influences the vulnerability of lakes to phase transitions; the processes connecting submerged MP HP to these alterations remain ambiguous. Eutrophication (EP) significantly affects plant stoichiometric properties and physiological condition by modifying nutrition and light accessibility in the water column. The mechanisms connecting plant functional features with the framework of ecosystems to explain the loss of submerged MPs remain inadequately clarified. Following a field examination of 25 macrophytic shallow-water lakes on the Yangtze Plain, the research established a plant trait system at the whole-plant level to identify the pivotal features of submerged MPs that exert key regulatory influence on plant phenotype. The findings indicated that Phosphorus (P) contents in organs (leaves, stems, and roots), starch, and Total Nonstructural Carbohydrate (TNC) levels were essential features. The organ starches and TNC aligned with the findings from the experiment-based networks derived from a three-month manipulation study. The mechanisms connecting the hub qualities to essential elements of ecological function were meticulously examined utilizing field investigation data. The stoichiometric HP, starch, and TNC positively correlated with species predominance and population at the species scale and neighborhood population at the group level. Diminished community biomass and elevated nutrient levels and nutrient ratios in plants resulting from EP suggest reducing the carbon sink within biomass, which promotes litter breakdown rates and the cycling of nutrients. Modifying plant reactions to EP reveals stoichiometric and physiological responses that connect plant traits with the environmental framework, which has significant consequences for comprehending ecological processes. These findings aid in the effective management of restoring submerged MPs and environmental offerings.

Keywords: Macrophytes, Bio-geochemical cycling, Aquatic ecosystem, Homeostasis

1- Assistant Professor, Department of Management, Kalinga University, Raipur, India.
Email: ku.parvindarkaurchhabda@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0006-9775-7254
2- Assistant Professor, Department of Management, Kalinga University, Raipur, India.
Email: ku.shyammaurya@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0006-3442-8621
3- Professor, New Delhi Institute of Management, New Delhi, India. Email: veena.kumar@ndimdelhi.org, ORCID: https://orcid.org/0009-0003-8698-9787
DOI: 10.70102/IJARES/V5I1/5-1-21

Introduction

Eutrophication (EP) (Chen *et al.,* 2022), resulting from the overabundance of phosphorus (P) or nitrogen (N), can induce a regime change in aquatic environments from a clear-water condition characterized by buried macrophytes (MP) (Liu *et al.,* 2023) to a turbid state filled with phytoplankton (Yang, 2024). Elevated nutrient concentrations not only inflict physiological harm on submerged MPs by inducing oxidative damage and disrupting carbon and nitrogen metabolism but also promote excessive growth of phytoplankton and microorganisms, which can obscure the buried MPs. Since recognizing human-caused EP in lakes as a significant ecological issue in the mid-twentieth century, a growing number of shallow waters have undergone regime shifts, jeopardizing the environmental integrity of these lakes and the global human water supply (Janssen *et al.,* 2021; Jayapriya, 2021). The vulnerability of lakes to phase transitions is mainly influenced by the aquatic communities present, especially submerged MP communities (Saidova *et al.,* 2024). Environmental stoichiometry, which pertains to the equilibrium of different chemicals in biological processes, is associated with numerous ecological processes (Gladkova and Gladkov, 2021) (e.g., EP and nutrient relationships) that are vital for immersed MP groupings, thereby highlighting its potential to enhance the comprehension of submerged MP collections and changes in regimes in shallow-water lakes (Zhao, Richardson and You, 2024).

Stoichiometric homeostasis, a fundamental concept in ecological stoichiometry, denotes how organisms preserve a consistent elemental composition in their tissues despite varying nutritional limitations. It illustrates the physiological adaptations of organisms to their surroundings and serves as a crucial mechanism connecting abiotic variables with biological processes within environments. Diverse stoichiometric equilibrium, particularly stoichiometric Homeostasis Phosphorus (HP) (Asada *et al.*, 2022), a critical macroelement that initiates aquatic EP, is associated with the distinct development strategies of plants. Prior research has shown that high-HP species, capable of sustaining a reasonably stable phosphorus content in tissues despite variations in ambient phosphorus levels, typically exhibit a slow-growth approach and significant resilience to outside conditions (e.g., light supply). In contrast, low-HP species, characterized by increased cell P concentration with rising ambient P levels, typically exhibit a rapid development strategy and limited resilience to changes in external settings.

Species-specific growth methods result in niche distinction, which, in addition to interspecies interactions, further induces alterations in subsurface MP communities across ecological gradients. Prior research has shown discrepancies in the significance of plant growth approaches (reflected by species-specific reactions to external variations) and interspecies interactions regarding alterations in plant assemblages (Sanczuk *et al.,* 2024). Prior field investigations have shown that high-HP species typically prevail in oligotrophic habitats characterized by low productivity and incredible biodiversity, while low-HP species are prevalent in eutrophic environments (Agarwal and Yadhav, 2023). The pivotal influence of different approaches to growth on the alterations in buried MP communities across nutrient gradients could not be substantiated, as interspecific connections were infrequently assessed in these investigations (Shi *et al.*, 2023). A stress gradient theory has been offered in investigations of interspecific connections, suggesting that heightened ecological stress transitions those connections from competitive to facilitative; this idea is still contentious (Adams *et al.*, 2022).

Materials and Methods

Field Samples and Inquiry

Survey sampling occurred in 25 macrophytic wetlands in the floodplain throughout the 2023 period of growth. The sample technique employed by MPs was the altered belt transversal approach, with the quantity of sampling sites determined by the extent of the macrophytic region. The lake surface and average water depth ranged from 2.3 to 2600.4 km^2 and 1.5 to 4.1 m, respectively. The present research meticulously examined six types of prevalent submerged MPs commonly found in these lakes. The biomass of these algae comprised the majority of the overall submerged MPs (Petrova and Kowalski, 2025), and they were harvested using a rotating reaping hook that covered 0.3 m^2, conducted on three occasions at every sampling location. The vegetation was meticulously sanitized, categorized by species, and weighed to determine the Fresh Weight (FW).

The six kinds of plants were collected and partitioned into stem, leaf, and root components. Sea specimens and sample sediments were obtained from 0.6 m beneath the sea level and the upper layers of sediment, respectively. The specimens were stored in portable refrigerators and transported to the testing facility for further processing. In the 2020 field survey, the dried weight of components (leaves, stems, and roots) was determined by meticulously examining the average mass percentage and water content of six kinds of plants across four MP lakes with varying nutrient levels in 2022, including a total of 175 plant specimens.

Measurements and Data Acquisition

The stem, leaves, root, and sediment specimens were oven-dried at 80 °C and ground into a fine powder to determine elemental and physiological indices (plant cells alone). These specimens' carbon and nitrogen contents were assessed using an elemental analyzer. Before measuring phosphorus, the plant and sediment specimens underwent digestion with H2SO4-H2O2 and H2SO4-HClO4, respectively. All specimens were analyzed for phosphorus using the ammonium molybdate ascorbic acid technique. About 110 mg of leaf powder was subjected to two extractions with 5 mL of 85% ethanol at 85 °C for 25 minutes. Ten milliliters of the lysates were centrifuged at 10 g for 15 minutes. The concentrations of Free Amino Acids (FAA) and soluble Sugar Cube (SC) in the remainder and the quantity of starch in the residue were quantified using the methodologies outlined in these papers. The sediment pore fluid was extracted by spinning the wet sediment at 2750 g for 25 minutes. The Total Nitrogen (TN) and Total Phosphorus (TP) levels in the water columns and pore waters were assessed as nitrates and orthophosphate following digestion with K2S2O8 by conventional methodologies. Secchi Depth (SD) was evaluated using a Secchi disk. Photosynthetically Active Radiation (PAR) was measured using a data recorder. Dissolved Oxygen (DO), pH, and turbidity were quantified using the instrument. Chlorophyll a (Chl-a) was extracted via ethanol and measured using a spectrophotometer.

Analysis of Plant Trait Networks

A network comprises numerous edges and nodes alike. In plant trait networks, plant functional characteristics serve as nodes, whereas trait-trait connections operate as edges. A list of trait-trait associations (r) was computed utilizing Pearson's coefficients. Trait-trait correlations indicate direct molecular linkage, coselection via optimal design, or deliberate convergence. A relevance threshold of $r > 0.3$ and $P < 0.06$ was established to prevent false correlations among characteristics. An adjacency matrix was generated by designating values below the limit as 0. The relative correlation strength among each pair of plant attributes influenced Plant characteristic networks were depicted in Cytoscape with the Prefuse Forces Driven OpenCL architecture.

The magnitude of edge connection has been previously outlined, and two measures explicate node assets: degree (D) and betweenness (C), which quantify the connectivity and centrality of each node characteristic within the network. Additional details regarding the calculation are provided in the Supplementary Materials. Plant qualities exhibiting significant Cy can be considered hub variables that regulate every plant's phenotype. At the same time, traits with elevated betweenness CB serve as intermediaries that orchestrate various modules or subsidiary networks. A plant characteristic network derived from field research was established to identify the central properties of buried MPs at the whole-plant scale. The ten characteristics with the highest Connectivity Degree (CD) were identified as the hub characteristics.

Manipulation Experimentation

After the validation of hub traits within the field-based system, the associations between these hub characteristics and eleven ecological factors (namely, sediment total nitrogen and phosphorus, water total nitrogen and phosphorus, pore water total nitrogen and phosphorus, chlorophyll-a, sediment depth, pH, turbidity, and dissolved oxygen) were investigated utilizing Canonical Correspondence Assessment (CCA). Substantial environmental factors ($P < 0.05$) were identified using the forward choice in the CCA, and the uncorrelated impact of these variables on the explained variance was assessed using the statistical software. A Monte Carlo randomization test was conducted to evaluate the importance of the complete model and every axis. The findings revealed that these essential factors explained 21.4% of the variation in hub attributes from the field-based system, with TP, SD, and SDP accounting for 63.2% of this explanation. The manipulation laboratory was regulated by varying water TP and Soluble Reactive Phosphorus (SRP) levels, alongside limited light availability to replicate field conditions. The primary objective was to ascertain the uniformity of hub features across both field- and experiment-derived networks.

Data Analysis

Initially, 24 plant parameters (i.e., organ (leaves, stems, or root) carbon, nitrogen, phosphorus, dry weight, free amino acids, soluble carbohydrates, starch, and total non-structural polysaccharides (TNC, the aggregate of soluble carbohydrates and starch) were standardized using the Box-Cox method to establish a network derived from the 2020 field survey. The hub qualities in the field-based system were validated, and the associations between these hub characteristics and external variables were examined to identify the critical environmental variables by CCA performed using the R program "vegan". A modification study investigated the consistency of hub qualities in plant trait systems based on essential environmental factors from outdoors.

Secondly, to investigate the process linking these hub qualities with species and communal characteristics, the research computed organ, species, and communal indices (H, starch, and TNC), along with species carbon dioxide, dominance, and communal biomass. Item biomass was quantified by the biomass of every kind within a quadrat. At the same time, species domination was determined as the population of each item relative to the overall biomass in the quadrant.

The overall biomass represented the aggregate biomass of all live submerged vegetation inside a quadrat, averaged across each lake. Complete least squares regression analysis investigated the bivariate connections between cell H and storage substances, individual biomass and authority, and the associations among communal H and storage carbohydrate and communal biomass.

To investigate the ramifications of altered basal resource equilibrium and physiological condition on the movement of nutrients in lakes, a linear regression technique was employed to clarify the impact of nutrient enrichment and modified light conditions on group nutrient concentrations and proportions. The data set comprised 176 squares in the 2018 field research. All data analyses were conducted using R Core Team software.

Discussions

Attributes of Water Quality Parameters

Throughout the study, the water body's temperature was approximately 31°C. In the treatment subgroups (TI-T3), the elevated nitrogen levels resulted in varying algal development in the water section, raising chlorophyll concentration. The Dissolved Oxygen (DO) in the water columns was supersaturated (exceeding 100%). The rising levels of additional nutrients resulted in a considerable increase, while exhibiting an upward trajectory.

Development Attributes of Submerged MPs

The mean starting masses of the above-ground and below-ground components of V. natans were 0.65 ± 0.21 g and 0.32 ± 0.05 g, respectively. The proliferation of V. natans was sluggish, with typical growth rates approaching zero at 25 and 45 days. The initial mass of the above-ground portion of H. verticillata (HV) was 0.28 ± 0.05 g. The mean growth ratios of the aboveground portion were 0.07 ± 0.04 and 0.03 ± 0.02 d^1, respectively, at 25 and 45 days. The initial mass of the above-ground portion of C. demersum (CD) was 0.55 ± 0.21 g. The mean rate of development of the above-ground portion was 0.03 ± 0.05 and 0.03 ± 0.03 d^1, respectively, over 25 and 45 days. The development rate of CD exceeded that of V. natans but was inferior to that of HV. No noteworthy variations were seen in the growth rates of the above-ground and below-ground components across all three therapies and control groups during both growth phases for all three genera.

Phosphorus Contents and Balanced Homeostasis of Immersed MPs

The starting phosphorus concentration in the aboveground portion of V. natans (VN) was 2.55 ± 0.4 mg/g, and the phosphorus levels in the aboveground sections of both the therapy and control groups on the 20th day exceeded the original values. On the 40th day, all therapy categories, except for the CK groups with P levels below the starting point, exhibited an increase in P levels in the above-ground portion. The initial phosphorus level of the below-ground portion of VN was 2.5 ± 0.2 mg/g. The phosphorus contents of the control groupings on the 20th and 40th days were lower than the initial stages, whereas the phosphorus contents of the treatment groups exceeded the initial ranges. The phosphorus concentration in VN's aboveground and belowground components considerably increased with elevated phosphorus levels in the aquatic environment.

The initial phosphorus content in the aboveground portion of HV was 5.3 ± 0.4 mg/g. The phosphorus levels in the categories diminished on the 25th and 45th days, but the phosphorus levels in the T2 and T3 categories escalated. The phosphorus content in the aboveground and belowground components of HV considerably increased with the rising phosphorus levels in the aquatic environment. The initial phosphorus concentration in the aboveground portion of CD was 4.51 ± 0.46 mg/g. On the 21st day, the phosphorus contents of the groupings were less than the original levels, whereas the phosphorus concentrations of the T2 and T3 categories exceeded the initial levels. The phosphorus content of the aboveground portion of CD dramatically rose with elevated phosphorus levels in the water. In contrast, the phosphorus level of the belowground portion exhibited a slight rise on the twentieth day and an enormous rise on the 45th day.

The P balanced HP for the aboveground components of the three immersed MPs was lower than that of the belowground components. The readings on the 25th day exceeded those on the 40th day. Except for VN, all three submerged algae aboveground components demonstrated plastic or moderately plastic phosphorus-balanced homeostasis. All subterranean components of the three buried MPs demonstrated weak homeostatic or homeostatic phosphorus stoichiometric regulation across a growth period of 20 days.

Determinants Influencing Phosphorus Concentrations in Submerged MPs

The organ and nutritional requirements significantly influenced the phosphorus content, whereas growth lengths only considerably affected the phosphorus content. Of the three parameters, nutrient level significantly influenced the phosphorus content in buried MPs, with a variance contributing rate of over 50%. The organ exerted the second most significant influence on phosphorus concentration, with a variation contribution rate ranging from 12% to 25%. Growing length did not significantly influence the amount of phosphorus; its contribution ratio to the phosphorus content of CD reached 9.27%.

Conclusion

The research elucidates the hub traits governing the overall plant phenotype of submerged MPs, the processes connecting these hub characteristics with ecosystem functioning and structure, and the impacts of alterations in group biomass, basal asset stoichiometry, and crop physiological position on the cycling of nutrients in aquatic environments amid EP. The findings indicated that organ P and NSC concentrations were crucial in influencing the growth of plants and the balanced and physiological pathways connecting these attributes to species predominance and community output. Environments characterized by high-Hp species with elevated NSC levels exhibit greater primary productivity. In contrast, those that contain low-HP species with diminished NSC levels are more susceptible to environmental perturbations. EP significantly influences plant communities' nutrient composition and nutrient: C levels, potentially impacting critical ecological concerns, including aqueous biomass from plants and the cycling of nutrients in freshwater habitats.

References

Adams, A.E., Besozzi, E.M., Shahrokhi, G. and Patten, M.A., 2022. A case for associational resistance: Apparent support for the stress gradient hypothesis varies with study system. *Ecology Letters*, *25*(1), pp.202-217. https://doi.org/10.1111/ele.13917

Agarwal, A. and Yadhav, S., 2023. Structure and Functional Guild Composition of Fish Assemblages in the Matla Estuary, Indian Sundarbans. *Aquatic Ecosystems and Environmental Frontiers*, *1*(1), pp.16-20.

Asada, K., Kanda, T., Yamashita, N., Asano, M. and Eguchi, S., 2022. Interpreting stoichiometric homeostasis and flexibility of soil microbial biomass carbon, nitrogen, and phosphorus. *Ecological Modelling*, *470*, p.110018. https://doi.org/10.1016/j.ecolmodel.2022.110018

Chen, L., Zhao, J., Zhang, Z., Shen, Z., Dong, W., Ma, R., Chen, J., Niu, L., Chen, S., Wu, D. and Liu, J.,

2022. Lake eutrophication in northeast China induced by the recession of the East Asian summer monsoon. *Quaternary Science Reviews*, *281*, p.107448. https://doi.org/10.1016/j.quascirev.2022.107448

Gladkova, O.V., and Gladkov, E.A., 2021. Deicing Reagents in Urban Ecosystems, Using the Example of Moscow. *Archives for Technical Sciences*, *2*(25), pp.71–76. https://doi.org/10.7251/afts.2021.1324.071G

Janssen, A.B., Hilt, S., Kosten, S., de Klein, J.J., Paerl, H.W. and Van de Waal, D.B., 2021. Shifting states, shifting services: Linking regime shifts to changes in ecosystem services of shallow lakes. *Freshwater Biology*, *66*(1), pp.1-12. https://doi.org/10.1111/fwb.13582

Jayapriya, R., 2021. Scientometrics Analysis on Water Treatment During 2011 to 2020. *Indian Journal of Information Sources and Services*, *11*(2), pp.58-63. https://doi.org/10.51983/ijiss-2021.11.2.2889

Liu, C., Shen, Q., Gu, X., Zhang, L., Han, C. and Wang, Z., 2023. Burial or mineralization: origins and fates of organic matter in the water–suspended particulate matter–sediment of macrophyte-and algae-dominated areas in Lake Taihu. *Water Research*, *243*, p.120414. https://doi.org/10.1016/j.watres.2023.120414

Petrova, E. and Kowalski, D., 2025. Energy-Efficient Microalgae Filtering and Harvesting Using an Extremely Low-Pressure Membrane Filter with Fouling Control. *Engineering Perspectives in Filtration and Separation*, *3*(1), pp.25-31.

Saidova, K., Madraimov, A., Kodirova, M., Madraimov, A., Kodirova, K., Babarakhimov, T., Urinova, S., and Zokirov, K., 2024. Assessing the impact of invasive species on native aquatic ecosystems and developing management strategies. *International Journal of Aquatic Research and Environmental Studies*, *4*(S1), pp.45-51. https://doi.org/10.70102/IJARES/V4S1/8

Sanczuk, P., Landuyt, D., De Lombaerde, E., Lenoir, J., Lorer, E., Luoto, M., Van Meerbeek, K., Zellweger, F. and De Frenne, P., 2024. Embracing plant–plant interactions—Rethinking predictions of species range shifts. *Journal of Ecology*, *112*(12), pp.2698-2714.

Shi, J., Wang, Z., Peng, Y., Zhang, Z., Fan, Z., Wang, J. and Wang, X., 2023. Microbes drive metabolism, community diversity, and interactions in response to microplastic-induced nutrient imbalance. *Science of the Total Environment*, *877*, p.162885. https://doi.org/10.1016/j.scitotenv.2023.162885

Yang, Z., 2024. The Impact of Environmental Assessment of Green Innovation on Corporate Performance and an Empirical Study. *Natural and Engineering Sciences*, *9*(2), pp.94-109. https://doi.org/10.28978/nesciences.1569137

Zhao, B., Richardson, R.E. and You, F., 2024. Microplastics monitoring in freshwater systems: A review of global efforts, knowledge gaps, and research priorities. *Journal of Hazardous Materials*, p.135329. https://doi.org/10.1016/j.jhazmat.2024.135329