



Removal of soluble reactive phosphorus (SRP) from water by aquatic macrophytes

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Abstract: Monoculture of seven aquatic macrophytes viz., *Marcellia* spp., *Pistia stratiotes*, *Ipomea aquatica*, *Hydrilla verticillata*, *Trapa natans*, *Chara najas* and *Ludwigia repens* were investigated in mesocosms for the removal of soluble reactive phosphate (SRP) and other nutrient ions to improve water quality. The testing medium (amended water) containing higher concentrations of SRP 10 mg L⁻¹, NO₃⁻ 10 mg L⁻¹, Ca²⁺ 30 mg L⁻¹, and K⁺ 15 mg L⁻¹ was treated with individual plant species. Significant reduction of SRP from the water was observed by all the species especially *C. najas* and *H. verticillata*. The plant tissue P concentration was found maximum in *C. najas* followed by *H. verticillata*, and *P. stratiotes* with a value 1.15, 1.04 and 1.05 mg g⁻¹ dwt respectively. The overall performance indicates that the submerged aquatic macrophytes are potential accumulator of P. However, no single species was found to have a complete mitigation of nutrients from water.

Key words: Aquatic macrophyte, Monoculture, Mesocosm, Soluble reactive phosphate

Introduction

Water security, as an expression of water availability in terms of quality and quantity, is one of the key factors challenging the economic development in most of the developing countries. Nutrients are one of the major impairment of Indian lakes and ponds after the sedimentation and contamination through industrial effluents. The water quality of the lakes of wetlands of northern Uttar Pradesh in India is degrading because of the over exploitation of the catchment for cultivation of paddy, defecation by the cattle, agricultural runoff contain huge amount of nutrients such as P and N those are required for the growth of aquatic weeds. Phosphorus (P) is some times considered as the limiting nutrient in inland fresh waters (Wade *et al.*, 2001). The excessive level of 30 µg L⁻¹ P in river waters and in excess of 20 µg L⁻¹ P in lakes are considered to play the key role in eutrophication (Zhou *et al.*, 2001) and is one of the major factors in growth of phytoplankton (Correll, 1998).

The nutrient removal capability of aquatic plants has created substantial interest in their use for water treatment. Aquatic macrophytes are limited to the macroscopic flora including aquatic spermatophytes, pteridophytes and bryophytes. Their growth form usually classifies them in four groups: emergent macrophytes (*Phragmites australis*, *Typha latifolia*), floating-leaved macrophytes (*Nuphar luteum*), free-floating macrophytes (*Eichhornia crassipes*) and submerged macrophytes, *Myriophyllum spicatum* (Srivastava *et al.*, 2008). Aquatic plants have been commonly investigated for the removal of pollutants and excessive nutrients from the water since aquatic plants absorb and use the nutrient ions such as phosphorus and nitrate for their growth (Mahujcharyawong and Ikeda, 2001). Voluminous literature of various investigations from all

over the world is available on the nutrient removal by the aquatic plants (Tilton and Kadlec, 1979; Cornwell *et al.*, 1977; Nicholas, 1983; Aoi and Ohba, 1995; Reed *et al.*, 1995; Kadlec and Knight, 1996; Dierberg *et al.*, 2002; Sooknah and Wilkie, 2004; Deaver *et al.*, 2005). Some aquatic species investigated extensively for the removal of nutrients from the water include *Eichhornia crassipes* (Cornwell *et al.*, 1977; Reddy and Smith 1987; Imaoka and Teranishi, 1988) *Pistia stratiotes* (Aoi and Hayashi, 1996) *Typha domingensis*; *Potenderia cordata*; *Canna flaccida*; *Sagittaria lancifolia*; *Juncus effusus* and *Scirpus validus* (Debusk *et al.*, 1995) *Juncus effusus*, *Ludwigia peploides* and *Leersia oryzoides* (Deaver *et al.*, 2005).

In the present study we showed the seasonal variation in the water quality of lakes to understand the nutrient fluxing and emphasized our investigations on the potential of seven different aquatic macrophytes, *Marcellia* spp., *Pistia stratiotes*, *Ipomea aquatica*, *Hydrilla verticillata*, *Trapa natans*, *Chara* spp. and *Ludwigia repens* to remove SRP, nitrate, calcium, and potassium in simulations of hyper-eutrophic conditions.

Materials and Methods

The lakes and site of experimentation: The lakes under investigation are tropical shallow freshwater lakes (mean depth <3 m) well known as a small bird sanctuary located at Nawabganj (Lat. 26.55° N and Long. 80.48° E) with a stretch of 3 sq km. at Unnao district in Uttar Pradesh, India located at 45 km from experimental site. The only source of fresh water to this wetland is the river 'Sai' a tributary of the river 'Ganga'. The experiments were carried at National Botanical Research Institute (NBRI) Lucknow

UP India. The climate of Lucknow city is typically monsoon with hot summer (May to June) and cold winter (January to February). Experiments were conducted in a poly-house at 37°C and at 90% humidity.

Water quality monitoring: Water samples were collected from the shores of five locations of each lake encoded as N₁ and N₂ in the wetlands of Nawabganj in different season for summer (March – June), rainy (July – October) and winter in the month of November – February, in iodide washed white plastic bottles with the help of adjustable shaft provided with a clamp to hold the bottle. The parameters measured were pH, electrical conductivity (EC), dissolved oxygen (DO), bi-carbonates (HCO₃) chlorides (Cl) and ammonia (NH₄) immediately after collection. SRP in water was analyzed as per (APHA, 1996). Nitrate (NO₃⁻¹) ions in water were determined by the selective ion electrode with a help of potentiometer (Thermo Orion 900 A Plus).

Aquatic plants in mesocosm: Seven most common aquatic weeds viz., *Marcellia* spp., *Pistia stratiotes*, *Ipomea aquatica*, *Hydrilla verticillata*, *Trapa natans*, *Chara* spp. and *Ludwigia repens* were collected from the wetlands of Aurawan, and Banthra of Lucknow district of Uttar Pradesh India. The plants were grown in mesocosm made of plastic troughs (50 cm diameter and of 50 liters capacity). Roots and rhizomes were thoroughly washed with 1% EDTA (di-sodium salt) to remove any adhered ionic impurity. Each mesocosm was vegetated with a single species of aquatic plant and were acclimatized for about 2 weeks prior to initiation of experiments. The experiments were conducted with simulated lake water called as testing medium. The testing medium (simulation) was prepared with distilled water

amended with the addition of nutrients to final concentrations of 10 mg L⁻¹ SRP, NO₃⁻¹, and 30 mg L⁻¹, Ca²⁺ and K⁺ 15 mg L⁻¹. Each trough was filled with 40 liters of the testing medium. Respirators were provided to supply oxygen for aquatic plants to avoid anaerobic conditions that often give rise to root fungal diseases in mesocosm. Three replicates were taken for each plant species. Plant and water samples were taken every second day.

Nutrient concentration in plants: Oven dried (60°C for about 48 hr) plant samples were ground to fine powder for the determination of nutrient concentration in tissues. 1 g of powdered plant sample was digested in three replicates with HClO₄ and HNO₃ (1:4) at 300°C for about 1-2 hr (APHA, 1996). Calcium and potassium content was determined using atomic absorption spectrophotometer (Perkin Elmer 5100). Total P in plants was analyzed spectrophotometrically by acid-molybdenum blue method (EPA, 1979). For nitrates in tissue, 1 g of plant sample was boiled in 20 ml of distilled water for about 10 min followed by centrifugation at 3000 rpm for about 15 min. The extract was passed through a column packed with insoluble PVPP (polyvinylpolypyrrolidone) to remove the phenolic impurity. NO₃⁻¹ was determined by the selective ion electrode. The nutrient concentration in the tissues is expressed as mg g⁻¹ dry weight.

Plant biomass: Biomass of the plants were measured at the start of the experimentation and at the end of experiment, for a purposeful results, the representative plant sample was collected with the help of 0.25 m² quadrat in three replicates. The plant samples were oven dried at 75°C for 48 hr and weighed. The biomass is expressed as gram dry weight (g dwt).

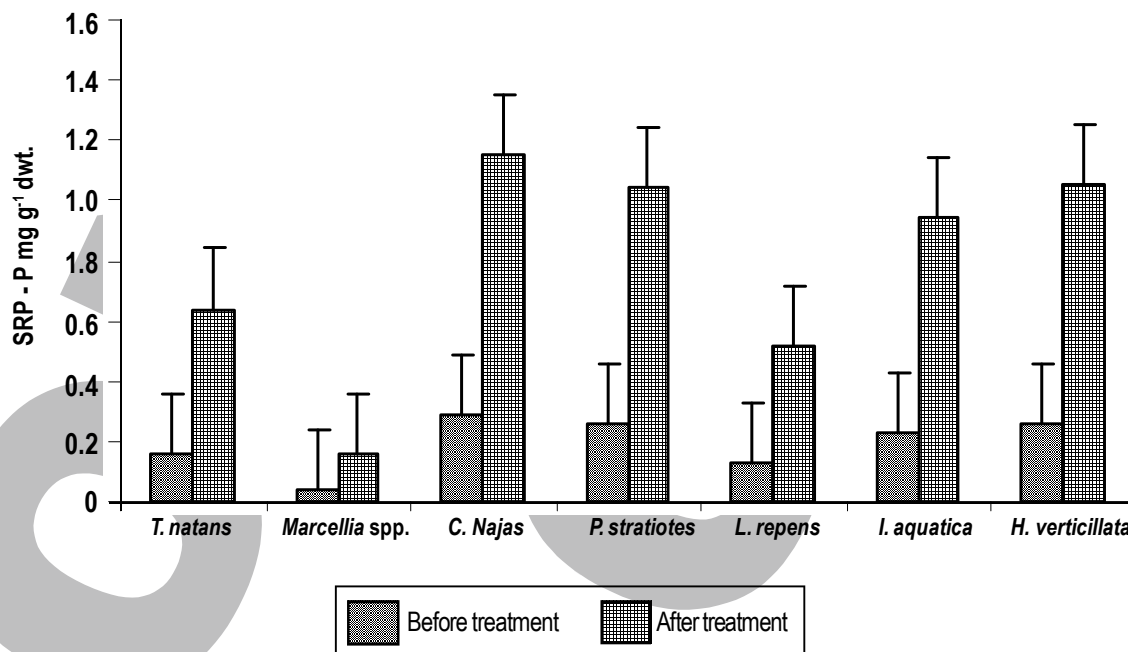


Fig. 1: P concentration in mg g⁻¹ dry wt. in plant tissues before and after the treatment of amended water

Results

Water quality of lakes: Results indicate higher contents of reactive phosphorous in summer within a range of 9.12 to 9.47 mg L⁻¹ in lake N₁ and 8.58 to 8.90 mg L⁻¹ in the lake N₂ (Table 1). Ammonia was next to the phosphorous found maximum within a range of 109.0 to 119.80 mg L⁻¹ in lake N₁ in summers. Nitrate ion concentration in summer ranged between 21.92 to 24.05 mg L⁻¹ in lake N₁ and lake N₂ respectively while in winter the value ranges between 72.0 mg L⁻¹ to 70.22 mg L⁻¹. The dissolved oxygen indicates the excessive organic loading in the lake water of N₁ with value 1.49 mg L⁻¹. The dissolved oxygen in the water of the lake N₂ ranged from 5 to 11 mg L⁻¹.

Nutrient removal by aquatic plants: Table 2 refer to the analysis of water (testing medium) treated with individual aquatic plant species. The result indicate the reduction of SRP in water in the experimental sets of *Chara* spp. with a value 5.2 ± 0.28 mg L⁻¹ followed by *H. verticillata* with a value 6.1 ± 0.12 mg L⁻¹. The results also showed the significant removal of nitrate ions by *Chara* spp. up to a value 1.0 ± 0.07 mg L⁻¹ which is the highest as compared to the other vegetated treatment. Ca²⁺ ions were found to be removed significantly by *H. verticillata* up to a mean value 12.6 ± 0.5 and K⁺ was significantly removed by the *Chara* spp. with a mean value 6.7 ± 0.4 mg L⁻¹.

Biomass and P accumulation in plants: Significant increase in the biomass was observed in all the weed species (Table 3). The biomass on gram dry weight basis was found highest 24.0 ± 1.32 g dwt of *H. verticillata* as compared to the initial 19.7 ± 0.56 g dwt followed by *I. aquatica* 9.25 ± 1.62 with a initial value 6.02 ± 0.70 g dwt, *L. repens* 8.86 ± 1.08 with 7.09 ± 0.61 g dwt as initial biomass and *T. natans* 7.70 ± 0.92 with a initial biomass 4.31 ± 0.20 g dwt. However; significant biomass was found to accumulate by *H. verticillata*, *Chara* spp. and *T. natans*. A comparative (initial to final) concentration of P in plant tissues in mg g⁻¹ dwt has been given in Fig. 1. The initial concentration of P was found maximum in *Chara* spp. 0.29 ± 0.02 and minimum in *Marcellia* spp. 0.04 ± 0 mg g⁻¹ dwt.

Final concentration of P was observed maximum in *Chara* spp. followed by *H. verticillata*, *P. stratiotes* and minimum in *Marcellia* spp.

Nutrients other than P in plant tissues: Table 3 refers to the concentration of Ca²⁺, K⁺ and NO₃⁻ in the plant tissues. The results indicate higher contents of calcium ions in the tissues of *H. verticillata* (21.6 ± 2.07) mg g⁻¹ dwt followed by *T. natans* (6.43 ± 0.49) mg g⁻¹ dwt and *P. stratiotes* (6.24 ± 0.46) mg g⁻¹ dwt. Potassium ion concentration was found maximum in *Chara* spp. (84.30 ± 3.94) mg g⁻¹ dwt followed by *P. stratiotes* (64.10 ± 0.11) mg g⁻¹ dwt, *I. aquatica* (61.10 ± 2.69) mg g⁻¹ dwt, *L. repens* (46.67 ± 3.31) mg g⁻¹ dwt, *Marcellia* spp. (25.13 ± 0.33) mg g⁻¹ dwt and least in *H. verticillata* (6.29 ± 0.29). Nitrate ion concentration was found maximum in the *Chara* spp. (5.82 ± 0.90) mg g⁻¹ dwt, *Marcellia* spp. (4.76 ± 0.08) mg g⁻¹ dwt and *I. aquatica* (4.41 ± 0.03) mg g⁻¹ dwt. *H. verticillata* was found to have nitrate contents below detection limits.

Discussion

The ambient temperature in summer of north India is 38 – 42°C from morning to evening (water column temperature 24 - 31°C) that favor the growth of algae. In summer lowering of water table enhances the nitrogen mineralization (Updegraff *et al.*, 1995) by the aerobic microbes (Singh *et al.*, 2005). Algal bloom caused by the higher contents of reactive phosphorous and nitrogen reduce the carbonate and bicarbonate ions from the water that disrupt the natural buffering capacity of the water as a result of which water becomes alkaline (Tchobanoglous and Schroeder, 1985) especially in summer. During rainy season, diffusion of nutrients increase depending upon the physico-chemical structure of the soil at soil water interface because of the swelling of the clay due to sodium ions reduce the leachability of the ions in to the water. The result of water analysis showed the significant increase of nutrients especially in summer. These hyper-eutrophic conditions were simulated in the testing medium.

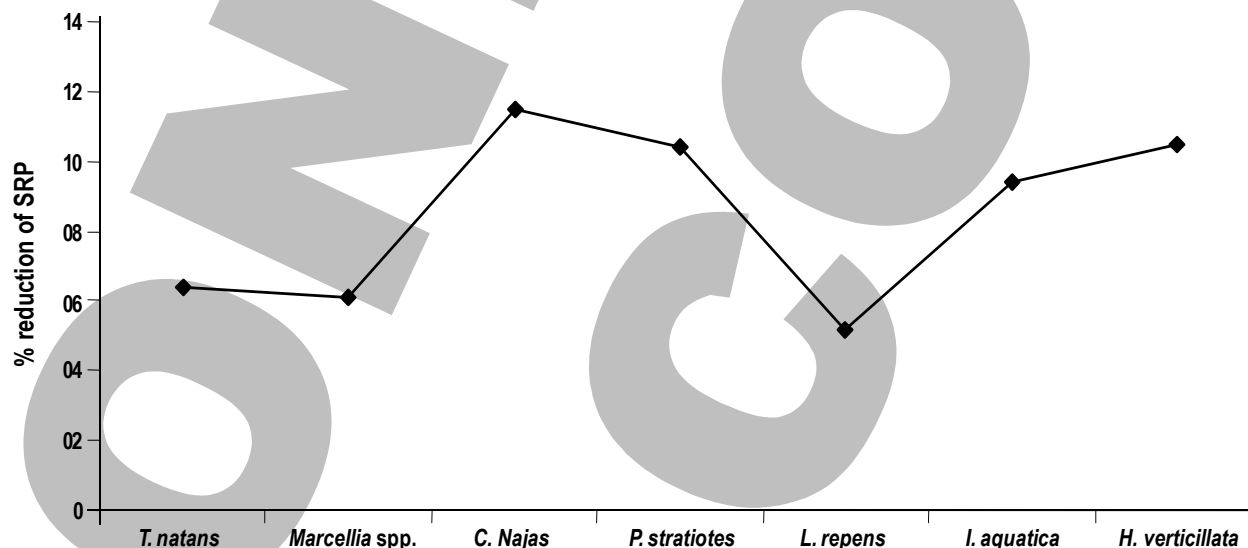


Fig. 2: Percentage reduction of SRP in the water by the individual aquatic macrophyte

Table -1: Quality parameters of water collected from the shores of the lakes in different seasons

Group (Season)	Parameters									
	Range	pH	EC	DO	HCO ₃	SRP	NH ₄	NO ₃ ¹⁻	Cl ¹⁻	
Lake N ₁	Summer	Min.	8.81	1707	1.49	510.0	9.12	109.0	14.0	93.0
		Max.	9.12	1940	4.00	580.0	9.57	119.8	21.50	120.0
	Rainy	Min.	6.46	656	2.20	240.0	0.16	1.26	21.0	94.0
		Max.	7.56	788	4.80	280.0	0.19	2.28	21.92	98.0
	Winter	Min.	7.76	728	3.13	558.0	1.81	BDL	18.45	127.0
		Max.	8.06	812	3.57	630.0	2.04	BDL	24.05	162.5
Lake N ₂	Summer	Min.	8.65	631	3.70	260.0	8.58	16.4	38.61	98.71
		Max.	9.02	711	4.20	280.0	8.90	18.0	40.03	101.0
	Rainy	Min.	8.70	586	11.20	163.0	0.87	0.06	70.0	27.17
		Max.	9.10	459	12.00	160.0	1.01	0.08	72.0	37.99
	Winter	Min.	8.10	613	5.90	325.0	1.30	0.10	67.3	31.27
		Max.	8.50	800	6.10	355.0	1.77	0.13	70.2	33.93

EC = Electrical conductivity in ms cm⁻¹, DO = Dissolved oxygen in mg L⁻¹, HCO₃ = Bi-carbonates in mg L⁻¹, PO₄ = Phosphate in mg L⁻¹, NH₄ = Ammonium in mg L⁻¹, NO₃ = Nitrate in mg L⁻¹, Cl = Chlorides in mg L⁻¹. N₁ and N₂ are the codes given to the lakes to hide the identity, values in parenthesis are std. dev, BDL = Below detection limit of 0.001 mg L⁻¹

Table- 2: Removal of anions and cations from the amended water by the aquatic weeds

Plant spp.	Anions in ATW				Cations in ATW			
	SRP mg L ⁻¹		NO ₃ ¹⁻ mg L ⁻¹		Ca ²⁺ mg L ⁻¹		K ⁺ mg L ⁻¹	
	Initial conc.	Final conc.	Initial conc.	Final conc.	Initial conc.	Final conc.	Initial conc.	Final conc.
<i>Trapa natans</i>	10 mg L ⁻¹	8.0 ± 0.47	10 mg L ⁻¹	3.1 ± 0.17	30 mg L ⁻¹	24.8 ± 3.0	15 mg L ⁻¹	9.75 ± 0.6
<i>Marcellia</i> spp.	10 mg L ⁻¹	8.9 ± 0.10	10 mg L ⁻¹	2.1 ± 0.11	30 mg L ⁻¹	19.4 ± 0.5	15 mg L ⁻¹	8.35 ± 0.3
<i>Chara</i> spp.	10 mg L ⁻¹	5.2 ± 0.28	10 mg L ⁻¹	1.0 ± 0.07	30 mg L ⁻¹	27.2 ± 1.2	15 mg L ⁻¹	6.70 ± 0.4
<i>Pistia stratiotes</i>	10 mg L ⁻¹	6.7 ± 0.66	10 mg L ⁻¹	4.1 ± 0.08	30 mg L ⁻¹	24.2 ± 3.7	15 mg L ⁻¹	9.54 ± 0.2
<i>Ludwigia repens</i>	10 mg L ⁻¹	9.2 ± 0.29	10 mg L ⁻¹	5.8 ± 0.54	30 mg L ⁻¹	24.5 ± 1.2	15 mg L ⁻¹	10.7 ± 0.5
<i>Ipomea aquatica</i>	10 mg L ⁻¹	8.2 ± 0.12	10 mg L ⁻¹	2.7 ± 0.37	30 mg L ⁻¹	18.0 ± 2.0	15 mg L ⁻¹	9.44 ± 0.5
<i>Hydrilla verticillata</i>	10 mg L ⁻¹	6.1 ± 0.12	10 mg L ⁻¹	7.3 ± 0.66	30 mg L ⁻¹	12.6 ± 0.5	15 mg L ⁻¹	11.1 ± 1.0

ATW = Amended treatment water

Table - 3: Concentration of ions in aquatic plant tissues (mg g⁻¹ dwt) after treatment

Plant spp.	Biomass in g dwt (I)	Biomass in g dwt (F)	Ca ²⁺	K ⁺	NO ₃ ¹⁻	PO ₄ ³⁻
<i>Trapa natans</i>	4.31 ± 0.20	7.70 ± 0.92	6.43 ± 0.49	25.13 ± 0.33	3.37 ± 0.09	0.64 ± 0.51
<i>Marcellia</i> spp.	2.49 ± 0.60	5.16 ± 1.0	2.09 ± 0.22	42.80 ± 4.43	4.76 ± 0.08	0.61 ± 0.10
<i>Chara</i> spp.	2.17 ± 0.19	5.66 ± 1.10	1.89 ± 0.18	84.30 ± 3.94	5.82 ± 0.90	1.15 ± 0.05
<i>Pistia stratiotes</i>	2.89 ± 1.01	4.10 ± 0.70	6.24 ± 0.46	64.10 ± 0.11	3.18 ± 0.29	1.04 ± 0.07
<i>Ludwigia repens</i>	7.09 ± 0.61	8.86 ± 1.08	5.67 ± 0.80	46.67 ± 3.31	1.10 ± 0.01	0.52 ± 0.13
<i>Ipomea aquatica</i>	6.02 ± 0.70	9.25 ± 1.62	3.00 ± 0.03	61.10 ± 2.69	4.41 ± 0.03	0.94 ± 0.02
<i>Hydrilla verticillata</i>	19.7 ± 0.56	24.0 ± 1.32	21.6 ± 2.07	6.29 ± 0.29	BDL	1.05 ± 0.12

(I) Initial, (F) Final, BDL = Below detection limit of 0.001, g dwt = Grams of dry weight

Aquatic plants were used to treat the testing medium a simulation of natural lake water with higher levels of nutrient ions assuming the extreme conditions of enrichment. Aquatic plants are beneficial for nutrient mitigation since they are capable of direct uptake and increase the hydraulic retention time in wetlands (Brix, 1994). The growth of aquatic plants in a mesocosm and choosing a species of aquatic macrophyte for mitigation of a specific nutrient is a

skillful task. The current study of nutrient mitigation by the aquatic macrophytes indicate the efficiency of certain aquatic weed species to remove significantly the reactive phosphorus, nitrates, calcium and potassium individually, although reduction in the concentration of the ions was observed in all the treatment sets. The removal mechanism in water is unknown however; the biomass and tissue concentrations of ions especially of phosphorus indicate variation in

accumulation of ions by the plants. The uptake mechanisms can be explained on the basis of morphological dissimilarity in the rooted floating and rooted submerged plants. Thinner and longer root enhance geometry for uptake of nutrients from the water hence, P uptake depends on root length, diameter and surface area in contact with the environment. The floating plants have their roots and shoots completely under water and take up the ions with help of rootlets and to some extent by mechanism of sorption. However, the role of mycorrhizal association in uptake of P from water can not be ignored as reports of Vassilev *et al.* (1999) suggest that in water the mycorrhization along with the supplements of enterobacters enhance phosphorus uptake. In this study *Chara* spp. showed higher removal of phosphorus ions because of the capability to assimilate the cations and anions directly from the water (Graneli and Solander, 1988). Alkaline aqueous conditions are associated with algal growth and increased dissolved oxygen in day time because of the photosynthesis (Tchobanoglous and Schroeder, 1985). The reason of higher nitrate content in tissue of *Chara* can be explained by nitrogen assimilation and dissolved oxygen that oxidizes available ammonia on the surface water to form nitrates. We observed the least uptake of Ca ions from the water by the Characean biomass which can be explained by the precipitation of CaPO_4 (Dierberg *et al.*, 2002) in alkaline conditions on the surface of the plant however, the presence of other factors such as microbes in removing P can not be overlooked even in the mesocosm (Mulkerrins *et al.*, 2004). *H. verticillata* in the study showed significant reduction of SRP similarly as *Chara* spp. but has no role in nitrate assimilation. Macrophytes not only directly take up nutrients, but they provide a surface for periphyton growth. Much of the nutrients which were removed in mesocosm in this study have probably been taken up by periphyton algae growing on the surface on the plants/roots. Least growth of *P. stratiotes* in the mesocosm was observed in the present study although having no size or material related difficulties with the *P. stratiotes* were found to present in the troughs. The tissue concentrations of potassium and calcium and in the treated water indicate that *T. natans* and *Chara* spp. has potential to remove these cations from the water. *L. repens* grow very slow in the mesocosm and found to have no significant impact on the ionic concentration. In other words the rooted submerged plants such as *Chara* spp. are more efficient as compared to the free floating ones such as *T. natans* a rooted free floating plant. The floating aquatic macrophytes however; are sensitive to the environmental variables especially the abiotic components although they can survive raging atmospheric and hydrologic conditions.

Conclusion

The study evaluated the general nutrient status of lakes in different seasons, which was used to prepare a simulated testing medium assuming a greater condition of enrichment. Out of seven aquatic macrophytes, the submerged plants, *Chara* spp., *H. verticillata*, showed greater potential to remove SRP, calcium and potassium from the water. The findings also suggest that with a slight amendment in ionic composition (ion such as Ca) of water,

macrophytes can mitigate nutrient significantly from the waste waters. Aquatic macrophyte in monoculture showed the removal of one or two nutrients however, polyculture of these macrophytes can be used in most of the treatment facilities for improving the water quality.

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References

- Aoi, T. and Ohba, E.: Rates of Nutrient Removal and Growth of the Water Lettuce (*Pistia stratiotes*). 6th International Conference on The Conservation and Management of Lakes Kasumigaura' 95 Proceedings (1995).
- Aoi, T. and Hayashi, T.: Nutrient removal by water lettuce (*Pistia stratiotes*). *Water Sci. Technol.*, **34**: 407 – 412 (1996).
- APHA: Standard methods for the examination of water and wastewater, AWWA, and WPCF, Washington, D.C. (1996).
- Brix, H.: Functions of macrophytes in constructed wetlands. *Wat. Sci. Tech.*, **29**: 71 – 78 (1994).
- Cornwell, D.A., Zoltek, J. Jr., Patrinely, C. D., Furman, T. D. and Kim, J. I.: Nutrient removal by water hyacinths. *JWPCF.*, **57** - 65 (1977).
- Correll, D. L.: The role of phosphorus in the eutrophication of receiving waters: A review. *J. Environ. Qual.*, **27**: 261 – 266 (1998).
- DeBusk, T.A., Peterson, J.E. and Reddy, K.R.: Use of aquatic and terrestrial plants for removing phosphorus from dairy waste waters. *Ecol. Eng.*, **5**: 371 – 390 (1995).
- Dierberg, F.E., DeBusk, T. A., Jackson, S. D., Chimney, M. J. and Pietro, K.: Submerged aquatic vegetation based treatment wetlands for removing phosphorus from agricultural runoff: Response to hydraulic and nutrient loading. *Water Res.*, **36**: 1409 – 1422 (2002).
- Deaver, E., Moore, M.T., Cooper C. M. and Knight, S. S.: Efficiency of three aquatic macrophytes in mitigating nutrient run-off. *Int. J. Ecol. Environ. Sci.*, **31**: 1-7 (2005).
- EPA: Methods for the chemical analysis of water and wastes, EPA – 600/4 – 79 – 020, Washington, D.C. (1979).
- Graneli, W. and Solander, D.: Influence of aquatic macrophytes on phosphorus cycling in lakes. *Hydrobiol.*, **170**: 245 – 266 (1988).
- Imaoka, T. and Teranishi, S.: Rates of nutrient uptake and growth of the water hyacinth [*Eichhornia crassipes* (Mart.) Solms]. *Water Res.*, **22**: 943 – 951 (1988).
- Kadlec, R. and Knight, R.: Treatment Wetlands. Boca Raton, FL: Lewis Publishers (1996).
- Mahujcharyawong, J. and Ikeda, S.: Modelling of environmental phytoremediation in eutrophic river - the case of water hyacinth harvest in Tha – chin river, Thailand. *Ecol. Model.*, **142**: 121 - 134 (2001).
- Mulkerrins, D., Dobson, A. D. W. and Colleran, E.: Parameters affecting biological phosphorus removal from wastewater. *Environ. Int.*, **30**: 249 – 259 (2004).
- Nichols, D. S.: Capacity of natural wetlands to remove nutrients from wastewater. *J. Water Pollut. Control Fed.*, **55**: 495 – 505 (1983).
- Reddy, K.R. and Smith, W.H.: Aquatic plants for water treatment and resource recovery. Mangolia Publishing Inc., Orlando, FL, 1032 (1987).
- Reed, S. C., Crites, R. W. and Middlebrooks, E. J.: Natural system for waste management and treatment. McGraw-Hill, New York. p. 433 (1995).
- Singh, V. P., Dass, P., Kaur, K., Billore, S. K., Gupta, P. K. and Parashar, D.C.: Nitrous oxide fluxes in a tropical shallow urban pond under influencing factors. *Current Sci.*, **88**: 478 – 483 (2005).

- Sooknah, R.D. and Wilkie, A.C.: Nutrient removal by floating aquatic macrophytes cultured in anaerobically digested flushed dairy manure waste water. *Ecol. Eng.*, **22**: 27-42 (2004).
- Srivastava, J., Gupta, A. and Chandra, H.: Managing water quality with aquatic macrophytes. *Rev. Environ. Sci. Biotechnol.*, **7**: 255-266 (2008).
- Tilton, D. L. and Kadlec, R.H.: The utilization of a freshwater wetland for nutrient removal from secondarily treated wastewater effluent. *J. Environ. Qual.*, **8**: 328 – 334 (1979).
- Tchobanoglous, G. and Schroeder, E.D.: *Water Quality*, Addison – Wesley Publishing Company USA (1985).
- Updegraff, K., Pastor, J., Bridgeham, S. D. and Johnston, C. A.: Environmental and substrate control over carbon and nitrogen mineralization in northern wetlands. *Ecol. Appl.*, **5**: 151 – 163 (1995).
- Vassilev, M., Azcon, R., Barea, J. and Vassilev, N.: Effect of encapsulated cells of *Enterobacter* sp. On plant growth and phosphorus uptake. *Biores. Technol.*, **67**: 229 – 232 (1999).
- Wade, A.J., Hornberger, G.M., Whitehead, P.G., Jarvie, H.P. and Flynn, N.: On modeling the mechanisms that control in-stream phosphorus, macrophyte, and epiphyte dynamics: An assessment of a new model using general sensitivity analysis. *Water Resour. Res.*, **37**: 2777–2792 (2001).
- Zhou, Q., Gibson C. E. and Zhu Y. M.: Evaluation of phosphorus bioavailability in sediments of three contrasting lakes in China and the UK. *Chemosphere*, **42**: 221–225 (2001).

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