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(REVIEW ARTICLE)

Constructed floating wetlands mediated nutrient management of eutrophic lakes

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Abstract

Eutrophication is the process of enrichment of water source due to excess of nutrients or organic matter that promotes primary production owing to the growth of algae and other plants and also reduce total dissolved oxygen. It is a concern as it has numerous negative impacts not only on ecology but also aesthetically, recreationally and economically. Constructed floating wetlands have been recognized as effective mechanisms for water treatment. They are engineered system designed to enhance the interaction that occurs in natural wetlands between water, plants, microbes, soil and atmosphere in order to remove pollutants from water in a more natural and passive manner. If Constructed Floating wetlands are able to reduce nutrient load of eutrophic water then they can be implemented to restore the conditions of various lakes, which are suffering with contamination by point and non- point sources of pollution. Predominantly, these floating wetlands themselves being eco-friendly can be extremely successful in reinvigorating animal populations and providing natural beauty in areas that are otherwise lacking.

Keywords: Constructed floating wetlands; Eutrophication; Lake management; Phosphorous; Nitrogen.

1. Introduction

Lakes hold an aesthetic importance in every culture. From time immemorial lakes are not just being used for fulfilling human needs but also are highly revered. With the advent of time and development the demand of water increased and the natural lakes wasn't enough to cater to the needs. The situation demanded creation of man- made lakes. Water from these sources finds multiple uses viz a viz in agriculture, industrial and domestic. They also act as a natural balance reservoir as they control floods. They are a rich site for different flora and fauna therefore a well-established ecosystem in itself. But with the growth of urban economy and also rise in population these natural and man-made lakes are under immense threat of losing their identity. One of the biggest threats that is commonly being faced by these water reservoirs is Eutrophication.

The phenomenon of hypertrophication or Eutrophication as commonly known is the process of enrichment of water source due to excess of nutrients or organic matter that promotes primary production owing to the growth of algae and other plants and also reduce total dissolved oxygen [1]. The excessive growth of autotrophs is due to availability of one or more of the limiting growth factors required for photosynthesis such as carbon dioxide, sunlight and nutrient fertilizers [2]. According to Carpenter [3], in natural lakes eutrophication is a natural ageing process as there is a development of sediment. But the process happens over centuries and such lakes are not interrupted by human activities.

However, growing human population and industrialization have increased the rate and extent of eutrophication trough point sources (e.g. municipal and industrial effluent) and non-point (diffuse) source (e.g. agricultural runoff from fertilised top soils and livestock operation [3]. Enrichment of phosphorus and nitrogen may happen from both external and internal sources.

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Eutrophication is a concern as it has numerous negative impacts not only on ecology but also aesthetically, recreationally and economically. Given the high ecological and water quality value associated with lakes, it's very important to save these freshwater resources from drying away. Two possible solutions to control the eutrophication of these freshwater or marine sources are:

- Prevention through a radical change in our lifestyles.
- Water treatment to remove existing contaminants, including excess nutrients.

Although the foremost solution is difficult to achieve the latter part looks more promising. Ponds and wetlands have become widely accepted water quality improvement devices over the past two decades. This growing popularity has been largely due to the fact that these systems provide relatively passive, natural, low maintenance and operationally simple treatment solution. Wetlands rely upon natural processes to mechanically and biologically filter water as it passes slowly through shallow areas of dense aquatic vegetation, and through permeable bottom soils. The primary mechanisms for nutrient removal are microbial transformation and uptake; macrophyte assimilation, absorption into organic and inorganic substrate materials; and volatilization. While the system can be complex, with various plant and microbial species occupying specific niches. Surface area is essential for bacterial growth within a wetland. More surface area allows for a larger bacterial population and therefore greater nutrient uptake [4]. Wetlands occur as stationary ecosystems as well as floating wetland islands or mats. Floating wetland although not a very common type of wetland ecosystem, can occur naturally in many parts of the world and offer some useful insights into the long-term function and operation of artificially created floating wetlands or Constructed floating wetlands (CFWs).

Constructed floating wetlands have been recognized as effective mechanisms for water treatment. They are engineered system designed to enhance the interaction that occurs in natural wetlands between water, plants, microbes, soil and atmosphere in order to remove pollutants from water in a more natural and passive manner.

These wetlands have a wide range of applications such as water quality improvement of stormwater, acid mine drainage, sewage treatment plants besides their use in habitat enhancement and aesthetic use [5]. Plant roots are believed to play a major role in treatment process by virtue of water passing through its long extended and hanging roots. The other process are release of extracellular enzyme, development of microbial biofilm and flocculation of suspended matter all of which participate in contaminant removal mechanism.

Several studies have investigated the effectiveness of constructed floating wetlands however, the variability between the studies makes it difficult for direct comparison. Thus, the aim of this study is to investigate the feasibility of using constructed floating wetlands to treat eutrophic water with very high nutrient load.

The process of eutrophication was first observed by a German scientist Weber [6]. He invented terms like eutrophe, oligotrophe and mesotrophe. These terms described the state of flora in peat bogs which changed with time. A similar phenomenon was described by Nuamann [7] but in context of water. He categorized freshwater and marine water based on their appearance as they looked in summer and also the dominant phytoplankton algae. Algal biomass can be estimated using three independent variables such as chlorophyll content, total phosphorus and secchi depth. According to Carlson [8], the following classification can be used to determine the trophic state of a freshwater or a marine water:

Table 1 Classification of water

Trophic State Index	Trophic Class	Water Quality
<30	Oligotrophic	Clear water, oxygen through the year in the Hypolimnion.
30-40	Oligotrophic	Deeper lakes still exhibit, oligotrophic but some shallowerlakes will become anoxic in the hypolimnion during the summer.
40-50	Mesotrophic	Water moderately clear, but increasing probability of anoxia in hypolimnion during summer.
50-60	Lower boundary of classical eutrophy	Decreased transparency, anoxic hypolimnion during the summer, macrophyte problems evident.
60-70	Eutrophic	Dominance of blue-green algae, algal scums probable, extensive macrophyte problems.
70-80	Eutrophic	Heavy algal blooms possible throughout the summer, dense macrophyte beds, but extent limited by light penetration.
>80	Hypereutrophic	Algal scums, summer fish kills, few macrophytes.

Eutrophication is a universal phenomenon and no inland water body is spared from this serious ecological stress. Water conservation projects in the vicinity of the lake are a cause of concern, since seepage of water from reservoirs is changing the water quality of the lake and, in turn, affecting its unique limnology [9].

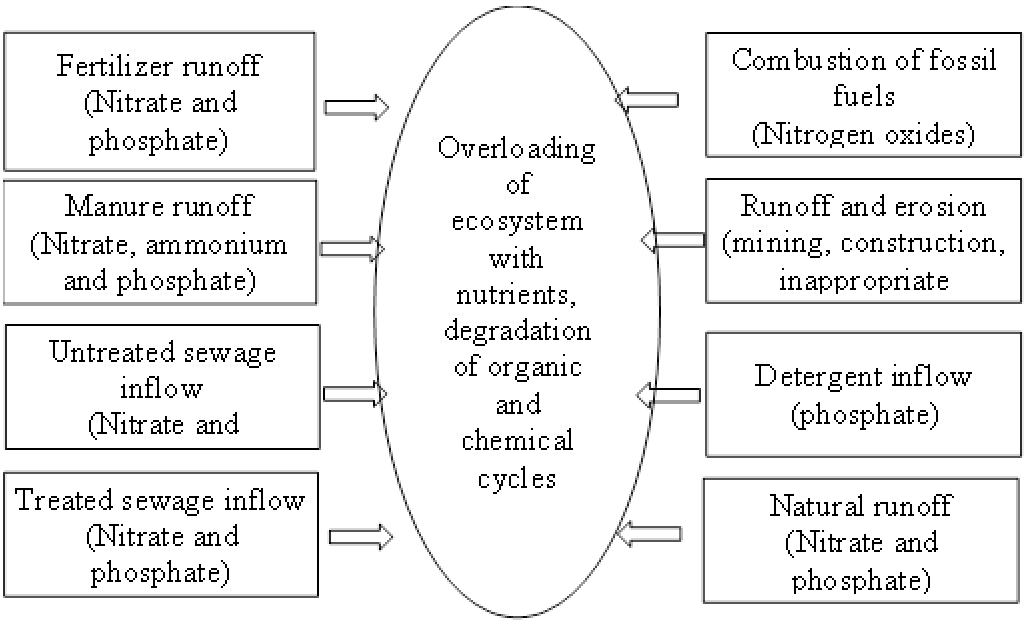

Figure 1 External causes of Eutrophication

Above are the suspected drivers of eutrophication which are expected to increase in the future [10].

2. Internal causes of eutrophication

2.1. Role of different nutrients like phosphorus and nitrogen

According to Notestein *et al.*, [11], phosphorus only occurs in the pentavalent form in aquatic systems. Examples are orthophosphate, pyrophosphate, longer-chain polyphosphates, organic phosphate esters and phosphodiesters, and organic phosphonates. Phosphorus is delivered to aquatic systems as a mixture of dissolved and particulate inputs. This efficient trapping of phosphorus inputs makes these systems sensitive to pollution with excessive amount.

Besides Phosphorus, Dissolved Inorganic Nitrogen (DIN) occurs in different forms and oxidation states. DIN is assimilated and converted to organic nitrogen by phytoplankton, other plants, or bacteria. Organic nitrogen can be regenerated as ammonium (NH_4^+) or dissolved organic nitrogen (DON) compounds, reassimilated by plants or heterotrophs, or oxidized by bacteria. The function of nitrogen as a limiting factor needs more research as its role in controlling eutrophication is not very clear [12].

2.2. Role of macrophytes

Macrophytes play a major role in maintaining the nutrient levels in urban aquatic systems. However, their prolific growth result in spread of invasive species such as water hyacinth (*Eichhornia crassipes*) due to the availability of higher nutrient concentrations. This hinders aerobic functioning of the lake by restricting sunlight penetration and also affecting algal photosynthesis. This also results in anoxic environment due to blockage of air-water interface, influencing oxygen diffusivity. Reduction in Dissolved Oxygen (0 mg/l) impacts the viability of aquatic biota and result in the disappearance of biodiversity [13].

2.3. Role of algae (Cyanobacteria)

While there is universal agreement that cyanobacterial blooms are most likely to occur in systems with high-nutrient inputs, a complex array of additional factors are known to affect their predominance including the relative availability of nitrogen to phosphorus, ferrous iron, dissolved inorganic carbon , turbulence, high temperature, zooplankton grazing, and light [14].

3. Effects of eutrophication

3.1. Impact on aquatic biogeochemistry

Nutrient enrichment of aquatic ecosystems typically results in significant alterations in biogeochemical cycling over both space and time [15].

3.2. Impact on ecological integrity and aesthetic values

Of critical concern is the biodiversity of lakes. Macrophyte invasions prevent the growth of other aquatic plants. Similarly, algal and cyanobacterial blooms consist of species that out-compete other species for the available nutrients and light. Particularly surface scums that might form, are unsightly and can have unpleasant odours. If the water is being used for water treatment purposes, various taste and odour problems can occur.

Cyanobacteria are particularly problematic because they release toxic substances (cyanotoxins) into the water. Cyanotoxins are recognised to have caused the deaths of wild animals, farm livestock, pets, fish and birds in many countries. It is also possible that people exposed to odours from waterways contaminated with decaying algae of cyanobacteria may suffer chronic ill-health effects. The primary target organ of most cyanotoxins in mammals is the liver (i.e. they are hepatotoxic). Some cyanotoxins are neurotoxic and others dermatotoxic.

3.3. Impact on the economy

Nearly all of the above-mentioned impacts have direct or indirect economic impacts. Algal or cyanobacterial scums increase the costs of water treatment in order to avoid taste, odour and cyanotoxin problems in the treated water. Excessive blooms can clog filters and increase maintenance costs.

4. Lake management

Early attempts to manage eutrophication largely involved treating symptoms, using copper sulfate or herbicides, rather than the source of the problem. Until the linkage of algal blooms with increasing nutrient supply due to human activities in the catchment of lakes was made, remediation technologies remained limited. Despite advances in the understanding of eutrophication, it still remains one of the foremost issues in protecting freshwater ecosystems.

Success or failure of restoration technologies involves many factors; and it is accepted that permanent effects of restoration can only be achieved if external nutrient loading is reduced to sufficiently low levels [16]. Past water-quality treatment and restoration has relied heavily on chemical, physical or mechanical treatment. An alternative to these treatments is the implementation of Constructed floating wetlands (CFWs).

5. Constructed floating wetlands (CFWs)

Constructed Floating Wetlands (CWs) are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and the associated microbial assemblages to assist in treating wastewaters. They are designed to take advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment [17].

6. Design considerations

To date a wide range of materials have been used in the construction of floating wetland. Kerr-Upal *et al* [18] suggested following factors to be considered when determining the material and construction method used in creating floating wetland.

- Durability
- Functionality
- Environmental sensitivity
- Buoyancy
- Anchoring
- Flexibility and
- Cost

Most significant design parameters include the vegetation, percentage of vegetation cover, growth substratum and methods for achieving buoyancy. In India a low-cost method of floating wetland construction has been developed using lengths of large diameter bamboo interwoven with mats of natural fibre. The articulated nature of the bamboo means that it contains sealed chambers of air throughout the stem which are naturally buoyant [19].

7. Selection of plant species

The plant species and design of a wetland can greatly affect the ability of the wetland to act as a sink for specific contaminants. The nature of the plants, wetland conditions, and biota can greatly affect the residence times of elements in a wetland. For these reasons, specific considerations as to plant selection, location, climate, hydrology, and contaminant tolerance should be assigned high level of importance.

8. Growth media and plant establishment

Selection of an appropriate growth medium will be particularly important in terms of the physical properties of the growth medium. Those materials are used that provide adequate small pore spaces to hold water for plant uptake, whilst allowing enough large pores to allow exchange of air in the medium to maintain aerobic conditions [20].

9. Water quality improvement

9.1. Mechanism of removal

There are three basic categories of removal processes: physical, chemical and biological. These removal processes are all reliant on three main wetland constituents: the aquatic vegetation, the substrate and soil and the movement and distribution of water within the water body [21].

Physical removal is through addition of a root system, the roots help to slow down the flow velocity which also helps increase surface attachment of particles to the roots. The available surface area on the root system helps trap sediment and particles thus reducing the amount remaining in the water column.

Chemical removal occurs as pollutants are volatilized (breakdown into gaseous states and released to air). Another chemical process involves photodegradation. Unfortunately, as CFWs prevent sunlight penetration directly below the mats, this chemical process is unlikely to occur directly below the floating wetland [22].

Aquatic vegetation plays an important role in biological removal through plant uptake to shoots and transpiration through the leaves. Microorganisms also play a significant biological role in the removal of contaminants through oxidation and reduction processes. The root mass of CFWs provide an attachment substrate for micro-organisms to break down and mineralize organic material, solubilize inorganics and increase microbial activity within the water column [4].

9.1.1. Role of vegetation in removal

The phyto-uptake capacity depends on the anatomical and physiological properties of plant species, such as uptake efficiencies for nutrients, growth rate, translocation factor from below water to above water tissues, photosynthetic rates and root types. The establishment of an extensive root matrix is crucial for the performance of the system. Weragoda *et al*. [23] highlighted that the root system formation affects nutrient removal rates. They concluded that *Typha angustifolia* showed better nitrogen and phosphorus removals due to its high and steady root growth that enhances water-plant interactions compared to *Canna iridiflora* whose root mat is thick and compact. The accumulation of the nutrients by plants can be analysed by various ways. Eaton *et al* [24] analyzed ammonia (NH_4–N) using the dichloroisocyanurate method Nitrate (NO^{3-}–N) and orthophosphate (PO_4^{3-}–P) were determined by ion chromatography using a Dionex ICS-1000 with DV sampler ion chromatography Total nitrogen (TN) was analysed using TOC-VCPN or TOC-LVCPN total organic analyser.

9.1.2. Role of microbial diversity in removal

Microbial diversity in freshwaters belongs mainly to the culturable bacterial group viz., actinobacteria, alpha-proteobacteria, beta-proteobacteria, gamma-proteobacteria, firmicutes, and bacteriodetes [25]. Microbial assemblages are found as biofilm on solid substrata and on plant surfaces. In most of the aquatic regimes including the engineered wetlands, aquatic plants interact with microbes from symbiotic to parasitic, irrespective of the species of plant and microbe. Oxygen is utilized mostly as a primary electron acceptor for energy generation and to carry out number of beneficial oxidation processes. Further the diagenesis of organic matter in sediments takes place via oxic and anoxic microbial activities with the consumption of electron acceptors such as oxygen causing an oxygen deficient zone. Under such anoxic conditions, bacterial cells (facultative anaerobes) capable of using NO_3^{1-}, SO_4^{2-} and CO_2 as terminal electron acceptor decompose the organic matter [26].

9.1.3. Microbiological Analysis

Microorganism identification can be done from the collected biofilm sample. The community composition can be further analysed by growing the bacteria on different media and employing various biochemical test for their identification. Microbial activity for the root zone, water column, and gravel and sludge was assessed using the fluorescein diacetate assay (FDA) method by Adam and Duncan, [27]. Different Nitrification and Denitrification tests were conducted to identify denitrifying Microbial communities by [28, 29].

9.1.4. Removal of Nitrogen

Nutrient assimilation refers to the biological processes in plants which convert the inorganic form of nutrients into their organic forms. The amount of nutrients a plant is able to assimilate is limited by the concentration of available nutrients and the rate of productivity. The amounts of nitrogen present in emergent species range between 0.6-88 g Nm^{-2} [7].

9.1.5. Removal of phosphorus

In addition to nitrogen, orthophosphate is directly absorbed by algae and macrophytes and converted into tissue phosphorous. The uptake of phosphorous by microbes is rapid, but the amount of phosphorous stored is low. Absorption also depends on the water's trophic status, as microbial uptake is lower in eutrophic sites [7]. Phosphorous is taken up into the plant roots, and uptake is at its highest during the growth season. As biomass decays, phosphorous is again released into the water [30]. Therefore, harvesting such plants at right time is very important to maintain the right nutrient level in the water.

9.1.6. Removal of organic pollutants

Massive field application of organic compounds such as poly-aromatic hydrocarbons (PAHs), chlorinated organic compounds, poly-brominated biphenyls ethers (PBEs) and poly-chlorinated biphenyls (PCBs) have been a major cause of contaminated environmental media [31] and the aquatic systems are the most vulnerable of all. Because of the catabolic activity, microbes are well-known bioremediators able to degrade virtually all classes of organic chemicals [32] In addition, the organic carbon, provided by the plants to the rhizospheric microbes helps degrading the complex recalcitrant organic compounds such as PAHs and pyrenes [33]. Additionally, rhizoplane of aquatic plants are also rich in ubiquitous methanotrophs a group of a and c proteobacteria, utilizing methane for energy and as carbon source degrade a wide variety of toxic organic compounds [34].

9.1.7. Removal of inorganic pollutants

Excessive metal ions in waters are mainly of industrial, agricultural and municipal waste origin in many parts of the world. Most of the aquatic macrophytes possess iron plaque around the roots and submerged parts and sequester metal ions from water [35]. Sulfate reducing bacteria associated with aquatic macrophytes as biofilm reduce sulfate into sulfides thereby lowering the pH which is required by the microbial cell to biosorb the metal ions from the water column.

9.2. Factors affecting removal efficiency

9.2.1. Dissolved oxygen

Sasser et al. [36] reported consistently low dissolved oxygen concentrations (0.2-1.0 ppm) in the floating wetland mat and underlying free-water zone of a natural floating marsh in Louisiana. This would suggest that a dense cover of floating wetland over a pond will be more conducive to the generation of anaerobic conditions in the water column than an uncovered pond would be. The cover of floating vegetation provides a barrier against aeration due to wind, air diffusion across the air-water interface and excludes photosynthetic algae. The decomposition of organic matter sourced from the floating vegetation mat also acts to deoxygenate the water column.

A more passive approach for introducing oxygen into the water column may be to include open water sections throughout or following a floating treatment wetland system, thereby facilitating the processes of algal photosynthesis and diffusion.

9.2.2. Plant species

The speed and effectiveness of water quality improvement by CFWs is highly dependent on plant species; how they are used, grown and maintained [37]. There is a wide range of aquatic plants that can be used for CFWs, however, the performance of different species has not been thoroughly investigated. Studies indicate the importance of accounting for both surface area coverage density and biomass of plant species when considering or comparing plant selection and performance for a treatment system.

Success and challenges

- Artificial floating wetlands and constructed wetlands have yielded striking results with removal of up to 90% nitrogen, 73% phosphorus, and more than 92% organic carbon [38]. Their popularity is due to their low cost, use of natural mechanisms, and achievements in sustainable water reuse.
- They do not need costly additives since they rely solely on biological reactions, while many conventional processes require chlorine, ozone, or other chemicals [39].
- Another advantage is that they have the potential to be aesthetically pleasing or to provide an area for animal habitat.
- Nonetheless, there are still uncertainties about their design, cost, and reliability. Until now, many case studies and implementations have been done on a small test scale.
- Another problem that has been observed in nearly all studies of constructed floating wetland is that removal rates of nutrients, metals, and pesticides are highly variable due to changes in temperature.
- Floating wetlands have also been implemented with the purpose to increase animal populations in an area and to improve breeding rates. One such project was implemented in Sheepy Lake in California as part of the Caspian Tern Management Project.

10. Significance of the work

Rapid eutrophication in past 25 years has drastically changed the physical, chemical, biological and ecological states of lakes. This has not only made the lake water difficult for drinking but has also deteriorated the ecosystem of lakes, causing the habitat to become unsustainable for the local flora and fauna. Bioremediation for revival of such lakes is one of the best management practices being followed these days. One of the bioremediation techniques that holds a promising solution to this problem is the application of Constructed Floating Wetlands. Hence, this research would help in developing better remediation measures for lake conservation by implementation of Constructed Floating Wetlands.

11. Conclusion

If Constructed Floating wetlands are able to reduce nutrient load of eutrophic water then they can be implemented to restore the conditions of various lakes, which are suffering with contamination by point and non- point sources of pollution. Predominantly, these floating wetlands themselves being eco-friendly can be extremely successful in reinvigorating animal populations and providing natural beauty in areas that are otherwise lacking.

Compliance with ethical standards

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Disclosure of conflict of interest

The author declares no conflict of interest.

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