Chapter 4

Phosphorus Eutrophication and Mitigation Strategies

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Additional information is available at the end of the chapter

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Abstract

Phosphorus (P) eutrophication in the aquatic system is a global problem. With a negative impact on health industry, food security, tourism industry, ecosystem health and economy. The sources of P include both point and nonpoint sources. Controlling P inflow from point sources to aquatic systems have been more manageable, however controlling nonpoint P sources especially agricultural sources remains a challenge. The forms of P include both organic and inorganic. Runoff and soil erosion are the major agents of translocating P to the aquatic system in form of particulate and dissolved P. Excessive P cause growth of algae bloom, anoxic conditions, altering plant species composition and biomass, leading to fish kill, food webs disruption, toxins production and recreational areas degradation. Phosphorus eutrophication mitigation strategies include controlling nutrient loads and ecosystem restoration. Point P sources could be controlled through restructuring industrial layout. Controlling nonpoint nutrient loads need catchment management to focus on farm scale, field scale and catchment scale management as well as employ human intervention which includes ferric dosing, on farm biochar application and flushing and dredging of floor deposits. Ecosystem restoration for eutrophication mitigation involves phytoremediation, wetland restoration, riparian area restoration and river/lake maintenance/restoration. Combination of interventions could be required for successful eutrophication mitigation.

Keywords: agriculture, aquatic, eutrophication, mitigation, phosphorus

1. Introduction

Globally many aquatic ecosystems have been negatively affected by phosphorus (P) eutrophication [1]. Phosphorus is a primary limiting nutrient in both freshwater and marine systems [2, 3]. Phosphorus eutrophication is defined as the over enrichment of aquatic ecosystems with P leading to accelerated growth of algae blooms or water plants, anoxic events, altering biomass and species composition [4–8], eutrophication is a persistent condition of surface waters and a widespread environmental problem. Aquatic systems affected by eutrophication often exhibit harmful algal blooms, which foul water intakes and waterways, fuel hypoxia, disrupt food webs and produce secondary metabolites that are toxic to water consumers and users including zooplantkton, shellfish, fish, domestic pets, cattle and humans [9]. Excess phosphorus inputs to lakes usually come from industrial discharges, sewage and runoff from agriculture, construction sites, and urban areas [1, 6]. Many countries have regulated point sources of nutrients for example industrial and municipal discharges, however, nonpoint sources of nutrients such as runoff from urban and agricultural lands have replaced point sources as the driver of eutrophication in many countries [10].

The plant availability of phosphate fertilizer is reduced by sorption and organic complexation in the soil, therefore fertilizer applications greater than the amount required by the crop are used to counteract the strong binding of the phosphate to the soil matrix leading to increased P content of managed soils [11]. Mining phosphorus (P) and applying it on farm for animal feed and crop production is altering the global P cycle, leading to P accumulation in some of the world's soils [4]. Over application of P fertilizer to soil is in itself wasteful, but the transport of P to aquatic ecosystems by erosion is also causing widespread problems of eutrophication [12, 13]. Using global budget [4] estimated the increase in net P storage in terrestrial and freshwater ecosystems to be at least 75% greater than preindustrial levels of storage. Large portion of P accumulation occurs as a result of increased agriculture intensification, land use change and increased runoff [14–16].

2. Sources of phosphorus

Excess phosphorus inputs to lakes usually come from industrial discharges, sewage and runoff from agriculture, construction sites, and urban areas [6]. The input of P to soil creates the potential for an increase in transfer to the wider environment. Phosphorus sources can be natural which includes indigenous soil P and atmospheric deposition and/or anthropogenic which includes fertilizers, animal feed input to the farm and manure applied to the soil [17]. In addition ground water can potentially contribute significant amount of P in water bodies driving eutrophication process [18].

As a result of P point source control in many countries the nonpoint P source especially agriculture is the main pollutant of aquatic systems [10]. The major source of nonpoint nutrient input to water bodies is the excessive application of fertilizer or manure on farm which cause P accumulation in soils [4]. Phosphorus retention has been caused by an excess of fertilizer and animal feed inputs over outputs of agricultural products [19]. For example [12] indicated that less than 20% of P input to the Lake Okeechobee watershed in fertilizers was output in agricultural as well as other products.

3. Forms of phosphorus

Most studies on plant nutrition often consider only inorganic P to be biologically available, however organic phosphorus is abundant in soils and its turnover can account for the majority of P taken up by vegetation [20, 21]. Soil phosphorus exists in a range of organic and inorganic compounds that differ significantly in their biological availability in the soil environment [22]. The inorganic P compounds mainly couple with amorphous and crystalline forms of Al, Fe, and Ca [23] which is highly influenced by soil pH [24]. The organic phosphorus in most soils is dominated by a mixture of phosphate monoesters (e.g., mononucleotides, inositol phosphates) and phosphate diesters (mainly nucleic acids and phospholipids), with smaller amounts of phosphonates (compounds with a direct carbon-phosphorus bond) and organic polyphosphates (e.g., adenosine triphosphate) [25]. Plants can manipulate their acquisition of P from organic compounds through various mechanisms, some of the mechanisms allow plants to utilize organic P as efficiently as inorganic phosphate [26, 27]. In lake sediment in China, the heavily polluted sediments contained higher organic P fractions compared to moderately and no polluted sediments [28]. Increased pH can alter the availability of P binding sites on ferric complexes as a result of competition between hydroxyl ions and bound phosphate ions [29]. Anoxic condition leads to release of P as a result of reduction of ferric to ferrous iron [30]. In addition presence of sulfate could lead to reaction of ferric iron with sulfate and sulfide to form ferrous iron and iron sulfide leading to release of P [31]. Increased temperature can reduce adsorption of P by mineral complexes in the sediment [32]. Other physicochemical processes affecting release of P from the sediment include temperature, pH potential, redox, reservoir hydrology and environmental conditions [33]. These physical chemical processes are further complicated by the influence of biological processes for example mineralization, leading to a complex system governing the release of P across sediment water interface [33].

4. Translocation/mobilization of phosphorus

Phosphorus in most cases enters aquatic ecosystems sorbed to soil particles that are eroded into rivers, lakes and streams [34, 35]. Watershed land use and P concentration in watershed soils strongly influence potential P pollution of aquatic ecosystems [4]. In addition any factor accelerating erosion or elevating P concentration in the soil increases the potential P runoff to aquatic systems [34, 35]. Mobilization of P involves biological, chemical and biochemical processes. The processes are grouped into solubilization or detachment mechanisms and are defined by the physical size of the P compounds that are mobilized [17] and it has been indicated that the potential for solubilization increases with increasing concentrations for extractable P. However, organic P has an important but little understood role in determining P solubilization [25]. Detachment of soil particles and associated P is mainly linked to soil erosion, which provides a physical mechanism for mobilizing P from soil into waters bodies [36].

Depending on site conditions diffuse P transport occurs as particulate or dissolved P in overland flow, channelized surface runoff, drainage, or groundwater [18]. In ground water

P concentration is considered to be low [37]. This is as a result of orthophosphate P being adsorbed in the soil and sediment in the vadose or the saturated zone [18]. However, wastewater has been reported to cause heavy groundwater contamination leading to P elevation [38, 39].

5. Consequences of eutrophication

Consequences of eutrophication include excessive plant production, blooms of harmful algae, increased frequency of anoxic events, and death of fish, leading to economic losses and health implications which include costs of water purification for human and industry use, losses of fish and wildlife production and losses of recreational amenities [10, 40]. Some of the consequences of eutrophication includes:

5.1. Food/fishing industry

High level of Lake Eutrophication has led to suffocating of fish population on a massive scale with a very negative repercussions on the economy [41]. The total economic loss incurred from 1998 algal bloom in the Lake Tai China catchment area was estimated at U.S.$6.5 billion. During winter of 2002–2003, a severe oxygen deficit induced a fish kill in the eutrophicated two-basin Lake Aimajarvi in southern Finland, which resulted in cascading effects on the lower trophic levels of the lake [42].

5.2. Tourism

Coastal areas are an important economic source for tourism [43]. The algal bloom have degraded the investment environment and damaged the hospitality and tourism industry [41].

5.3. Human/animal healthy

Toxin producing algae can cause mass mortalities of fish marine mammals, birds and human illness through consumption of sea food [44]. It is estimated that 60–80 species of about 400 known phytoplankton are toxin producing and capable of producing harmful algal blooms [8]. In humans, toxins arising from harmful algal blooms have mainly been from shellfish consumption [44], bivalve shellfish have been reported to graze on algae and concentrate toxins effectively. As a result the poisoning can lead to paralytic shellfish poisoning, diarrhetic shellfish poisoning, neurotoxic shellfish poisoning, amnesic shellfish poisoning and azaspiracid shellfish poisoning. In addition there are many respiratory complaints from inhaling contaminated aerosols [45]. A case reported that in July 2002 teenage boys swam in a blue-green algae covered golf course in Dane County, Wisconsin. They all became ill, the most severe symptoms occurred in the boys who swallowed water. Approximately after 48 h one of the boys suffered a seizure and died of heart failure, the coroner identified anatoxin-a as the most likely underlying cause of death [46, 47].

In May and June 1998, over 200 California sea lions died and others displayed signs of neurological dysfunction along the central California coast, this was linked to a harmful algal blooms [48].

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5.4. Water quality

Harmful algal blooms is a cause of restriction on drinking water, fisheries and recreation water uses leading to significant economic consequences [49]. The presence of algal bloom and other species have disrupted the normal supply of drinking water in many parts of the world for example China [41]. The presence of algal blooms in Lake Tai severely affected industrial and agricultural production as well as lives of the urban dwellers. Whereby in 1990 algal bloom forced the shutdown of the entire water supply system and triggered a crisis in water security for the urban population. The direct economic loss was estimated at about U.S.$30 million. Harmful algal blooms present significant challenges for achieving water quality protection and restoration goals especially when these toxins confound interpretation of monitoring results and environmental quality standards implementation efforts for other chemicals and stressors [49].

6. Phosphorus eutrophication mitigation strategies

There is need to reduce anthropogenic nutrient inputs to aquatic ecosystems in order to reduce the negative effects of eutrophication [50]. It has been indicated that reducing P input in the water bodies leads to eutrophication mitigation [16, 51] (**Table 1**) [16]. Derived this conclusion from four methods, all long-term studies at ecosystem scales:

- **i.** long-term case histories,
- **ii.** multiyear whole lake experiments,
- **iii.** experiments where chemical treatments are used to remove phosphorus from the water column, and
- **iv.** chemical additions to inhibit return of phosphorus from the sediments to the water column.

However, [6, 52] argued that P based nutrient mitigation commonly regarded as the key tool in eutrophication, in many cases has not yet yielded the desired reductions in water quality and nuisance algal growth in water bodies has not reduced in decades of reducing P input. [52, 53] argued that these observations could be as a result of:

- **i.** legacies of past land-use management;
- **ii.** decoupling of algal growth responses to river P loading in eutrophically impaired aquatic system; and
- **iii.** recovery trajectories, which may be nonlinear and characterized by thresholds and alternative stable states.

Therefore, as a result of these contrasting findings there is need in some cases to consider a combination of different P mitigation strategies for example employing control of nutrient loading, physicochemical and physicomechanical method simultaneously. Control or mitigation of P eutrophication should encompass multiple components which could include; control of pollutant sources, restoration of the damaged ecosystem, and catchment management [41]. The mitigation strategies includes:

Name of water body	Country	Location
Little Otter Lake	Canada	45°N, 80°W
Gravenburst Bay	Canada	45°N, 80°W
Kootenay Lake	Canada	50°N, 117°W
ELA Lakes 226 NE, 303, 304, 261	Canada	50°N, 94°W
Lake Eric	Canada, USA	42°N, 81°W
Lake Ontario	Canada, USA	44°N, 78°W
Lake Huron	Canada, USA	44°N, 82°W
Lake Fure	Denmark	56°N, 12°E
Rhine River	Europe	49°N, 7°E
Schlachtensee	Germany	52°N, 13°E
Lake Tegel	Germany	53°N, 13°E
Lake Balaton	Hungary	47°N, 18°E
Lago Maggiore	Italy	46°N, 9°E
Lake Mjosa	Norway	61°N, 11°E
Lake Vattern	Sweden	48°N, 15°E
Lake Vanern	Sweden	59°N, 13°E
Lake Hjalmaren	Sweden	59°N, 16°E
Lake Malaren	Sweden	59°N, 17°E
Lake Norrviken	Sweden	59°N, 18°E
Murtensee	Switzerland	47°N, 7°E
Lake Lucerne	Switzerland	47°N, 8°E
Turlersee	Switzerland	47°N, 8°E
Hallwilersee	Switzerland	47°N, 8°E
Sempachersee	Switzerland	47°N, 8°E
Lake Zurich	Switzerland	47°N, 9°E
Pfaffikersee	Switzerland	47°N, 9°E
Lake Constance	Switzerland, Austria, Germany	48°N, 9°E
Lake Geneva	Switzerland, France	46°N, 6°E
Sacramento River	USA	40°N, 121°W
Lake onondaga	USA	43°N, 76°W
Lake Michigan	USA	44°N, 87°W
Moses Lake	USA	47°N, 119°W
Lake Washington	USA	48°N, 112°W

Table 1. Examples of fresh waters in some countries where eutrophication decreased following the control of phosphorus inputs. Latitudes and longitudes are given. Lakes recovered by using chemicals to precipitate phosphorus are not included, modified from [16].

6.1. Control of nutrient loads

6.1.1. Restructuring of industrial layout

Point source P originating from mines, factories and residence form one of the most important sources of P to water bodies [41]. For example Lake Tai in China, its catchment area used to be full of heavy industrial polluters, for example, chemical and dye factories. The township lacked adequate facilities for treating waste water before disposal. Therefore, to mitigate pollution coming from the industry it is important to shut down heavily polluting industries. While as the less polluting plants could be relocated to a designated industrial part to ensure centralization and effectiveness in handling pollution control.

6.1.2. Farm/field/catchment management

It has been much easier to control point source P, therefore making nutrient discharge from agricultural fields the chief source of pollution [41]. As a result nutrient discharge from agricultural fields could be addressed through farm, field and catchment management or rationalization of land use [41].

6.1.2.1. Farm scale management

In the farm scale environmentally sound fertilizer application and nutrient handing is important this would be achieved through appropriate placement and proper timing of application. This would result in moderate P levels in the soils. In Addition P input could be reduced through increasing digestible P in fodder and reducing total P [51] (**Table 2**).

6.1.2.2. Field scale management

To avoid transport of particulate P and leaching of P, increase soil storage there is need to change soil management. In addition there is need to change crop management in order to reduce run off and reduce leaching [51] (**Table 3**).

Strategy	Aim	Measure
Change P input	Avoid high P content in fodder by increasing digestible P and lowering total P content in feed	Use feed with a lower content of phytate-P or add phytase to feed to increase digestibility of phytate-P
Change P output	Exploit the commercial value of the manure surplus	Make products for export or for arable farms. Produce secondary P resources for industries by incineration to P-ash
Environmentally sound fertilizer application & nutrient handling	Reduce P content of the soil at high risk hot spots	Don't apply manure and P fertilizer at high risk hot spots
	Increase P efficiency of crop uptake via appropriate placement and time of application	Apply P near the roots instead of broadcast Avoid applying manure and P fertilizers before heavy rainfall or prolonged rainfall Phase nutrient fertilization application over the year
	Incorporate soil P into management strategy to achieve moderate soil P levels	Make use of available P in soils to avoid high risk hot-spots

Table 2. Mitigation strategies for nutrient management at farm scale. Modified from [51].

Strategy	Aim	Measure
Change crop management	Change cropping system	Introduce crop rotation and include more years of grass or develop mixed (perennial and annual) cropping systems
	Avoid erosion and reduce surface runoff	Grassland instead of arable crops or grow deep-rooting crops
	Avoid leaching	Apply catch crops (and harvest the products) Crop production without fertilization (P mining)
Change soil management	Avoid transport of particles or particulate P	No tillage/direct drilling: leaving more than 30% of the soil covered with plant residues or undisturbed stubble Shallow cultivation: Soil tillage to <10 cm depth. No inversion Contour ploughing Switch from autumn tillage to spring tillage Reduce soil compaction and improve soil structure
	Avoid leaching of dissolved P concentrations in soils	Conventional ploughing or interspersing periods of ploughless tillage with conventional ploughing
	Reduce nutrient budgets and increase soil storage capacity by extensification and agro-forestry	Introduce crop rotation and include more years of grass or develop mixed cropping systems with perennial and annual crops

Table 3. Mitigation strategies at field scale modified from [51].

6.1.2.3. Catchment scale management

In the catchment scale eutrophication mitigation strategy would involve water management, land use management and landscape management [51]. Water management could be achieved through reducing runoff flow and avoiding subsurface leaching. Land use management would involve protecting vulnerable areas and improving sink and sources of P by changing agricultural use patterns. Land scape management would include reducing direct sources of P from farmyard, livestock and reducing surface runoff and erosion from field to field within the catchment [51] (**Table 4**).

6.1.3. Human intervention

It has been demonstrated that often the nutrient load and algal blooms in water bodies respond slowly to interventions aimed at controlling external nutrient sources because of the nutrients replenished from waterbodies deposits [54]. As a result P could be reduced through physiochemical and physicomechanical methods. Whereby the P is trapped and removed from the system or trapped on farm and its mobility to aquatic system reduced.

6.1.3.1. Ferric dosing

Reduction in the external P loading for control of algal biomass in the water reservoirs can be achieved by the use of ferric dosing. Ferric dosing technique is a physiochemical method

Strategy	Aim	Measure
Land use management	Changing agricultural use patterns to improve location of sinks and sources of P	Alternate arable land and grassland Avoid certain crops in hilly areas Locate crops with high nutrient uptake on bottom lands
Landscape management	Reduce surface runoff and erosion from field to field within the catchment	Re-site gateways and paths: trails, roads, controlled access for livestock and machinery
	Reduce direct losses from livestock	Prevent contact with surface water: fences, bridges
	Reduce direct losses from farm yards	Minimize volume of dirty water produced and collect farm yard runoff
Water management	Change runoff flow by blocking or reducing overland flow	Create ponding systems Construct grassed waterways Improve surface irrigation
	Avoid subsurface losses through leaching	Remove trenches and ditches or allow to deteriorate Install drains Let drainage water irrigate meadows

Table 4. Mitigation strategies at catchment scale modified from [51].

and involves the addition of ferric sulfate or alternatives to the pumped input, to precipitate dissolved particulate and orthophosphate in the coming water. The system is coupled with filtration to remove the ferric/phosphorus floc [33]. Resulting in a significant reduction of P in the pumped inputs to the aquatic system.

6.1.3.2. Flushing and dredging of floor deposits

Flushing and dredging of floor deposits is a physicomechanical methods meant to remove the already accumulated P from the aquatic system floor [55]. The limitation with both ferric dosing and flushing and dredging of floor deposits is that they provide temporal solutions and do not address the root cause of the problem. Once the intervention is stopped nutrients levels goes back to the former status. However, the success of these methods are dependent on their being implemented together with control of nutrient load intervention.

6.1.3.3. Biochar potential in phosphorus adsorption on farm

Application of P on farm has potential to mitigate P eutrophication though P adsorption leading to reduction in P translocation (**Figure 1**). The P adsorption to biochar is favored by increased biochar pyrolysis temperature and is biochar biomass species specific [24]. The increase of biochar aromatic C (**Figure 2**) and pH adjustment with high biochar pyrolysis temperature is important for P retention [24]. Biochar is a byproduct of biofuel production, therefore increased production of biofuel will be consistent with biochar availability in future.

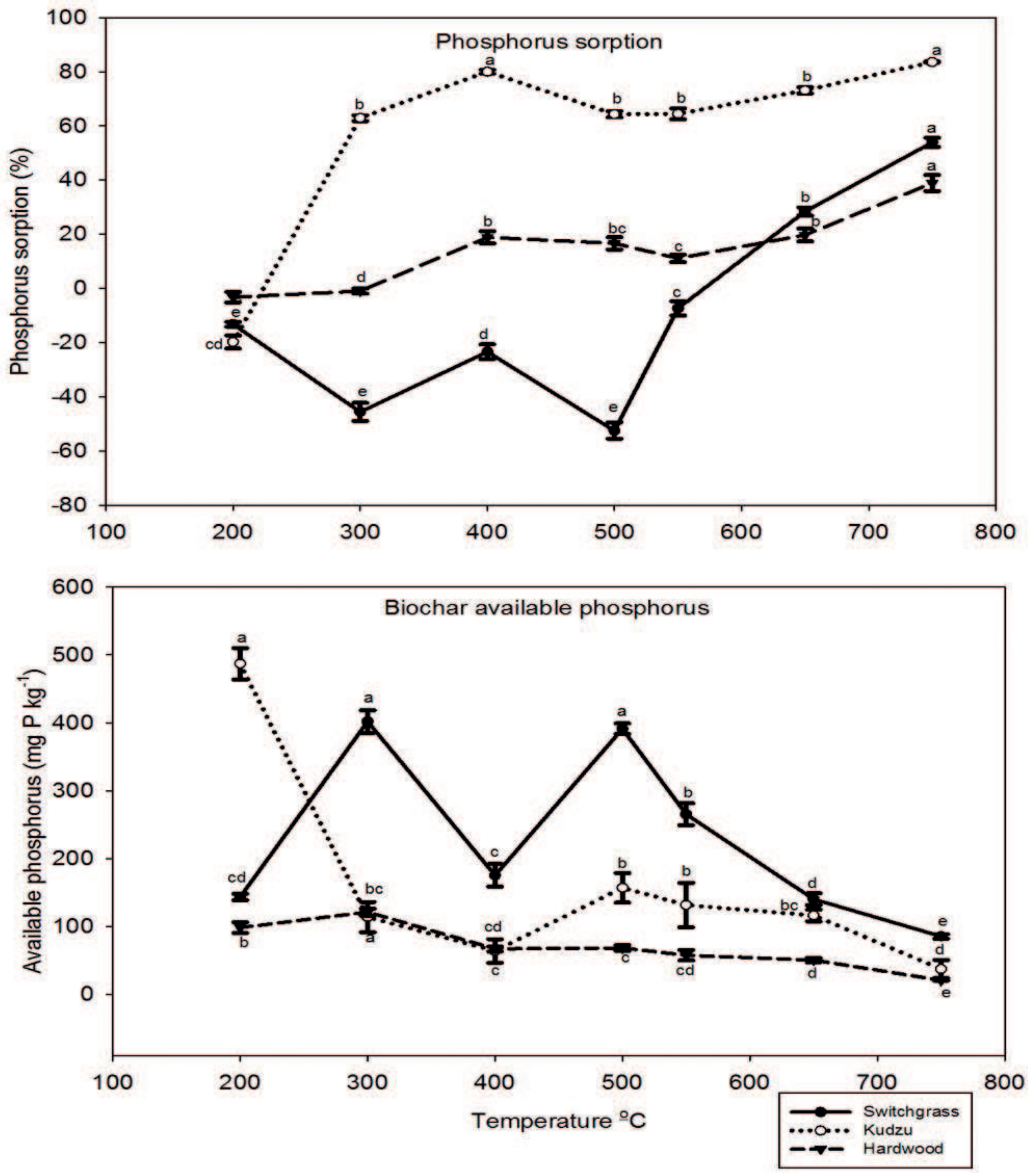

Figure 1. Biochar phosphorus adsorption; from [24].

6.2. Aquatic ecosystem restoration

Ecosystem restoration focus on rehabilitating the functionality of the damaged ecosystem and it relevant physical, chemical and biological properties [41].

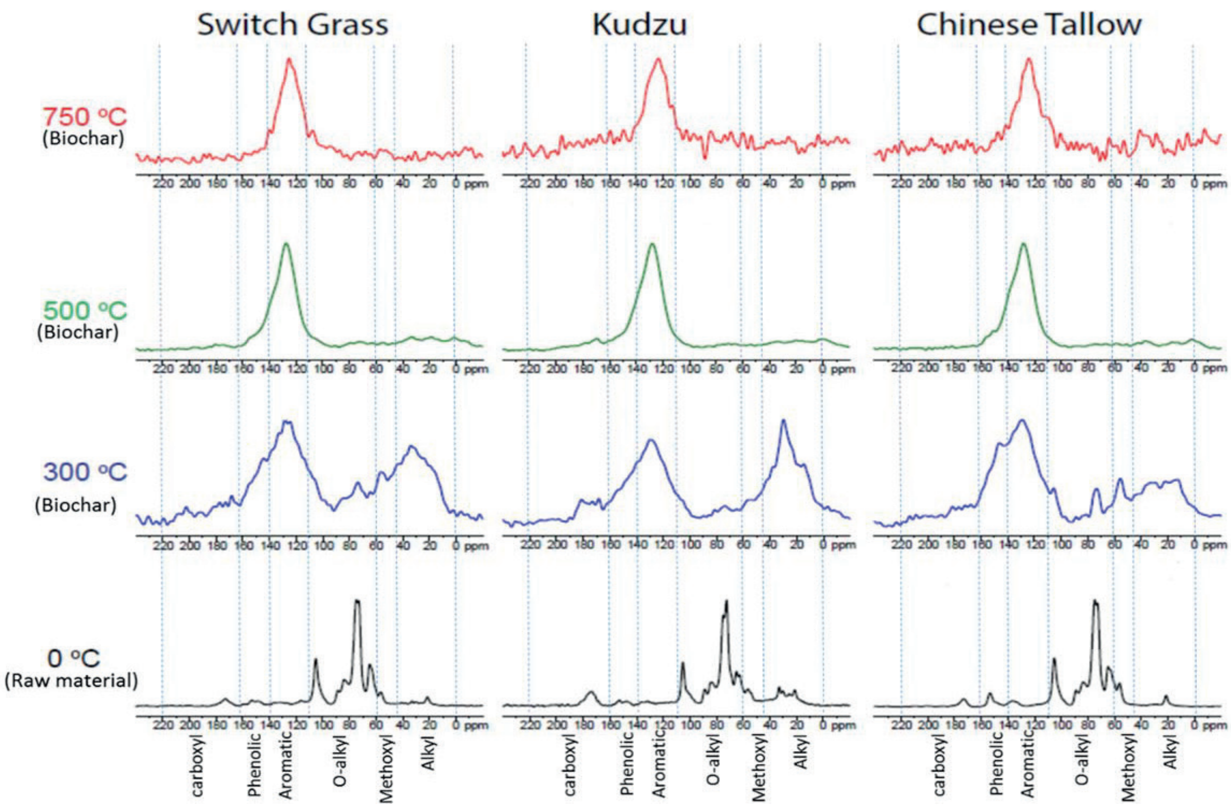

Figure 2. Biochar carbon functional groups as determined by nuclear magnetic resonance (NMR); from [24].

6.2.1. Phytoremediation

Ecological restoration may be accomplished through reduction of algae in the water bodies through aquatic plants. Being primary producers, advanced aquatic plants and micro-organisms compete with each other for ecological resources, such as light, nutrients, and living space. During their growth, advanced aquatic plants release chemical substances that are conducive to inhibiting algal production, as well as directly absorbing nitrogen and phosphorus in water. Storage of these elements in the plants means that they can be effectively extracted from the water through physical removal of these plants from the lake, thus reducing the nutrient level in lake waters [56].

6.2.2. Wetland restoration and constructed wetlands

Wetland restoration and constructed wetlands retain nutrient loss from upstream fields protecting the aquatic system (**Table 5**) [51]. Wetlands play a key role in P removal due processes that include peat accretion (sorption and burial in soil and sediments), uptake by microbes and vegetation and precipitation by iron and aluminum [57–59].

6.2.3. Riparian area restoration

Although [18] indicated that ground water contained elevated P which was a driver of eutrophication, there was no clear evidence of the location and sources of the pollution, as a result

Lake rehabilitation and restoration	Reduce the P concentration of lake water	Control P inlet and prolong residence time of water
River maintenance and restoration	Increase capacity to retain nutrient	Re-meander, restore flood plains and reconnect inundation areas Limit cutting of vegetation and reduce regular removal of gravel and impediments to flow
Wetland restoration and constructed wetlands	Retain nutrient loss from upstream fields in wetlands	Create wetlands in agricultural areas with substantial P losses

Table 5. Mitigation strategies in aquatic ecosystems. From [51].

measure to decrease groundwater derived P loads cannot target the contamination at its source in the catchment. Hence the need to implement measures in the riparian area to eliminate groundwater P directly before it enters the water body.

6.2.4. River/lake maintenance and restoration

River maintenance and restoration is important in increasing nutrient retention capacity. Lake rehabilitation and restoration reduce the P concentration of lake [51] (**Table 5**).

7. Conclusion

Phosphorus eutrophication is a major environmental problem globally resulting in negative impact on the economy, health and tourism sector. Phosphorus eutrophication is caused by both point and nonpoint sources of P. In many countries point source of P has been better controlled while nonpoint sources of P which is mainly agricultural sources have been an ongoing major challenge. The excessive P in the farm is a result of excessive fertilizer and manure application on farm. Phosphorus has mainly been translocated from the source to aquatic systems through run off and leaching and in some isolated cases through ground water. There is need to implement mitigation strategies. This chapter recommends implementation of measures to control nutrient loads through restructuring industrial layout which is a point sources of P pollution. To address nonpoint source of P there is need to implement catchment management measures and ecosystem restoration measures. The catchment management encompasses farm scale, field scale and catchment scale measures that will either reduce P availability for translocation or retain P in the catchment area. Human intervention is equally important to ensure removal of P from already contaminated aquatic system or prevention of P translocation to the water bodies; human intervention includes ferric dosing, flushing and dredging of floor deposits and biochar application on farm. The human intervention especially ferric dosing and flushing and dredging of floor deposits has limitation because once intervention is abandoned the P status could easily revert to pre-intervention status. Previous studies indicate contrasting finding on the success of the mitigation strategies, whereby some reported success while others indicated no response to P eutrophication mitigation. As a result, it seems there is need in some cases to combine multiple eutrophication mitigation interventions for example control of nutrient loading, physicochemical and physicomechanical interventions in order to take care of legacy P and ensure successful mitigation process.

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