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Limiting Sediment Phosphorus Recruitment to Mitigate Water Hyacinth (*Pontederia crassipes* (Mart.) Solms) Invasion of Aquatic Ecological Systems

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SUMMARY: Water hyacinth (*Pontederia crassipes* (Mart.) Solms) is aggressive invasive aquatic macrophytes. Its rapid vegetative growth, prolific reproduction and adaptation to varying environmental conditions enable its dominance in both tropical and subtropical freshwater ecosystems. Consequently, the objective of this paper was to review potential utilization and the mitigation of *P. crassipes* invasion of aquatic ecological systems by limiting recruitment of sediment phosphorus. The review adopted a narrative approach aimed at providing qualitative synthesis of existing literature. Relevant studies were identified across multiple academic databases including off-line library and online library sources such as Biosis, Biological abstracts, Science direct and Google scholar. Information gathered from these data bases reveal that despite its invasiveness, *P. crassipes* has been investigated for beneficial uses, such as phytoremediation, bioenergy production, and as source of organic fertilizer. However, its uncontrolled proliferation necessitates the development of array of effective management strategies, and the capping technology has emerged as a promising approach. By targeting internal phosphorus loading from the sediment, capping reduces nutrient availability that sustains its growth. Therefore, this review synthesizes current knowledge on the invasiveness, utilization, and control of water hyacinth, with a particular focus on the role of emerging capping technologies in mitigating the nutrient-driven proliferation.

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Aquatic ecosystems across the tropics and subtropics are increasingly threatened by invasive alien plants, and Water Hyacinth (*Pontederia crassipes* (Mart.) Solms) stands out as one of the most aggressive. Water hyacinth is a free-floating invasive macrophyte, native to the Amazon basin in South America. It was first described in the genus *Pontederia* by German naturalist Carl Friedrich Philipp von Martius in 1823, while studying Brazilian vegetation (Hill and Coetzee, 2008; Téllez *et al*., 2008). Later, Kunth (1842) established the genus *Eichhornia* to accommodate members of the Pontederiaceae family with trilocular ovaries and numerous seeds, leading Solms-Laubach (1883) to reclassify water hyacinth under *Eichhornia* (Simpson and Sanderson, 2002). It has spread rapidly across Asia, Africa, and other regions, largely through human-mediated pathways, such as ornamental trade and accidental introductions (Hill and Coetzee, 2008; Téllez *et al*., 2008). Its extraordinary reproductive capacity, both vegetative and sexual, enables exponential population growth, with mats doubling in size within 4 -7 days under favorable conditions (Gaikwad and Gavande, 2017). This capacity for explosive expansion has earned water hyacinth the reputation of being the world most noxious aquatic weed (Dersseh *et al*., 2019; Bulu and Oladoja, 2023). The ecological and socioeconomic impacts of water

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hyacinth are profound. Dense mats alter macrophyte community composition, reduce dissolved oxygen, and disrupt food webs, leading to biodiversity loss and fisheries decline (Villamagna and Murphy, 2010; Dersseh *et al*., 2019). Hydrologically, infestations impede river flow, clog irrigation canals, and increase evapotranspiration, resulting in significant water losses (Su *et al*., 2018; Dersseh *et al*., 2019; Bulu and Oladoja, 2023). For example, in Egypt, evapotranspiration from infested canals and lakes was estimated at 3.5 billion m³ annually, equivalent to irrigation water for 432 km² of farmland (Fayad *et al*., 2000). Economically, infestations raise transportation costs, reduce hydropower generation, and threaten the livelihoods of riparian communities. In Nigeria, the invasion of coastal lagoons and creeks has jeopardized the fishing industry, with over 20,000 fishermen at risk of losing their livelihoods (Akinyemiju, 1987). Similarly, in Ethiopia's Lake Tana, infestations have endangered endemic fish species and disrupted local economies, affecting nearly half a million people (Sisheber *et al*., 2015). The invasive potential of water hyacinth is enhanced by its adaptability to different environmental conditions. It thrives in nutrient-rich waters especially with high concentrations of nitrogen and phosphorus and optimal temperatures of 28-30 °C, pH between 6.5 and 8.5 (Bulu and Oladoja, 2023; Gaikwad and Gavande, 2017). Such conditions are increasingly common due to anthropogenic eutrophication, making control efforts more challenging. Different methods that have been used to control the excessive growth of this aquatic invasive species include mechanical removal (cutting, dredging), chemical treatment (herbicide, salt) or biological control (biocontrol agents such as herbivorous fish and insects or shading) (Hussner *et al*., 2017). However, all these methods either have negative side effects, or have not been effective in the management of the invasion.

Phosphorus (P) is one of the major plant growth-limiting nutrients that directly or indirectly influences all biological processes. The uncontrolled proliferation of *P. cras*sipes has been linked to stimulation by the inflow of phosphorus from external sources, as well as internal loads recruited from sediments that accumulated during periods of high external input (Søndergaard *et al*., 2003). Because sediments act as both nutrient sinks and sources, the recruitment of phosphorus from sediment into the overlying water column influences the eutrophication status of an aquatic system (Oladoja *et al*., 2025). Efforts to reduce the external P loading, as a means of combating eutrophication or the overgrowth of macrophyte have often proven ineffective, largely due to the persistent internal phosphorus reserves stored in sediments during earlier periods of elevated external loading (Jensen *et al*., 2015).

Amongst the approaches developed to reduce the release flux of nutrient from sediments, in-situ physical adsorption (i.e., sediment capping) promotes geochemical conditions that increase the net sink function of sediments by enhancing P sedimentation rates and/or decreasing P release rates (Hupfer *et al*, 2016). It has been used to control internal nutrient loading of water bodies and eutrophication in lakes and estuaries (Berg *et al*., 2004, Xiong and Peng, 2008). From the ecological safety viewpoint, chemical capping agent is a matter of concern, but the use of biogenic materials is assumed to be safe and eco-friendly. Given its ecological plasticity, socioeconomic burden, and hydrological disruption, this review provides an insight into the menace of water hyacinth, and the conventional management strategies. The emerging and promising sediment capping technique that mitigate the recruitment of the sediment phosphorus into the overlying water, to preclude the unfettered proliferation of this aquatic flora is also enunciated.

METHODOLOGY

The literature in this review were identified through targeted searches across multiple academic databases. The databases used for the search were online library sources such as biological abstracts, Science direct and Google scholar. Keywords specific to the objectives of the topic were chosen and each keyword was combined with "water hyacinth". The keywords used were "invasion", "utilization", "control methods"; "biological control"; "chemical control"; "physical control"; "integrated control"; "nutrient capping" and "sedimented phosphorus". Inclusion of study in the review was based on relevance to the research question, while exclusion was guided by lack of direct relevance or accessibility.

OUTCOME

Biology of Water hyacinth: Morphologically, water hyacinth is rhizomatous and stoloniferous, producing long adventitious roots that hang beneath the water surface. Mature plants consist of roots, rhizomes, stolons, leaves, inflorescences, and fruit clusters (Penfound and Earle, 1948). The glossy, broad, thick green leaves are borne on elongated or bulbous petioles, with the swollen "float" providing buoyancy in aquatic habitats (Coetzee *et al*., 2017). In sparse or terrestrial conditions, petioles elongate without the

float. The attractive lavender-colored flowers, often with a yellow spot, occur in inflorescences of 8–10 blooms (Penfound and Earle, 1948).

Water hyacinth reproduces both sexually, via seeds, and vegetatively, through budding and stolon production (Penfound and Earle, 1948). Vegetative propagation dominates invasion success, with clonal ramet formation ensuring genetic uniformity and rapid spread (Penfound and Earle, 1948; Gaikwad and Gavande, 2017). However, seed production remains important in seasonal environments where vegetative parts are destroyed, as seeds can remain dormant for 10–15 years until favorable conditions arise (Penfound and Earle, 1948). Reports suggest that large-scale propagation may yield millions of plants within 200 days (Gaikwad and Gavande, 2017).

The successive invasion characteristics of *P. crassipes* are explained by mechanisms such as enemy release, evolution of increased competitive ability, phenotypic plasticity, and the empty niche hypothesis (Fleming and Dibble, 2015). Its rapid growth is supported by voracious nutrient uptake, particularly nitrogen and phosphorus, enabling the formation of dense mats that obstruct light penetration, reduce dissolved oxygen, and disrupt aquatic ecosystems.

Origin and distribution of Water hyacinth: Water hyacinth native range is the Amazon basin in South America, particularly Brazil and Argentina, where early records date back to 1816 (Penfound and Earle, 1948). Initially valued for its attractive flowers, the plant was introduced deliberately as an ornamental species to other regions, while accidental dispersal also contributed to its spread (Villamagna and Murphy, 2010). The first documented introduction into North America occurred at the Cotton Centennial Exposition in New Orleans in 1884, from where it spread rapidly across southeastern states, appearing in Florida by 1890 and later extending to California (Webber, 1897; Penfound and Earle, 1948). By the early 20th century, infestations were reported across the southern United States, particularly in Louisiana's freshwater systems such as the Atchafalaya River, Bayou Teche, and tributaries of the Mississippi River (Penfound and Earle, 1948). Its intolerance to saline conditions has limited its establishment along coastal zones, but inland freshwater bodies have experienced severe invasions.

Water hyacinth was introduced into Africa in the early 1900s, with reports from the Nile River as early as 1870 (Gopal, 1987) and has spread extensively across the continent, with major infestations in Nigeria, Ghana, Ethiopia, Kenya, and South Africa (Dersseh *et al*., 2019). In Nigeria, it was first observed in 1984 in the Badagry Creek area of Lagos, and by the 1990s had colonized major rivers such as the Niger and Benue, as well as reservoirs and coastal lagoons (Uka *et al*., 2009). In Asia, water hyacinth was introduced around 1890 and is now widespread in India, China, and Southeast Asia. In China, surveys in 2003 documented infestations in over 130,000 locations, covering approximately 270 km² in Fujian province alone (Yan *et al*., 2017). Australia and Japan also reported invasions during the late 19th and early 20th centuries (Coetzee *et al*., 2017). In Europe, the plant was introduced in the 1930s, with established populations in Portugal, Spain, Italy, and France (Téllez *et al*., 2008).

Today, water hyacinth is naturalized in more than 50 countries across tropical and subtropical regions, with its distribution constrained primarily by temperature. The species thrives in warm climates, tolerating air and water temperatures between 10-43 °C, but it is unable to survive prolonged exposure below 7 °C (Wilson *et al*., 2005). Its rapid vegetative growth and prolific seed production enable exponential population increases; under nutrient-rich conditions, biomass accumulation can reach 10 kg/m² within 50 days (Wilson *et al*., 2005). Consequently, large infestations have been reported in equatorial lakes and reservoirs, including Lake Victoria in East Africa and Mexican water bodies, where coverage exceeded 40,000 hectares in 1993 (Villamagna and Murphy, 2010).

Utilization of Water Hyacinth: Despite being recognized as one of the global most harmful aquatic weeds, water hyacinth has considerable potential for beneficial use due to its high productivity and nutrient-rich biomass. Its valorization has been explored across multiple sectors, including agriculture, energy, animal husbandry, and crafts, offering opportunities to transform its ecological challenge for sustainable resource management and community empowerment (Su *et al*., 2018; Nandiyanto *et al*., 2024). In South Africa, valorization of harvested biomass has been recommended to offset the high costs of mechanical removal while simultaneously generating value-added products such as bioenergy (Karouach *et al*., 2022).

Agricultural Applications: Water hyacinth biomass is rich in organic matter (>70% dry weight) and contains significant levels of nitrogen, phosphorus, and potassium, making it suitable for biofertilizer production (Nababi *et al*., 2025). Water hyacinth has been investigated for use in mulching, composting,

vermicomposting, and anaerobic digested for biofertilization purposes (Harun *et al*., 2021). Mulching improves soil moisture retention, regulates temperature, and increases yields in crops such as maize and turmeric (Harun et al., 2021). Anaerobic digestion of water hyacinth biomass produces biogas, with digestates serving as effective biofertilizers enriched with phytohormones and nutrients (Reales-Alfaro *et al*., 2013).

Animal Feed: Water hyacinth dry matter contains 10–20% crude protein as well as high cellulose and hemicellulose comparable to conventional forage crops and has been successfully used in feed formulations for cattle, goats, pigs, ducks, rabbits, and fish (Abdelhamid and Gabr, 1991; Harun *et al*., 2021). It can be used fresh, dried, ensiled, or composted, with ensilaging often preferred to improve palatability and digestibility (Indulekha and Thomas, 2019). Studies have demonstrated positive outcomes such as increased weight gain in pigs, improved nutrient digestibility in cattle, and enhanced protein content in fish and goat meat (Su *et al*., 2018).

Bioenergy Conversion: Water hyacinth is increasingly recognized as a promising bioenergy feedstock due to its low lignin (≈10%), high cellulose (≈20%) and hemicellulose (≈33%) content, which favor microbial decomposition and fermentation (Nandiyanto *et al*., 2023). Its biomass is classified as a second-generation biofuel resource, which helps avoid food-versus-fuel conflicts. As a sustainable feedstock, it holds significant potential for producing renewable energy in various forms, including bioethanol, biogas (through anaerobic digestion), and bio-briquettes.

Anaerobic digestion of water hyacinth yields methane-rich biogas, with reported production capacities of 100–134 L/kg of fresh biomass depending on pretreatment (Su *et al*., 2018). Co-digestion with cow dung or sewage sludge enhances degradation efficiency and methane yield. In briquette production, Firdaus and Octavianus (2021) demonstrated that cassava peel waste successfully bound with water hyacinth adhesives to produce bio-briquettes. Their study found that at a carbonization temperature of 400 ℃, briquettes using water hyacinth glue achieved a calorific value of 5461 cal/g, which was higher than those using banana stem adhesives (5265 cal/g). Similarly, Mibulo *et al*. (2023) showed that briquettes made solely from water hyacinth had calorific values of 16.22 MJ/kg, blending it with banana peels (20.79 MJ/kg) or pineapple peels (20.55 MJ/kg) significantly improved energy performance.

Phytoremediation and Metal Recovery: Water hyacinth exhibits strong phytoremediation capacity, removing heavy metals such as chromium, cadmium, lead, copper, and nickel, as well as nutrients like nitrogen and phosphorus from wastewater (Bulu and Oladoja, 2023; Su *et al*., 2018). Removal efficiencies can exceed 99% for certain contaminants, with metals primarily accumulated in the roots. Harvested biomass can be processed to recover metals via electrocoagulation or electro-flotation, providing raw materials for metallurgical industries (Nandiyanto *et al*., 2023). This dual role, pollution control and resource recovery, makes phytoremediation a particularly attractive utilization pathway.

Industrial and Craft Applications: Water hyacinth fibers are widely used in handicrafts, including mats, baskets, sandals, and furniture, supporting community-based enterprises in Asia and Africa (Rakotoarisoa *et al*., 2016). Beyond crafts, recent advances explore its use in bioplastics, automotive brake pads, and adsorbents. Water hyacinth-derived particles blended with starch produce biodegradable plastics, while composites with epoxy resins have been tested for brake pad production with promising mechanical properties (Nandiyanto *et al*., 2023). Its porous structure also makes it effective as an adsorbent for dyes and organic pollutants.

Management of Water hyacinth invasion: Over the past decades, a wide range of methods have been employed to control the spread of water hyacinth, and these include mechanical, chemical, biological and integrated approaches. Each method has distinct advantages and limitations, and their effectiveness is often shaped by ecological conditions, socio-economic contexts, and policy frameworks.

Mechanical control remains one of the most widely applied strategies, particularly in regions such as Europe and Africa. Techniques include harvesting, cutting, dredging, and shredding, as well as the use of barriers such as booms and cables to protect water intake pumps. For example, in Portugal's Pateira de Fermentelos lagoon, aquatic harvesters successfully removed more than 15,500 m^3 of hyacinth mats (Onyari *et al*., 2024). In South Africa, barriers have been used to safeguard hydropower facilities and water extraction pumps (Hill and Coetzee, 2008). Mechanical removal provides immediate clearance for navigation, fishing, and recreation, and harvested biomass can be valorized into compost, bioenergy, or animal feed (Karouach *et al*., 2022). However, mechanical methods often produce large numbers of

plant fragments that facilitate further spread, and the high costs of equipment and maintenance limit their feasibility in developing countries (Yan *et al*., 2017). Chemical control has been widely tested, involving the use of herbicides such as glyphosate, diquat, and 2,4-D. Herbicides are effective for rapid eradication, but their use is restricted in many countries due to environmental risks. For instance, in Europe only glyphosate is permitted for routine use on emergent aquatic species, while legislative bans prevent its application on submerged vegetation. In Nigeria, glyphosate has been applied in freshwater bodies, though concerns have been raised about its negative impacts on fish, non-target plants, and public health (Onyari *et al*., 2024). Moreover, chemical control often leaves behind dead biomass that depletes oxygen during decomposition, further harming aquatic ecosystems (Onyari *et al*., 2024; Karouach *et al*., 2022).

Biological control, relying on natural enemies to suppress water hyacinth populations, is considered more ecologically sustainable method. In South Africa, nine biological control agents including arthropods, such as *Neochetina eichorniae* (weevil) and *Orthogalumna terebrantis* (mite), as well as fungal pathogens have been released since the 1970s (Onyari *et al*., 2024). These agents reduce photosynthetic productivity and biomass of water hyacinth, while fungal pathogens such as *Acremonium zonatum* and *Cercospora rodmanii* caused severe infections, leading to the plant decline and sinking (Yan *et al*., 2017). However, success of biological control mechanism has been limited by ecological factors. For instance, in South Africa, cooler temperatures reduce the efficacy of insect populations, delaying their impact until late summer (Onyari *et al*., 2024). Although, biological control is cost-effective and environmentally friendly, but requires detailed knowledge of host specificity to avoid off-target effects.

The nutrient immobilization technique for controlling water hyacinth invasion: The proliferation of water hyacinth in aquatic ecosystems is strongly linked to eutrophication, driven by both external nutrient inputs and internal nutrient loading from sediments (Oladoja *et al*., 2025). Consequently, effective control strategies must not only target the plant directly through mechanical, chemical, or biological means, but also address the underlying nutrient dynamics that sustain its invasion. Nutrient immobilization has emerged as a promising complementary technique, designed to stabilize phosphorus (P) and nitrogen (N) in sediments and thereby reduce the nutrient availability that fuels hyacinth growth.

Phosphorus in aquatic ecosystem: Phosphorus (P) in lake water exists in both particulate and dissolved forms. Particulate phosphorus includes phosphorus found in living organisms, mineral phases of rocks and soils, and phosphorus adsorbed onto decomposing organic particles. Dissolved phosphorus comprises orthophosphate (PO_4^{3-}), polyphosphates, organic colloids, and low molecular weight phosphate esters, with orthophosphate being the most important inorganic form (Zhou *et al*., 2022). Cellular constituents and organic phosphates also contribute significantly to phosphorus in freshwater systems (Wetzel, 2001).

Lake sediments contain diverse phosphorus fractions, including labile P, iron-bound P (Fe-P), aluminium-bound P (Al-P), organic P, calcium-bound P (Ca-P), and residual P (Rydin and Welch, 1998; Zhou *et al*., 2022). Labile P represents soluble reactive phosphorus (SRP), which are loosely sorbed in pore water, while Fe-P is mobile under low redox conditions. Aluminium-P is relatively inert, unaffected by redox changes, and Ca-P is a stable sedimentary component. Residual P consists mainly of refractory organic and inert inorganic P forms. Sequential extraction methods distinguish these fractions, though they do not perfectly correspond to chemically defined species. Biological factors (e.g., bacterial activity, bioturbation, mineralization), physical processes (sediment mixing, resuspension), and chemical conditions (pH, redox state, iron-to-phosphorus ratio, nitrate availability) have all been found to influence phosphorus release from sediments.

In deep lakes, molecular diffusion drives phosphorus transfer into overlying anaerobic waters due to steep concentration gradients. Wind-induced turbulence, benthic invertebrate activity, and fish feeding can disrupt gradients and resuspend sediments. Microbial gases, such as CO_2, CH_4, and N_2 can cause ebullition, accelerating phosphorus release. Plant metabolism and growth within sediments further enhance phosphorus transport across the sediment-water interface (Wetzel, 2001). Laboratory studies confirm that phosphorus release is greater under alkaline conditions than acidic ones, with neutral environments showing relatively low release. Higher temperatures increase phosphorus release and prolong equilibrium times between sediment and overlying water. Additionally, anaerobic conditions favour phosphorus release compared to aerobic environments (Wu *et al*., 2014).

Sediments act as both sinks and sources of nutrients, releasing phosphorus (P) and nitrogen (N) into the overlying water column. Even when external nutrient inputs are reduced, internal loading from sediments continues to sustain eutrophication and invasive macrophyte growth (Søndergaard *et al*., 2003; Jensen *et al*., 2015). Phosphorus, often the primary growth-limiting nutrient, plays a decisive role in aquatic productivity, and its release from sediments directly influences biological processes. Internal phosphorus loads typically originate from pools accumulated during periods of high external input, making efforts to reduce external loading alone insufficient to curb eutrophication (Jensen *et al*., 2015).

Capping phosphorus in sediment: Sediment capping is an in-situ remediation technology that involves placing a clean substrate over contaminated sediments to reduce contaminant release into the overlying water (Reible *et al*., 2003). It functions by containing contaminated solids, isolating pollutants from benthic organisms, and limiting contaminant transport to the sediment surface and water column. The substrate used for capping may be an inert material such as sand, a natural sorbing materials like clays, or amendment with reactive properties designed to enhance the contaminant isolation. These amendments can reduce permeability to divert groundwater flow, act as sorbents to retard contaminant migration or introduce reagents that promote degradation or transformation of contaminants.

Conventional (passive) capping employs clean, neutral materials such as sand, silt, clay or organic carbon to form a physical barrier that isolates contaminated sediments from the surrounding environment and reduces contaminant migration into the water column. While effective and relatively economical, passive caps are limited in shallow waters, beneath marine structures, or in sensitive habitats due to their thickness. In contrast, active or reactive capping incorporates materials that chemically or physically interact with contaminants to reduce their mobility, toxicity, and bioavailability. Active capping offers a longer-lasting solution and can be applied in environments where conventional caps are impractical, making it a promising advancement in sediment remediation.

Materials containing aluminium (Al), iron (Fe), or calcium (Ca) enhance sediment sorption capacity, thereby immobilizing phosphorus and limiting its diffusion into overlying waters. Some agents also form barriers that physically isolate sediments from the water column, further reducing phosphorus flux. The success of chemical immobilization depends critically on selecting appropriate reagents tailored to site-specific conditions such as pH, alkalinity, and sediment composition (Wang and Jiang, 2016). Commonly applied materials include Al-based salts (e.g., alum), Fe-based compounds, Ca-based amendments, zeolites, and other engineered sorbents. A review of the examples of chemical materials used for sediment phosphorus capping is presented below:

Aluminium (Al) based compounds: Many aluminium-based compounds, such as aluminium sulphate ($Al_2(SO_4)_3$), aluminium chloride ($AlCl_3$), polyaluminium chloride, and sodium aluminate ($NaAlO_2$), have been extensively investigated for controlling internal P loading in lakes. Among these, $Al_2(SO_4)_3$ is the most commonly applied agent, often used in combination with buffering compounds, such as $NaAlO_2$ or $NaHCO_3$ to stabilize pH during treatment (Nogaro *et al*., 2013). The longevity of aluminium treatments varies widely, with effectiveness lasting from less than a year to over four decades (Huser *et al*., 2016).

Calcium based compounds: Calcium-based compounds, such as calcium chloride ($CaCl_2$), calcium hydroxide ($Ca(OH)_2$, including slaked lime), gypsum ($Ca_2SO_4.2H_2O$), calcium oxide (CaO, including lime), calcium carbonate ($CaCO_3$, mainly referring to calcite), Gastropod shell (Oladoja *et al*., 2025), and limestone, have been investigated for their potential to control internal P loading. Among these, calcium hydroxide and calcium carbonate are the most widely applied. The use of Ca compounds is inspired by natural processes, such as biogenic calcite-P precipitation, a phenomenon enhanced by photosynthetic uptake of carbon dioxide (Hamilton *et al*., 2009; Wang and Jiang, 2016). This mechanism, sometimes referred to as the "self-cleansing process," stabilizes phosphorus in sediments (Wang and Jiang, 2016).

Iron based compounds: Iron-based amendment/capping materials have attracted considerable attention due to their availability, cost-effectiveness and relatively low environmental impact. A wide range of iron-based amendment/capping materials have been investigated to target the internal P loading. Iron-based compounds, such as ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), solid ferric hydroxide ($Fe(OH)_3$), ferric chloride sulfate ($FeClSO_4$), ferrous chloride ($FeCl_2$), ferrous sulfate ($FeSO_4$), and ferric oxide (Fe_2O_3), have all been evaluated for lake internal P loading control. The effectiveness of Fe treatments is strongly dependent on redox conditions. Under

anaerobic or anoxic conditions, Fe-bound phosphorus (BD-Pi) is readily released due to reductive dissolution of Fe compounds (Kleeberg *et al*., 2013). Thus, Fe amendments are most effective under oxic conditions.

Zeolites: Zeolite are aluminosilicate mineral containing water and alkali (or alkaline-earth metal). Raw zeolites adsorb moderate organic P under weakly acidic and alkaline conditions, and at elevated temperature and dissolved oxygen (Sun *et al*., 2012). Modified zeolites have exhibited enhanced performances over the natural zeolite (Gibbs and Özkundakci, 2011). To date, the most commonly used modified zeolites for internal P loading control is Z2G1 (Aqual-PTM), an aluminized modified zeolite (Gibbs and Özkundakci, 2011).

Other Materials used for sediment capping: Several other chemicals have also been used for internal P loading control with varying success achieved. Examples include Dewatered drinking water treatment residuals, Nitrate, Lanthanum-modified bentonite (LMB), Algal bloc, allophone, Ca rich sepiolite, ferrihydrite-modified diatomite, fly ash, etc. (Wang and Jiang, 2016). From an ecological point of view, these methods may be hazardous to the quality of the aquatic ecosystem and expensive. Therefore, the use of biogenic materials that is safe, readily available and eco-friendly should be encouraged in mitigating P release from sediment.

Conclusion: Water hyacinth remains one of the most persistent aquatic invaders, driving extensive scientific and technological efforts for its control. Capping technology, has emerged as a notable achievement, targeting internal phosphorus release from sediments, to reduce nutrient availability sustaining its proliferation. Materials such as aluminium, iron, calcium compounds, and modified zeolites demonstrated promising potential for immobilizing phosphorus. Integrating capping technology with other management approaches may provide a holistic framework for sustainable control of water hyacinth, balancing ecological restoration with socio-economic needs. Future research should prioritize long-term field trials, ecological risk assessments, and the development of eco-friendly capping materials to ensure effective and environmentally responsible management of this invasive species.

DECLARATIONS

Ethical Approval: This study did not involve human participants or animal experimentation and therefore did not require formal ethical approval. All procedures involving data handling and analysis were conducted responsibly and in accordance with standard academic and institutional guidelines.

Disclaimer (Artificial Intelligence): Author(s) hereby declare that no generative Artificial Intelligence (AI) technologies have been used during writing or editing of this manuscript.

Declaration of Conflict of Interest: The author declares that there is no known conflict of interest or personal relationships that could have influenced the work reported in this paper.

Declaration of Data Availability: There are no data used in this study.

REFERENCES

Abdelhamid, AM; Gabr, AA (1991). Evaluation of water hyacinth as feed for ruminants. *Arch. Tierernähr.* 41: 745–756. DOI: https://doi.org/10.1080/17450399109428519

Akinyemiju, OA (1987). Invasion of Nigerian waters by water hyacinth. *J. Aquat. Plant Manage.* 25 (1): 24–26. URL: https://apms.org/wp-content/uploads/japm-25-01-024.pdf

Berg, U; Neumann, T; Donnert, D; Nüesch, R; Stüben, D (2004). Sediment capping in eutrophic lakes - efficiency of undisturbed calcite barriers to immobilize phosphorus. *Appl. Geochem.* 19 (11): 1759 - 1771. DOI: https://doi.org/10.1016/j.apgeochem.2004.05.004

Bulu, YI; Oladoja, NA (2023). Process variables that defined the phytofiltration efficiency of invasive macrophytes in aquatic system. Intern. J. Phytoremediat. 25 (13): 1774 - 1792. DOI: https://doi.org/10.1080/15226514.2023.2194999

Coetzee, JA; Hill, MP; Ruiz-Téllez, T; Starfinger, U; Brunel, S (2017). Monographs on invasive plants in Europe N° 2: Eichhornia crassipes (Mart.) Solms. *Bot. Lett.* 164 (4): 303–326. DOI: https://doi.org/10.1080/23818107.2017.1381041

Dersseh, MG; Melesse, AM; Tilahun, SA; Abate, M; Dagnew, DC (2019). Water hyacinth: review of its impacts on hydrology and ecosystem services - lessons for management of Lake Tana. *Extreme Hydrol. Climate Variabil.* 237 - 251. DOI: https://doi.org/10.1016/B978-0-12-815998-9.00019-1

Fayad, YH; Ibrahim, AA; El-Zoghby, AA; Shalaby, FF (2000). Ongoing activities in biological control of water hyacinth in Egypt. *ACIAR Proc.* 43 - 46. URL: http://www.bio-nica.info/biblioteca/Fayad2001Eischhornia.pdf

Firdaus, A; Octavianus, B (2021). Biobrickets made from cassava skin waste utilizing banana plastic waste glue and water hyacinth. *Indones. J. Eng. Sci.* 2 (2): 007–013. DOI: https://doi.org/10.51630/ijes.v2i2.14

Fleming, JP; Dibble, ED (2015). Ecological mechanisms of invasion success in aquatic macrophytes. *Hydrobiologia* 746 (1): 23–37. DOI: https://doi.org/10.1007/s10750-014-2026-y

Gaikwad, RP; Gavande, S (2017). Major factors contributing growth of water hyacinth in natural water bodies. *Intern. J. Eng. Res.* 6 (6): 304–306. DOI: https://doi.org/10.5958/2319-6890.2017.00024.1

Gibbs, M; Özkundakci, D (2011). Effects of modified zeolite on P and N processes and fluxes across lake sediment-water interface using core incubations. *Hydrobiologia* 661 (1): 21–35. DOI: https://doi.org/10.1007/s10750-009-0071-8

Hamilton, SK; Bruesewitz, DA; Horst, GP; Weed, DB; Sarnelle, O (2009). Biogenic calcite-phosphorus precipitation as negative feedback to lake eutrophication. *Can. J. Fish. Aquat. Sci.* 66 (2): 343–350. DOI: https://doi.org/10.1139/F09-003

Harun, I; Pushiri, H; Amirul-Aiman, AJ; Zulkeflee, Z (2021). Invasive water hyacinth: ecology, impacts and prospects for rural economy. *Plants* 10 (8): 1613. DOI: https://doi.org/10.3390/plants10081613

Hill, MP; Coetzee, JA (2008). Integrated control of water hyacinth in Africa. *EPPO Bull.* 38 (3): 452–457. DOI: https://doi.org/10.1111/j.1365-2338.2008.01263.x

Hupfer, M., Reitzel, K., Kleeberg, A. and Lewandowski, J. (2016). Long-term efficiency of lake restoration by chemical phosphorus precipitation: Scenario analysis with a phosphorus balance model. *Water research*, *97*, 153-161. DOI: https://doi.org/10.1016/j.watres.2015.06.052

Huser, B. J., Egemose, S., Harper, H., Hupfer, M., Jensen, H., Pilgrim, K. M., ... and Futter, M. (2016). Longevity and effectiveness of aluminum addition to reduce sediment phosphorus release and restore lake water quality. *Water research*, 97, 122-132. DOI: https://doi.org/10.1016/j.watres.2015.06.051

Hussner, A., Stiers, I., Verhofstad, M. J. J. M., Bakker, E. S., Grutters, B. M. C., Haury, J., ... and Hofstra, D. (2017). Management and control methods of invasive alien freshwater aquatic plants: a review. *Aquatic Botany*, *136*, 112-137. DOI: https://doi.org/10.1016/j.aquabot.2016.08.002

Jensen, HS; Reitzel, K; Egemose, S (2015). Evaluation of aluminum treatment efficiency on water quality and internal phosphorus cycling in six Danish lakes. *Hydrobiologia* 751: 189–199. DOI: https://doi.org/10.1007/s10750-015-2186-4

Mibulo, T; Nsubuga, D; Kabenge, I; Wydra, KD (2023). Characterization of briquettes developed from banana peels, pineapple peels and water hyacinth. *Energy Sustain. Soc.* 13 (1): 36. DOI: https://doi.org/10.1186/s13705-023-00414-3

Gopal, B (1987). Water Hyacinth. Elsevier Sci. Publ., New York. DOI: https://doi.org/10.1017/S0266467400002571

Uka, UN; Chukwuka, KS; Daddy, F (2007). Water hyacinth infestation and management in Nigeria inland water. *J. Plant Sci.* 2 (5): 480–488. DOI: https://doi.org/10.3923/jps.2007.480.488

Nababi, J; Kokou, B.K., Kamanula, J F; Wanjala, FP; Nakawoombe, M., Balde, I; Wanda, EMM. (2025). Agronomic potential of water hyacinth (Eichhornia crassipes) based organic-phosphate liquid fertilizer on strawberry growth, yield and fruit quality in contrasting soil types. Environmental Challenges, 101274. DOI: https://doi.org/10.1016/j.envc.2025.101274

Nandiyanto, ABD; Ragadhita, R; Hofifah, SN; Al Husaeni, DF; Al Husaeni, DN; Fiandini, M; Aziz, M (2024). Progress in utilization of water hyacinth as effective biomass material. *Environ. Dev. Sustain.* 26 (10): 24521–24568. DOI: https://doi.org/10.1007/s10668-023-03655-6

Nogaro, G; Burgin, AJ; Schoepfer, VA; Konkler, MJ; Bowman, KL; Hammerschmidt, CR (2013). Aluminum sulfate (alum) application interactions

with coupled metal and nutrient cycling in hypereutrophic lake ecosystem. *Environ. Pollut.* 176: 267–274. DOI: https://doi.org/0.1016/j.envpol.2013.01.048

Oladoja, NA; Bulu, YI; Akinyeye, JO; Ahmed, RO; Ololade, IA; Ogunniyi, JA (2025). Mitigating exchange flux of sedimented phosphorus in invasive water hyacinth bloom system using biogenic waste material. *Ecohydrol. Hydrobiol.* 25 (1): 54–73. DOI: https://doi.org/10.1016/j.ecohyd.2024.01.004

Onyari, EK; Fayomi, GU; Jaiyeola, AT (2024). Unveiling situation of water hyacinth on freshwater bodies in Nigeria and South Africa: management, workable practices and potentials. *Case Stud. Chem. Environ. Eng.* 10: 100974. DOI: https://doi.org/10.1016/j.cscee.2024.100974

Penfound, WT; Earle, TT (1948). Biology of water hyacinth. *Ecol. Monogr.* 447–472. DOI: https://doi.org/10.2307/1948585

Rakotoarisoa, TF; Richter, T; Rakotondramanana, H; Mantilla-Contreras, J (2016). Turning problem into profit: using water hyacinth for handicrafts at Lake Alaotra, Madagascar. *Econ. Bot.* 70 (4): 365–379. DOI: https://doi.org/10.1007/s12231-016-9362-y

Reales-Alfaro, JG; Trujillo-Daza, LT; Arzuaga-Lindado, G; Castaño-Peláez, HI; Polo-Córdoba, ÁD (2013). Acid hydrolysis of water hyacinth to obtain fermentable sugars. *CTF-Cienc. Tecnol. Futur.* 5 (2): 101–111. DOI: https://doi.org/10.29047/01225383.60

Reible, D; Hayes, D; Lue-Hing, C; Patterson, J; Bhowmik, N; Johnson, M; Teal, J (2003). Comparison of long-term risks of removal and in situ management of contaminated sediments in Fox River. *Soil Sediment Contam.* 12 (3): 325–344. DOI: https://doi.org/10.1080/713610975

Rydin, E; Welch, EB (1998). Aluminum dose required to inactivate phosphate in lake sediments. *Water Res.* 32 (10): 2969–2976. DOI: https://doi.org/10.1016/S0043-1354(98)00055-4

Simpson, D; Sanderson, H (2002). Plate 434. Eichhornia crassipes Pontederiaceae. *Curtis's Bot. Mag.* 19 (1). DOI: https://doi.org/10.1111/1467-8748.00326

Sisheber, B; Fente, D; Adgo, E; Nyssen, J (2015). Regional geography of Dek Island, Lake Tana, Ethiopia. In *TropiLakes 2015: Trop. Lakes Changing Environ.* pp. 39–55. Bahir Dar Univ. URL: http://hdl.handle.net/1854/LU-6956980

Søndergaard, M; Windolf, J; Jeppesen, E (2003). Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia* 506–509: 135–145. DOI: https://doi.org/10.1023/B:HYDR.0000008611.12704.dd

Su, W; Sun, Q; Xia, M; Wen, Z; Yao, Z (2018). Resource utilization of water hyacinth and its challenges. *Resources* 7 (3): 46. DOI: https://doi.org/10.3390/resources7030046

Sun, SQ; Qiu, Y; Jiang, CB; Jiang, WX; Zhou, Q; Nie, XB; Tan, WC (2012). Study on mechanisms of in-situ moderately labile organic phosphorus control by zeolite in shallow lake sediments. *Appl. Mech. Mater.* 209–211: 1142–1146. DOI: https://doi.org/10.4028/www.scientific.net/AMM.209-211.1142

Téllez, TR; López, EMDR; Granado, GL; Pérez, EA; López, RM; Guzmán, JMS (2008). Water hyacinth, Eichhornia crassipes: invasive plant in Guadiana River Basin (Spain). *Aquat. Invasions* 3 (1): 42–53. DOI: https://doi.org/10.3391/ai.2008.3.1.8

Kleeberg, A; Herzog, C; Hupfer, M (2013). Redox sensitivity of iron in phosphorus binding does not impede lake restoration. *Water Res.* 47 (3): 1491–1502. DOI: https://doi.org/10.1016/j.watres.2012.12.014

Villamagna, AM; Murphy, BR (2010). Ecological and socio-economic impacts of invasive water hyacinth: a review. *Freshw. Biol.* 55 (2). DOI: https://doi.org/10.1111/j.1365-2427.2009.02294.x

Wang, C; Jiang, HL (2016). Chemicals used for in situ immobilization to reduce internal phosphorus loading from lake sediments for eutrophication control. *Crit. Rev. Environ. Sci. Technol.* 46 (10): 947–997. https://doi.org/10.1080/10643389.2016.1200330

Webber, HJ (1897). Water hyacinth and its relation to navigation in Florida. *Div. Bot. USDA Bull.* 18, Washington, D.C. URL: https://upload.wikimedia.org/wikipedia/commons/b/b5/The_water_hyacinth%2C_and_its_relation_t

o_navigation_in_Florida_%28IA_waterhyacinthits18webb%29.pdf

Wetzel, RG (2001). Limnology: lake and river ecosystems. Gulf Prof. Publ. URL: https://books.google.co.in/books?id=no2hk5uPUcMC&source=gbs_navlinks_s

Wilson, JR; Holst, N; Rees, M (2005). Determinants and patterns of population growth in water hyacinth. *Aquat. Bot.* 81 (1): 51–67. https://doi.org/10.1016/j.aquabot.2004.11.002

Wu, Y; Wen, Y; Zhou, J; Wu, Y (2014). Phosphorus release from lake sediments: effects of pH, temperature and dissolved oxygen. *KSCE J. Civ. Eng.* 18: 323–329. DOI: https://doi.org/10.1007/s12205-014-0192-0

Xiong, W; Peng, J (2008). Development and characterization of ferrihydrite-modified diatomite as phosphorus adsorbent. *Water Res.* 42 (19): 4869–4877. DOI: https://doi.org/10.1016/j.watres.2008.09.030

Yan, SH; Song, W; Guo, JY (2017). Advances in management and utilization of invasive water hyacinth in aquatic ecosystems – a review. *Crit. Rev. Biotechnol.* 37 (2): 218–228. DOI: https://doi.org/10.3109/07388551.2015.1132406

Zhou, H; Margenot, AJ; Li, Y; Si, B; Wang, T; Zhang, Y; Bhattarai, R (2022). Phosphorus pollution control using waste-based adsorbents: material synthesis, modification, and sustainability. *Crit. Rev. Environ. Sci. Technol.* 52 (12): 2023–2059. DOI: https://doi.org/10.1080/10643389.2020.1866414