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Aquatic Greenery: Managing Aquatic Vegetation and Harnessing their Potential

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aquatic vegetation plays a critical role in maintaining the ecological balance of aquatic ecosystems. Maintaining water quality, biodiversity, and ecosystem stability necessitates the management of aquatic vegetation. It delves into the methods and strategies for effectively controlling and utilizing

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aquatic plants, highlighting the benefits they offer in terms of nutrient cycling, habitat provision, and shoreline stabilization. Aquatic vegetation holds significant ecological value, contributing to nutrient cycling, providing habitat, and enhancing water quality. Aquatic weeds include impediments to navigation, decreased water flow, and altered biodiversity. We evaluate various management approaches, including mechanical control, biological control, and chemical control, based on their effectiveness, environmental impact, and sustainability. This includes utilizing aquatic plants for wastewater treatment, carbon sequestration, biofuel production, and habitat restoration. By understanding and harnessing the potential of aquatic greenery, we can promote sustainable aquatic environments and improve our bodies' overall well-being.

Keywords: Fish; aquatic weed; utilization; control; biofuel.

1. INTRODUCTION

Aquatic weeds play a crucial role in the ecosystem, providing oxygen, food, and shelter for various organisms. There are four major types of aquatic vegetation: floating, submerged, emergent, and algae. Floating vegetation, such as water hyacinth and mosquito fern, floats on the surface of the water and has roots suspended directly in the water, absorbing nutrients directly from it [1,2]. Submerged vegetation, like eelgrass, grows below the surface of the water, providing habitat and food for small fish and invertebrates, as well as supporting the life cycle of many fish [3]. Caterpillars and rushes, rooted in the substrate with the majority of their plant mass out of the water, provide habitat for songbirds, wading birds, and insects, while also preventing shoreline erosion [4]. Algae, which are some of the most basic and oldest types of aquatic vegetation, have no real root system and can form extensive mats that drift across the surface of the water, supporting the life cycle of many fish and invertebrates.

Aquatic plants provide many benefits to the ecosystem, including acting as a habitat for small fish, removing carbon dioxide, producing oxygen through photosynthesis, and providing food for various organisms, including humans. They also provide several items used by humans, such as rice, cranberries, blueberries, fiber for rope, reeds for caning, herbs, medicinal compounds, and aesthetic items such as flowers, colorful fruits, and berries for decoration [5]. However, aquatic plants can also be invasive, causing harm to the ecosystem by outcompeting native species and altering the physical and chemical properties of the water. Invasive aquatic plants, such as *Hydrilla verticillata* and *Eichhornia crassipes,* can reduce biodiversity, disrupt food chains, and impair water quality, making it difficult for native species to survive [6]. To limit nuisance amounts of plant growth, it is essential to protect the waterbody's shoreland by maintaining a healthy, well-distributed stand of trees, saplings, shrubs, and groundcover, which act as a filter for nutrients and sediments. Specifically, maintaining a wooded shorefront will go a long way toward providing a canopy for shading the shoreline and reducing the overall amount of direct sunlight to the lake bottom, providing conditions for expanded plant growth [5] The aquatic vegetation plays a vital role in the ecosystem, providing oxygen, food, and shelter for various organisms, as well as acting as a habitat for small fish and invertebrates. However, it is essential to manage aquatic plants properly to prevent invasive species from causing harm to the ecosystem. By protecting the waterbody's shoreland and maintaining a healthy, well-distributed stand of trees, saplings, shrubs, and groundcover, we can ensure that aquatic vegetation continues to provide benefits to the ecosystem while minimizing the negative impacts of invasive species [7].

2. TYPES OF AQUATIC VEGETATION

Aquatic vegetation encompasses various categories, including floating, submerged, emergent, and algae. The term "floating aquatic vegetation" refers to plants that float on the water's surface, their roots directly immersed in the water. These organisms extract nutrients directly from the water in order to sustain their existence and have the capacity to occupy the entirety of coves or small bodies of water, resulting in the formation of areas devoid of fish and other aquatic organisms [8]. Submerged vegetation is characterized by its growth beneath the water's surface, with its roots firmly established in the substrate of the pond floor. These habitats provide ideal conditions for young fish to evade predators and can form extensive mats on the surface. Emergent vegetation relies on a substrate, like the pond bottom or the bank, and displays a dominant plant mass outside the water. Ali et al. [9] posit that these structures not only mitigate the erosion of the bank due to strong winds and wave action but also impede the flow of water towards the primary body of water. Consequentially, they help to prevent turbidity in the pond. Algae are a fundamental, ancient, and perplexing category of aquatic flora. These plants lack a true root system and have the ability to create large mats that give the impression of floating vegetation drifting across the surface of the pond. Floating aquatic vegetation commonly consists of giant duckweed, giant salvinia, water hyacinth, and mosquito fern. Submerged vegetation commonly encompasses various species, such as baby pondweed, coontail, American pondweed, and bushy pondweed. Common types of emergent vegetation include rushes and sedges, lilies, willows, cattails, and water primrose. Common types of algae include planktonic algae, filamentous algae, and blue-green algae [10].

1. Emergent Aquatic Weeds: These are plants with stems and leaves protruding above the water's surface, rooted to the substrate or lakebed. Examples include Cumbungi, Narrowleaf Cumbungi, and Broadleaf Cumbungi.
2. Free-Floating Aquatic Weeds: These weeds have stems, leaves, or flowers that may or may not protrude above the water's surface, with roots not attached to the substrate. Examples include Parrotfeather and Water Primrose.
3. Submerged Aquatic Weeds: These plants grow entirely underwater, whether attached to the substrate or not. Examples include Pondweeds, Hydrilla, and Milfoil.
4. Floating Aquatic Weeds: These are seed-bearing plants that float freely on the water's surface, never becoming rooted in the soil. Examples include Water Lettuce and Duckweed.

3. ECOLOGICAL ROLES OF AQUATIC VEGETATION

A. Habitat Provision

Aquatic weeds play crucial roles in providing habitat for fish in aquatic ecosystems. These plants offer structural benefits that create habitats suitable for fish, providing shelter, spawning grounds, security, and food resources for various aquatic organisms, especially fish [11]. The shade created by aquatic macrophytes attracts fish and enhances their foraging efficiency, ultimately leading to increased growth and survival rates. Substrate type and the presence of submersed vegetation are significant factors influencing cichlid habitat preferences, with certain species favoring muddy bottom areas with abundant aquatic vegetation for shelter and prey availability [12]. The presence of aquatic plants like water lilies, Nuphar lutea, and other macrophytes creates spatial complexity in aquatic habitats, offering critical refuge sites for smaller fishes, important spawning grounds, and increased survival and recruitment rates for juvenile fish [13]. The structural complexity of aquatic plants deters predation by altering predator-prey interactions, enhances the growth rates of young fish by providing a rich food source, and contributes to the overall productivity and biodiversity of aquatic ecosystems [14].

B. Nutrient cycling

Aquatic weeds play significant roles in nutrient cycling within aquatic ecosystems. These plants are essential for nutrient uptake and recycling, contributing to the overall health and balance of aquatic environments. Aquatic weeds, such as water hyacinth and other floating plants, are capable of assimilating excess nutrients directly from the water, serving as important nutrient sinks and helping to maintain water quality by removing nutrients like phosphorus and nitrogen [15,16]. These plants play a crucial role in nutrient cycling by absorbing nutrients from the water column and storing them in their tissues, thereby reducing nutrient concentrations in the surrounding water and preventing eutrophication. Additionally, aquatic weeds act as nutrient reservoirs, binding significant amounts of nutrients within their biomass. The decomposition of aquatic weeds is slower compared to algae and phytoplankton, allowing for a gradual release of nutrients back into the ecosystem, which can benefit other organisms and contribute to the fertility of aquatic habitats [16,17].

C. Biodiversity Enhancement

Aquatic weeds play crucial roles in enhancing fish biodiversity by providing essential habitat components that support various life stages of fish species. These plants offer shelter, spawning grounds, and food resources for fish, contributing to increased fish diversity and abundance in aquatic ecosystems. The structural complexity provided by aquatic weeds creates diverse microhabitats that attract different fish species, promoting species richness and overall biodiversity. The presence of aquatic weeds helps create a more stable and productive environment for fish, offering protection from predators, suitable breeding sites, and foraging opportunities. The structural diversity provided by aquatic plants supports a wide range of fish species with varying habitat preferences, leading to the coexistence of multiple fish populations within the same ecosystem. Additionally, aquatic weeds contribute to the overall health of the aquatic ecosystem by improving water quality, regulating nutrient levels, and enhancing the availability of food resources for fish, which further supports fish biodiversity [18,19].

4. AQUATIC WEEDS HARMFUL EFFECTS ON FISH

Aquatic weeds can have harmful effects on fish due to various reasons outlined in the provided sources:

1. Reduction in Dissolved Oxygen (DO): When aquatic weeds are killed by herbicides, they decompose and are broken down by oxygen-using organisms, leading to a reduction in dissolved oxygen levels in the water. This decrease in DO can be detrimental to fish survival [20].
2. Fish Kills: Excessive aquatic weed growth can lead to fish kills, especially after herbicide applications. The decomposition of dead plant matter by bacteria and microbes consumes oxygen in the water, potentially causing oxygen depletion and creating conditions that are harmful to fish [21].
3. Habitat Degradation: Aquatic weeds can interfere with a balanced fish population by creating too much habitat, which can lead to fish becoming stunted and overpopulated. Additionally, excessive weed growth can inhibit larger fish from effectively feeding on smaller fish, impacting the overall health of the fish population.
4. Oxygen Depletion: The decay and decomposition of dead aquatic plants can lead to oxygen depletion in the water, especially when microbes and bacteria consume the dead matter. This oxygen demand can exceed the natural replenishment rate, potentially causing fish kills [21].
5. Algae Bloom Die-Offs: Aquatic weeds can contribute to algae bloom die-offs, which are often responsible for fish kills during the summer. The decay of plant material and the subsequent oxygen depletion caused by bacteria can further exacerbate the situation, impacting fish survival [22].

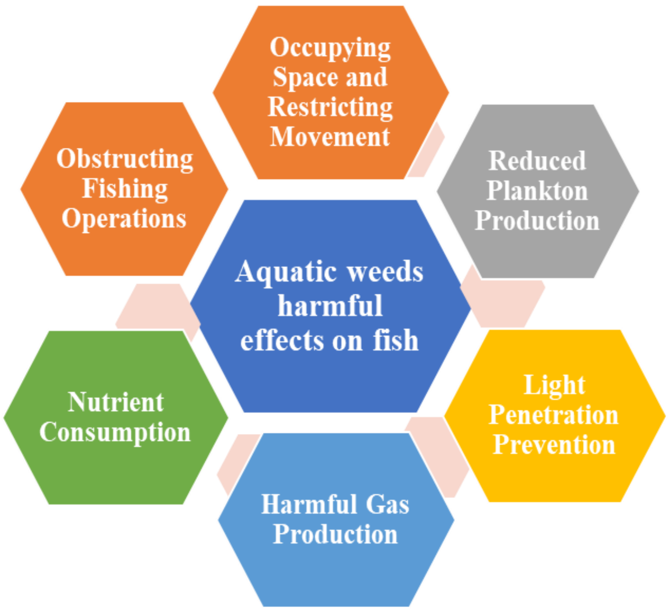

Fig. 1. Aquatic weeds can harmful effects on fish

5. TECHNIQUES FOR MANAGING AQUATIC VEGETATION

The control measures for aquatic weeds outlined in the provided sources include a combination of preventive, mechanical, biological, and chemical techniques.

1. Preventive Methods: Manual and preventive methods for controlling aquatic weeds involve various techniques aimed at physically removing or preventing the growth of weeds in water bodies. Manual methods include hand-pulling, diver-operated suction harvesting, rototilling, harvesting, cutting, shredding, or the use of weed rakes. These techniques require labor-intensive efforts and continual follow-up to ensure effective control, especially with woody species. Preventive measures involve proper pond design and construction to minimize shallow water areas, which are prone to weed growth. Additionally, manipulating the aquatic environment through methods like drawdowns, where water levels are lowered over the winter, can effectively limit the growth of certain types of submersed weeds [23]. These manual and preventive methods play a crucial role in managing aquatic weed infestations and maintaining the health of water bodies.

2. Mechanical Methods: Mechanical control involves the physical removal of aquatic vegetation using methods such as cutting, seining, raking, and the use of underwater weed cutters and harvesters. While effective in removing biomass, mechanical methods may not address the root causes of rampant weed growth and can be costly due to the disposal of harvested weeds. Mechanical control is particularly useful in larger lakes where the size of the water body allows for the operation of such equipment. However, the effectiveness of mechanical control can vary depending on the specific weed species, the environment, and the frequency of maintenance required to achieve control [24,25].

3. Biological Methods: Biological control involves using organisms like grass carp to control certain types of pond weeds. Grass carp are effective in controlling weeds with tender vegetation but may not be effective against weeds with tough, woody vegetation. It is essential to check with local authorities regarding regulations on the use of grass carp for weed control [26]. Biological methods for the control of aquatic weeds involve the use of natural enemies, typically insects, to manage invasive weed populations. These bio-control agents are introduced from the weeds' native range to target invasive populations and reduce their impact on natural ecosystems. In the context of the Delta Region Areawide Aquatic Weed Project (DRAAWP), the objective of biological control is not eradication but rather environmentally and economically sustainable integrated management of weeds like water hyacinth, Brazilian water weed, and arundo. The biocontrol agents, usually insects, are carefully tested to ensure they feed, develop, and reproduce only on the targeted weed, requiring several years of laboratory research to determine their effectiveness. Successful biological control aims to reduce the weed's ability to grow, spread, and compete with other plants, ultimately benefiting the ecosystem and reducing the need for other control methods [27,28].

4. Chemical Methods: Chemical control involves the use of herbicides to kill aquatic plants or disrupt their growth. Aquatic herbicides are effective in controlling vegetation without harming fish when used properly. However, it is crucial to follow safety guidelines and use registered herbicides in a safe and effective manner to prevent harm to aquatic organisms [29].

6. HARNESSING THE POTENTIAL OF AQUATIC VEGETATION

1. Biofuels Production

Aquatic weeds have the potential to be a valuable resource for the production of various types of biofuels. They contain high levels of carbohydrates, proteins, and lipids, which can be converted into biofuels through thermo-chemical methods or fermentation processes. Aquatic weeds possess lignin and sugar constituents that can be harnessed for the production of several valuable products, including bio-oil, combustible gasses, heat energy, bio-ethanol, bio-methanol, and bio-butanol. According to Alam et al. [30], the lipid fraction derived from aquatic weeds has the potential to be utilized in the production of biodiesel. Additionally, biological processes can be employed to generate bio-methane and bio-hydrogen from the biomass of aquatic weeds. The methane production of aquatic weeds, including water hyacinth, water lettuce, and common duckweeds, has been observed to be higher in comparison to water spinach. This characteristic renders them suitable for anaerobic digestion, a cost-effective method for the management and utilization of these biowastes. According to Koley et al. [31], the aquatic weeds possess favorable characteristics such as high reproduction rates, high cellulose and hemicellulose content, and low lignin content. These attributes render them very suitable as feedstock possibilities for anaerobic digestion, resulting in a substantial production of biogas.

The feasibility of producing biogas for biofuels by anaerobic digestion of aquatic weeds as substrates has been the subject of multiple investigations. Anaerobic digestion has been the subject of several research that have tested its viability as a tool for controlling invasive aquatic weeds. The research conducted by Wilkie and Evans [32] found that aquatic weeds can be used as a feedstock for anaerobic digestion, which can produce a significant amount of biogas. Aquatic weeds have several potential uses beyond just producing biofuel, such as a source of nutrition for humans, fish, and other animals; a material for paper; and even a medicine. The total process is anticipated to be sustainable, ecologically benign, and cost-effective through the biorefinery technique, which utilizes aquatic biomass to produce biofuel, fertilizer, chemicals with industrial applications, and wastewater remediation. Enzymes and polymers, two value-added byproducts of aquatic weed biomass, can increase the process's commercial viability [33].

2. Phytoremediation

Phytoremediation using aquatic plants is a promising method for removing inorganic, organic, and biological waterborne pollutants, including arsenic [17]. Aquatic and semi-aquatic weeds, such as water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), duckweed (*Lemna minor*), *Hydrilla verticillata*, *Ceratophyllum demersum, Spirodela polyrhiza*, Azola, and Wolfia spp., have been identified as capable of extracting higher amounts of arsenic from contaminated water. These aquatic weeds have arsenic tolerance mechanisms that allow them to remediate arsenic-contaminated water while continuing to grow. Phytoremediation of arsenic-contaminated water using aquatic plants has several advantages over traditional chemical methods, which are often expensive and not suitable for large-scale use in drinking and agriculture. Phytoremediation utilizes green plants to remove pollutants from contaminated water through various mechanisms, including phytoextraction, phytostabilization, phytodegradation, and phytovolatilization [34,35].

Table 1. Managing aquatic vegetation, control, benefits and their utilization

Aspect	Managing Aquatic weeds	Control	Benefits	Utilization
Description	Various methods available to control aquatic weeds.	Integrated pest management approach should be adopted.	Aquatic plants provide oxygen, stabilize shorelines, absorb nutrients, provide habitat, enhance beauty.	Preventing weed problems through nutrient and watershed management.
Causes of Growth	Clear, shallow water with high nutrient levels. Exotic species reproduce rapidly and outcompete native plants	Excessive nutrients, particularly nitrogen and phosphorus, promote weed growth	Aquatic plants benefit shorelines, reduce erosion, improve water quality, provide habitat, enhance aesthetics	Limiting nutrient input, avoiding phosphorus fertilizers, establishing buffer strips, deepening shallow areas
Control Methods	Physical, mechanical, biological, chemical suppression practices	Identification of weed species, economic, aesthetic, and recreational considerations	Reducing weed impacts to acceptable levels, not complete elimination	Preventing weed overgrowth through nutrient management, buffer strips, deepening shallow areas
Environmental Impact	Excessive growth hinders water flow, recreational activities, habitat value	Reduction in oxygen levels, adverse impact on aquatic flora and fauna	Strengthening substrates, reducing shoreline movement, improving water quality	Reducing nutrient input, maintaining buffer strips, preventing weed overgrowth

Salvinia (*Salvinia Molesta*) and Water Hyacinth (*Eichhornia crassipes*) are aggressive aquatic weeds that have considerable promise for phytoremediation. These aquatic weeds have been found to be effective in removing pollutants from water, including heavy metals and nutrients [36]. Phytoremediation of nutrients from water by aquatic floating duckweed (*Lemna minor*) has also been found to be effective in rearing African cichlid (*Labidochromis lividus*) fingerlings, indicating the potential of aquatic weeds in aquaculture [37].

3. Carbon sequestration

Carbon sequestration through aquatic plants, including aquatic weeds, is a promising method for removing carbon dioxide (CO2) from the atmosphere and storing it in the ocean or in biomass. Seaweed farming, for example, can sequester CO2 through photosynthesis, with some of the fixed carbon being transported to sediments and deep waters as fragments and dissolved organic carbon (DOC). This intervention has the potential to yield numerous significant co-benefits, such as the enhancement of food production, the improvement of fisheries, the provision of biodiversity, and the augmentation of socio-ecological resilience, all while posing minimal risk of unfavorable social, economic, or ecological consequences [38].

Azolla, a rapidly proliferating aquatic fern, exhibits the capacity to store carbon dioxide (CO2) via the processes of photosynthesis and biomass generation. Under ideal circumstances, Azolla has a high growth rate, so presenting a potential avenue for the sequestration of a portion of the carbon dioxide (CO2) that is being emitted into the environment. Azolla species have a variety of maximum biomass values, varying from 64 to 520 g dry weight/m2 [39]. Aquatic weeds, including water hyacinth, water lettuce, and common duckweeds, have remarkable reproductive capabilities, include substantial quantities of cellulose and hemicellulose, and exhibit minimal lignin content. Consequently, these weeds hold significant potential as a viable crop for the development of future biofuels. The management or utilization of aquatic weeds can be achieved by the implementation of anaerobic digestion, which is a viable and economically efficient method for handling these biowastes. These aquatic weeds are great candidates for this purpose due to their high reproduction rates, high cellulose and hemicellulose content, and low lignin concentration. Water hyacinth, water lettuce, and common duckweeds demonstrate greater methane generation in comparison to water spinach among the examined aquatic weeds [31,40].

7. THE UTILIZATION OF AQUATIC WEEDS

The utilization of aquatic weeds can involve various methods and applications, as highlighted in the provided sources. Aquatic weeds, such as *Eichhornia crassipes* (water hyacinth), can be utilized in different ways, including: The dried stalks of aquatic weeds like water hyacinth can be used for weaving mats. These mats serve as raw materials for various products, showcasing a sustainable utilization of aquatic weeds [41].

The use of aquatic weeds as biopesticides has been investigated for promoting sustainable agriculture. Aquatic weeds like muskgrass, water hyacinth, water lettuce, hydrilla, filamentous algae, and duckweed have been studied for their potential allelopathic effects and as sources of bio-fertilizers and mulching materials [42]. These weeds have shown antimicrobial, insecticidal, antifeedant, and herbicidal properties, indicating their potential as biopesticides to manage pests and weeds in agricultural settings. Research has focused on evaluating the effects of aquatic weed extracts on bacterial growth, insect pests like fall armyworm, and the germination and growth of various weed species, demonstrating promising results for their use in pest and weed management. The investigation into utilizing aquatic weeds as biopesticides aligns with the goal of reducing herbicide use and promoting sustainable agricultural practices [43].

Salvinia Molesta, an aquatic weed, has been used as a substrate for the production of Cellulase Enzyme, showcasing its potential as a biorefinery resource for biofuels and value-added products [30]. *S. molesta* has been effectively utilized for cellulase enzyme production in various studies. Researchers have used this aquatic weed as a carbon source to produce cellulase enzymes. Specifically, a study conducted with a wild type *Pseudomona*s strain found that *S. molesta* was a suitable substrate for cellulase production. Additionally, another study utilized *Aspergillus* species to produce cellulase enzymes from S. *molesta*. These findings highlight the potential of Salvinia Molesta as a valuable resource for cellulase enzyme production [44,45].

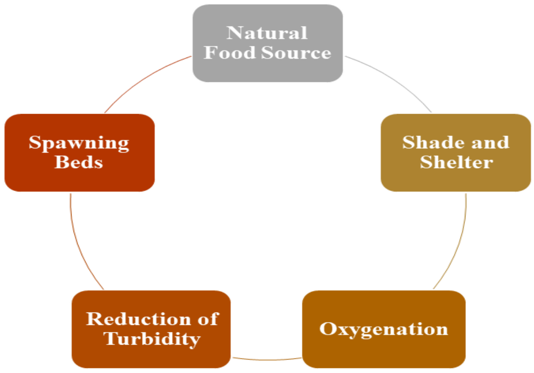

Fig. 2. Aquatic weeds several beneficial effects on fish in aquatic environments

Table 2. Aquatic weed as a fish feed, benefits, and other uses

Aquatic Weed Species	Fish feed	Benefits	Other uses
Water Hyacinth	High	Cost-effective feed ingredient, reduces cost of production	Oxygenates water, provides habitat for fish and other aquatic organisms
Azolla	High	Substitutes up to 20% of commercial fish meal in feed of common carp	Fixes and assimilates atmospheric nitrogen, high nutrient content
Duckweed	High	Substitutes up to 30% of fish meal in diet of Nile tilapia	High nutrient content, cost-effective feed ingredient
Aquatic plants (in general)	High	Excellent source of nutrients for fish diet formulation	Bioremediation, fertilizer, compost, mulch
Submerged aquatic plants (e.g. chara, hornwort, oxygen weed)	High	Used to feed fish as fresh or dried powder form incorporated in diet formulation	Other uses
Unicellular microalgae (e.g. Chlorella, Scendesmus, Spirogyra, Spirulina)	High	Used in fish diet	Other uses
Alligator Weed	Moderate	Used for animal feed	Biofuel production, and paper production
Alligator Weed	Moderate	Grass carp prefer to feed on alligator weed	Other uses
Water Hyacinth	High	Grass carp prefer to feed on water hyacinth	Other uses

8. AQUATIC WEEDS AS A FISH FEED

The utilization of aquatic weeds as fish feed has gained significant attention in recent years, offering a sustainable and environmentally friendly alternative in aquaculture. The nutritional composition and potential benefits of aquatic weeds, such as *Ipomoea aquatica, Lemna minor, Pistia stratiotes, Eicchornia crassipes, Azolla pinnata, Nymphaea nouchali*, and *Nymphaea lotus*, have been observed and investigated in relation to fish production, health status, defense mechanisms, and disease resistance. The presence of these aquatic weeds has the capacity to decrease reliance on fish meal, providing environmental advantages in terms of weed control and preservation of habitats in different water bodies [46]. The utilization of aquatic weeds for the production of valuable commodities, such as fish feed, is of paramount importance in ensuring the long-term viability of the aquaculture sector and aiding in the reduction of environmental risks and pollution. Despite the existence of various challenges such as variations in nutritional composition, the presence of anti-nutritional factors, high fiber content, and potential health risks, the implementation of innovative methods such as semi-solid-state fermentation (SSSF) has the potential to mitigate these issues and enhance the cost-effectiveness of aquaculture feed production by reducing anti-nutritional factors and fiber in fish feed. By incorporating aquatic weeds into aquaculture feed, a new horizon for sustainability in the aquaculture feed industry is opened, showcasing the potential for utilizing aquatic weeds as a valuable resource in fish nutrition and aquaculture sustainability [47,48].

9. ROLE OF AQUATIC WEEDS IN POLLUTION CONTROL

The role of aquatic weeds in pollution control is multifaceted and crucial for maintaining water quality and ecosystem balance. Aquatic weeds, such as water hyacinth and other submerged, floating, and emergent plants, play a significant role in pollution control through various mechanisms [49].

1. Nutrient Uptake: Aquatic weeds play a crucial role in absorbing excess nutrients like nitrogen and phosphorus from the water, which are common pollutants leading to eutrophication. By absorbing these nutrients, aquatic plants help decrease nutrient levels in the water, thereby mitigating the risk of algal blooms and enhancing water quality. This process of nutrient uptake by aquatic plants contributes significantly to reducing nutrient concentrations in the water, ultimately aiding in maintaining a balanced aquatic ecosystem and preventing the negative impacts associated with nutrient pollution and eutrophication [50,51].

2. Sediment Trapping: Some aquatic weeds, especially those with dense root systems, can trap sediments suspended in the water. This process helps in reducing turbidity and sedimentation, which can carry pollutants and contaminants, thus contributing to water clarity and quality [52].

3. Oxygenation: Submerged aquatic plants play a vital role in oxygenating the water through photosynthesis. By releasing oxygen into the water, these plants help maintain dissolved oxygen levels, which are essential for aquatic life and the breakdown of organic matter, thereby aiding in pollution decomposition [53].

4. Habitat Provision: Aquatic weeds provide habitats for various organisms, including microorganisms, insects, fish, and birds. By supporting diverse aquatic life, these plants contribute to the overall health of the ecosystem and help in maintaining ecological balance, which indirectly aids in pollution control [15]. Aquatic weeds act as natural filters and purifiers in water bodies, contributing to pollution control by absorbing nutrients, trapping sediments, oxygenating the water, and providing habitats for diverse aquatic organisms. Their presence and healthy growth are essential for maintaining water quality and mitigating the impacts of pollution in aquatic environments [54].

10. DRUGS AND CHEMICAL USED CONTROL OF AQUATIC WEEDS

The drugs and chemicals used for the control of aquatic weeds include a variety of herbicides specifically formulated for aquatic environments.

1. 2,4-D (Weedar 64): Used for controlling floating weeds, 2,4-D is applied in liquid or granular formulations at specified rates per acre. It is essential to treat only a portion of the water body to prevent oxygen depletion issues [55].
2. Carfentrazone (Stingray): This herbicide is effective for controlling floating weeds, and it is recommended to ensure that 80% of the foliage is exposed to treatment. Tank mixes with other herbicides like 2,4-D, glyphosate, or diquat can enhance control at lower application rates [56].
3. Diquat (Diquat 2AS): Diquat is used for wetting exposed plants, with specific instructions on application rates and the addition of a nonionic surfactant. It is important not to apply diquat to muddy water and consider tank mixes with chelated copper formulations for resistant duckweeds [57].
4. Fluridone (Sonar AS): Fluridone is recommended for controlling duckweed and bladderwort. It should be applied as a surface treatment at specified rates and only once per year when duckweed is present. Watermeal control may require higher application rates.
5. Imazapyr (Habitat 2AS): Imazapyr is used for controlling various aquatic weeds, and the use of spreader-stickers is advised for improved results. Complete coverage is essential, and it should be applied with a specified amount of water per acre. These

herbicides play a crucial role in managing aquatic weeds in water bodies, offering effective control measures to maintain water quality and ecosystem balance [43].

11. FUTURE DIRECTIONS AND RESEARCH NEEDS

Emerging technologies for aquatic weed management include autonomous robotics for identification and management of invasive aquatic plant species, machine learning for aquatic vegetation classification, and hydroacoustic imaging. These technologies involve the development of autonomous boats with hull design and fabrication, propulsion and steering, navigation and control unit, herbicide dispersal system, and hydroacoustic imaging. Machine learning algorithms are used for vegetation classification, with data preprocessing, hardware and software configuration, deep neural network (DNN) training, reducing overfitting, generalizing over multiple species, and extracting GPS coordinates from images post-classification. These technologies have the potential to improve the efficiency and accuracy of aquatic weed management, while minimizing the impact on non-target species and the environment. The emerging technologies for aquatic weed management include autonomous robotics for identification and management of invasive aquatic plant species, machine learning for aquatic vegetation classification, and hydroacoustic imaging. Research is also being conducted on new aquatic herbicides and their efficient and safe application, as well as the development of new herbicidal control options and integrated control of aquatic weeds. These technologies and research efforts have the potential to improve the efficiency and sustainability of aquatic weed management, while minimizing the impact on non-target species and the environment [58].

Sustainable utilization of aquatic weeds can be achieved through various methods such as energy recovery, composting, biocontrol, and production of nitrogen-doped nanoporous carbon for CO_2 capture. One study found that utilizing aquatic weeds for generating energy as biogas via anaerobic digestion is a sustainable option [59]. Another study identified composting as an easily adapted and eco-friendly method for managing aquatic weeds, which can meet sustainable plant nutrient management needs. Biocontrol solutions have also been developed for sustainable management of aquatic weeds. Additionally, waste aquatic weeds can be used for the sustainable production of nitrogen-doped nanoporous carbon for CO_2 capture. These methods not only help in managing aquatic weeds but also contribute to sustainable resource management and environmental protection.

12. CONCLUSION

The aquatic greenery plays a crucial role in pond ecosystems by providing shelter and food for fish, promoting balanced fish populations, and improving water quality. Excessive aquatic vegetation can pose challenges such as obstructing recreational activities, impeding drainage, and causing oxygen depletion issues. Effective management of aquatic vegetation requires a stepwise approach that includes identifying and controlling invasive species, prudently utilizing herbicides, and considering trade-offs in managing aquatic plants for various purposes. Various methods such as energy recovery, composting, biocontrol, and the production of nitrogen-doped nanoporous carbon for CO_2 capture can achieve the sustainable utilization of aquatic weeds. These methods not only help in managing aquatic weeds but also contribute to sustainable resource management and environmental protection. By carefully managing aquatic vegetation, it is possible to maintain a beneficial plant community that supports ecosystem health, wildlife habitats, and recreational activities while minimizing negative impacts on water quality and native species.

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Authors have declared that no competing interests exist.

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