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MINI REVIEW

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Harnessing aquatic plants for carbon sequestration and water purification: A review

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ABSTRACT

Aquatic and wetland vegetation are vital elements of the worldwide carbon cycle, providing significant opportunities to alleviate climate change through carbon sequestration. These organisms, which include submerged, emergent, and floating varieties, capture and store carbon dioxide from the atmosphere in their biomass and sediments, aiding in long-term carbon retention. Moreover, they are essential for water purification, as they absorb excess nutrients, eliminate pollutants, and help mitigate eutrophication in aquatic environments. While the ecological advantages of these plants are well-established, challenges such as the invasive characteristics of some species, management difficulties, and site-specific environmental conditions present considerable constraints. To fully harness their potential, future studies should concentrate on species selection, improved management techniques, and incorporating aquatic plants into constructed wetland systems. Enhancing our knowledge of their genetic, physiological, and ecological attributes can increase efficiency. This review explores how aquatic plants sequester carbon and their ability to lessen greenhouse gas emissions, underlining their significance as nature-based strategies for mitigating climate change. Additionally, the function of aquatic plants in improving water quality is examined, particularly their capacity to absorb nutrients, eliminate heavy metals, and detoxify contaminated water bodies. Species like *Eichhornia crassipes* (water hyacinth) and *Phragmites australis* (common reed) are emphasized in their combined advantages in carbon capture and water purification.

KEYWORDS

Aquatic plants; Carbon sequestration; Wetland ecosystems; Water purification; Blue carbon

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Introduction

Climate change has become one of the most urgent challenges facing the planet, largely driven by the rising levels of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the atmosphere. These emissions stem from human activities like deforestation, industrialization, and fossil fuel combustion, leading to increased global temperatures, changing precipitation patterns, and more frequent extreme weather events [1]. In response to these issues, researchers and policymakers are exploring innovative solutions rooted in nature that can address climate change and improve ecosystem services. Among these solutions, aquatic and wetland plants have received considerable attention due to their remarkable ability to absorb and store carbon, a process known as carbon sequestration, while aiding in water purification and ecosystem restoration [2]. Aquatic and wetland plants are essential to freshwater, estuarine, and coastal ecosystems, including a variety of species that can be categorized into three groups: submerged plants like seagrasses, emergent plants such as reeds, and floating plants like water hyacinths. These plants serve a dual purpose in environmental management by sequestering carbon and enhancing water quality. Through photosynthesis, they take CO_2 from the air and transform it into organic matter, either stored in their biomass or deposited in sediments [3]. In wetland environments, the waterlogged and low-oxygen conditions of the soil slow the breakdown of organic matter, facilitating long-term carbon storage and positioning these ecosystems as significant carbon sinks globally. This phenomenon, often termed blue carbon in relation to coastal ecosystems, underscores the vital role of aquatic plants in combating climate change [4].

In addition to their ability to sequester carbon, plants found in aquatic and wetland environments play a role in purifying water by eliminating excess nutrients, such as nitrogen and phosphorus, and filtering pollutants. The influx of nutrients from agricultural approaches. Wetland ecosystems, such as marshes, swamps, mangroves, and peatlands, occupy only a small percentage of the Earth's surface but contribute an outsized proportion to global carbon sequestration [7]. One of the most remarkable aspects of aquatic and wetland plants is their ability to thrive in various environmental conditions, ranging from freshwater lakes and rivers to saline coastal areas. However, while their ecological benefits are well-documented, the socioeconomic implications and knowledge gaps in their management, such as the challenges posed by invasive species, regional variations in carbon sequestration capacities, and their economic feasibility, require further exploration [8].

Role of Aquatic and Wetland Plants in Carbon Sequestration

Mechanisms of carbon sequestration

Aquatic vegetation captures carbon mainly through the process of photosynthesis, where carbon dioxide (CO_2) is

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taken in from the atmosphere and transformed into organic carbon. This organic carbon is subsequently stored in various parts of the plant, including leaves, stems, and roots. In aquatic habitats, a considerable amount of this organic matter is also deposited in sediment, where it can persist for long durations, providing a means of long-term carbon storage. This mechanism is further amplified in wetland environments, such as mangroves, seagrasses, and freshwater macrophytes, which excel at creating anaerobic conditions within the sediments. In these low-oxygen settings, the microbial breakdown of organic materials is slowed, resulting in carbon preservation within sediment layers. Consequently, these plants not only capture and store carbon in their biomass but also play a role in establishing "blue carbon" ecosystems, where carbon sequestration occurs both in the vegetation and the adjacent sediments, making them vital for combating climate change [9].

Contribution to the global carbon budget

Wetlands, which make up only 6-9% of the Earth's area, play a critical part in the global carbon cycle by sequestering around 20-30% of the soil carbon on the planet. This notable contribution highlights their essential role in managing levels of atmospheric carbon dioxide (CO_2). Coastal wetlands, such as mangroves, salt marshes, and seagrasses, are especially acknowledged for their impressive carbon sequestration abilities and are commonly referred to as "blue carbon" ecosystems. These environments proficiently absorb and retain carbon in both vegetation and sediments, with their anaerobic conditions aiding in the reduction of decomposition and promoting long-term carbon storage [10]. Although the capabilities of coastal wetlands have been widely researched, freshwater wetlands like peatlands and freshwater marshes also contribute significantly to the reduction of greenhouse gas (GHG) emissions. Despite being less explored, these freshwater systems play a considerable role in carbon storage, establishing them as a crucial, yet frequently neglected, aspect of global strategies to address climate change and decrease atmospheric GHGs [11].

Factors influencing carbon sequestration

The capacity of aquatic plants to sequester carbon is affected by several factors, including the type of species, environmental conditions, and management practices. Various aquatic plant species differ in their efficiency at capturing and storing carbon, with some, such as mangroves and seagrasses, being particularly adept due to their rapid growth and significant biomass production. Environmental variables like nutrient levels, water temperature, and sediment characteristics are also critical. Environments rich in nutrients can boost plant growth, while optimal temperatures for water enhance the process of photosynthesis. Moreover, sediment characteristics, including the amount of organic matter and conditions of water saturation, affect the long-term carbon storage within sediments, thus influencing the effectiveness of sequestration [12].

Water Purification by Aquatic Plants

Nutrient removal

Aquatic vegetation has an essential function in the purification of water by extracting excess nutrients, especially nitrogen and phosphorus, from aquatic environments. These nutrients, which often originate from agricultural runoff or wastewater discharge, are contributors to eutrophication, resulting in harmful algal blooms and oxygen depletion [13]. Aquatic vegetation takes in these nutrients through their root systems, which enhances microbial activity that further assists in nutrient processing. The root structures of plants such as reeds and submerged macrophytes improve nutrient absorption, thus enhancing water quality and decreasing the likelihood of eutrophication, leading to healthier aquatic systems [14].

Pollutant absorption

Some aquatic plants have an extraordinary capacity to take in various pollutants, such as heavy metals, pesticides, and other hazardous substances, which makes them extremely beneficial for phytoremediation. Species like water hyacinth and duckweed are especially effective because of their fast growth rates and strong pollutant absorption abilities. These plants absorb contaminants through their root systems and accumulate them in their tissues, thereby purifying contaminated water bodies. By eliminating harmful substances, they help restore water quality, making them suitable for wastewater treatment processes and enhancing the overall health of aquatic ecosystems [15].

Role in constructed wetlands

Engineered wetlands are artificial systems designed to replicate the natural functions of wetland ecosystems for the treatment of municipal and industrial wastewater. These systems utilize the capacity of aquatic vegetation to filter, absorb, and break down pollutants, providing an efficient and sustainable method for wastewater treatment. The presence of aquatic plants in constructed wetlands improves the removal of organic substances, nutrients, and heavy metals, thereby enhancing water quality. They are affordable, require minimal upkeep, and are eco-friendly, serving as a natural alternative to traditional treatment methods. Additionally, constructed wetlands are capable of addressing a diverse range of pollutants, making them adaptable for various wastewater treatment applications [16].

Mechanisms of Carbon Sequestration

Aquatic and wetland plants sequester carbon through the process of photosynthesis, wherein they absorb CO_2 from the atmosphere or dissolve in water and convert it into organic carbon. This organic carbon is stored in plant tissues or deposited into surrounding sediments, where it can remain for extended periods. Wetlands, in particular, offer favorable conditions for long-term carbon storage due to their anaerobic (low-oxygen) environments, which slow the decomposition of organic matter. Coastal wetlands, such as mangroves, salt marshes, and seagrass meadows, are considered among the most efficient blue-carbon ecosystems. For example, mangroves store carbon not only in their biomass but also in the soils beneath their dense root systems, which can hold carbon for centuries [17].

Freshwater wetlands and peatlands are also vital in the global carbon cycle. Peatlands, which cover only about 3% of the Earth's land surface, store nearly 30% of the world's soil carbon. These ecosystems are dominated by slow-growing plants, such as sedges and mosses, that accumulate layers of organic material over thousands of years. The ability of aquatic

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and wetland plants to trap and store carbon highlights their critical role in mitigating climate change and maintaining the global carbon balance [18].

Water Purification and Ecosystem Health

Beyond their carbon storage capabilities, aquatic and wetland plants serve as natural water purifiers, enhancing the health of aquatic ecosystems. These plants absorb excess nutrients, such as nitrogen and phosphorus, which are often introduced into water bodies through agricultural runoff and urban wastewater. By reducing nutrient levels, aquatic plants prevent eutrophication a process characterized by excessive algal growth, oxygen depletion, and the eventual collapse of aquatic ecosystems. Furthermore, these plants act as biofilters, removing heavy metals, organic pollutants, and other harmful substances from contaminated water, making them invaluable for water quality management and restoration projects [19].

The phytoremediation potential of aquatic plants is particularly relevant in addressing water pollution in heavily industrialized and agricultural regions. Species like *Eichhornia crassipes* (water hyacinth) and *Typha* (cattails) have demonstrated exceptional efficiency in nutrient uptake and pollutant removal. Constructed wetlands, which utilize aquatic plants for wastewater treatment, have become increasingly popular due to their cost-effectiveness and sustainability. These systems not only improve water quality but also provide additional ecosystem services, such as habitat creation and flood mitigation [20].

Conclusions

Aquatic and wetland vegetation presents a distinctive and dual-purpose approach to addressing two of the most pressing global environmental issues: climate change and water pollution. These plants are vital for capturing carbon during photosynthesis by absorbing atmospheric CO_2 and storing it within their biomass and sediments. In this manner, they help alleviate the impacts of climate change, especially in coastal and freshwater ecosystems, which are frequently undervalued as carbon sinks. Along with their capacity to sequester carbon, aquatic and wetland plants function as natural biofilters, enhancing water quality by assimilating excess nutrients, removing contaminants, and curbing eutrophication. Their ability to filter out heavy metals, organic pollutants, and toxins renders them crucial for phytoremediation, thereby amplifying their importance to the environment. Despite their considerable ecological advantages, the widespread use of aquatic plants for carbon sequestration and water purification encounters various obstacles. Effectively managing these plants on a large scale necessitates thorough planning, adequate funding, and persistent collaboration with local communities. There are also technical challenges to tackle, such as ensuring appropriate sediment management, regulating plant growth, and overseeing the harvesting process. Moreover, the risk of certain species becoming invasive underscores the importance of careful species selection and management strategies tailored to specific ecosystems. If these challenges are not addressed, the benefits provided by aquatic and wetland plants may be undermined, leading to unintended ecological repercussions. Progress in research and technology, along with their incorporation into policy frameworks, is essential for realizing the full potential of aquatic plants in environmental management. Investigating the most effective species for carbon sequestration and water purification, alongside developing technologies to facilitate their management and harvesting, will be vital. Additionally, integrating these nature-based solutions into national and international policies regarding climate and water quality can pave the way for large-scale implementation, particularly within carbon credit systems and wetland restoration projects.

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No potential conflict of interest was reported by the authors.

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