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## REVIEW ARTICLE

# $CO_2$ Sequestration through Phytoremediation Techniques Using High Photosynthetic Plants: A Review

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**ABSTRACT**
*Climate change is exacerbated by rising concentrations of atmospheric carbon dioxide ($CO_2$), primarily from fossil fuel combustion and deforestation. Phytoremediation, a biological method of using plants for environmental remediation, offers a sustainable and cost-effective approach for $CO_2$ sequestration by leveraging photosynthesis to capture atmospheric carbon. This review examines the use of high-photosynthetic plants for $CO_2$ sequestration, focusing on their mechanisms of carbon fixation, storage in biomass and soils, and contributions to long-term carbon sinks. Key plant species, including fast-growing trees like poplar and eucalyptus, perennial grasses such as switchgrass and miscanthus and wetland plants like cattails and reeds are analysed for their sequestration potential. The review also addresses challenges in land use, genetic engineering for enhanced carbon capture, and ensuring the long-term stability of sequestered carbon. Finally, future directions are proposed for optimizing phytoremediation practices and integrating them into large-scale carbon mitigation strategies. These insights highlight the potential of phytoremediation to play a critical role in global climate change mitigation.*

***Keywords:*** *$CO_2$ Sequestration, Phytoremediation, High Photosynthetic Plants, Carbon Capture, Climate Change Mitigation*

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## INTRODUCTION

The increasing concentration of carbon dioxide ($CO_2$) in the atmosphere, primarily due to human activities such as fossil fuel combustion and deforestation, is a major contributor to global warming and climate change (1). $CO_2$ sequestration refers to the capture and storage of $CO_2$ from the atmosphere in an effort to mitigate the greenhouse effect. Various techniques have been explored for $CO_2$ removal, including biological, chemical, and geological methods. Among these, biological carbon sequestration using natural processes to capture and store $CO_2$ has emerged as a promising solution due to its potential for scalability, cost-effectiveness, and environmental sustainability. One particularly promising biological approach is phytoremediation, the use of plants to remove, degrade, or neutralize contaminants from the environment. In the case of $CO_2$ sequestration, phytoremediation involves the use of plants to capture atmospheric $CO_2$ through photosynthesis and store it as organic carbon in plant biomass and soils (2). During photosynthesis, plants absorb $CO_2$ through their stomata, converting it into sugars and other organic compounds, which are then stored in various plant tissues. This process provides a natural, cost-effective mechanism for $CO_2$ removal from the atmosphere. High-photosynthetic plants those with greater rates of carbon fixation are particularly well-suited for enhancing $CO_2$ sequestration through phytoremediation. These plants typically exhibit high growth rates, large biomass production, and efficient carbon uptake mechanisms. As such, they can be strategically employed to increase the capacity of terrestrial ecosystems to act as carbon sinks (3). This review examines the potential of high-photosynthetic plants for $CO_2$ sequestration through phytoremediation, focusing on the mechanisms involved, plant species with the highest sequestration capacity, and the environmental benefits of this approach. We also discuss the challenges associated with scaling up phytoremediation and potential future directions for improving its effectiveness in addressing climate change.

**Mechanisms of $CO_2$ Sequestration in High Photosynthetic Plants**

Phytoremediation for $CO_2$ sequestration is based on the core process of photosynthesis, where plants capture atmospheric $CO_2$ and convert it into organic matter. This process not only contributes to the reduction of atmospheric $CO_2$ but also has the potential to store carbon for extended periods. The primary mechanisms involved in $CO_2$ sequestration by high photosynthetic plants include the fixation of carbon through photosynthesis, its storage in plant biomass, and efficient use of environmental resources to enhance carbon capture.

**Photosynthesis and Carbon Fixation**

During photosynthesis, plants absorb $CO_2$ from the atmosphere through stomata, specialized pores primarily on the surfaces of leaves. The enzyme RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) facilitates the fixation of $CO_2$ in the Calvin cycle, producing glucose ($C_6H_{12}O_6$), which is then utilized as an energy source for various metabolic functions and growth processes. This glucose is also converted into other forms of organic matter such as cellulose and starch, which serve as structural components and energy reserves, respectively. High photosynthetic plants are typically more efficient at carbon fixation due to their enhanced ability to capture light energy and convert it into chemical energy. These plants often have larger leaf areas, higher concentrations of chlorophyll, and more effective photosynthetic pathways. For example, C4 plants, such as maize and sugarcane, are more efficient in $CO_2$ fixation under high-temperature and high-light conditions, as they concentrate $CO_2$ in specialized cells, reducing the occurrence of photorespiration (4). In contrast, C3 plants (e.g., wheat, rice) are less efficient under similar conditions, as they fix $CO_2$ in a single cell type, leading to higher photorespiration rates under certain environmental conditions. Therefore, C4 plants tend to have an advantage in areas with intense sunlight and high temperatures (5). In addition, recent research highlights the role of chloroplast biogenesis and photosynthetic efficiency in high-photosynthetic plants. Improvements in these mechanisms can significantly enhance carbon fixation potential, especially in engineered crops designed for climate-smart agriculture (6).

**Carbon Storage in Biomass**

After carbon is fixed through photosynthesis, it is stored in the plant's biomass in both aboveground and belowground components:

**Aboveground Biomass:** This includes the stems, leaves, and branches of the plant, which temporarily store carbon. The carbon remains sequestered as long as the plant is alive. Once the plant dies or decomposes, this carbon can be released back into the atmosphere. However, living biomass, especially in long-lived species like trees, can store significant amounts of carbon for many years or even decades, making them valuable for long-term carbon sequestration (7).

**Belowground Biomass:** The root system plays a critical role in sequestering carbon in soils. Deep-rooted species, such as certain grasses, trees, and shrubs, are particularly important in soil carbon sequestration. These species can transfer carbon into the soil through root exudates and decaying root matter. Carbon stored in soils can remain locked in the form of soil organic carbon (SOC) for long periods, especially in anaerobic conditions, where microbial decomposition is slow. Recent studies have shown that plants with deeper root systems contribute more to SOC accumulation and that perennial species can increase soil carbon storage by building more organic matter over time (8).

**Soil Organic Carbon (SOC):** Carbon transferred from plants to soils through root exudates and decomposing plant material contributes to the formation of soil organic carbon. Long-term sequestration occurs when this carbon is stabilized through interactions with soil minerals or the formation of humic substances (stable organic compounds). Some studies suggest that plant species with high carbon turnover rates, such as certain grasses and fast-growing trees, may accelerate the process of carbon stabilization in soils (9). Additionally, the role of mycorrhizal fungi in facilitating carbon storage in soil has gained attention in recent years, as these fungi help stabilize soil carbon through their symbiotic relationships with plant roots (10).

**High Photosynthetic Efficiency**

High photosynthetic efficiency is a key trait of plants that are particularly effective at $CO_2$ sequestration. High-photosynthetic plants typically exhibit one or more of the following characteristics:

**High Biomass Production:** Rapidly growing plants, such as bamboo, poplar, and certain grasses, tend to accumulate large amounts of carbon via photosynthesis. These species have short growth cycles and can capture large amounts of $CO_2$ in a relatively short period. Bamboo, for example, is known for its exceptional growth rate, making it a significant player in carbon offset projects. Additionally, bamboo's ability to regenerate quickly through rhizome growth makes it an attractive species for sustainable carbon sequestration practices (11).

**Efficient Carbon Fixation:** C4 plants like maize, sugarcane, and switchgrass, as previously mentioned, are more efficient at fixing $CO_2$ compared to C3 plants under certain environmental conditions. C4 plants utilize a unique photosynthetic pathway that concentrates $CO_2$ in specialized leaf cells, enhancing their efficiency in carbon fixation. This efficiency makes C4 plants suitable for cultivation in regions with high temperatures and intense sunlight, where other crops may struggle to thrive (4). Furthermore, the C4 pathway is being actively researched for crop improvement to enhance its application in global carbon capture efforts (12).

**Adaptation to Environmental Stress:** Many high-photosynthetic plants are adapted to marginal or degraded lands, making them ideal candidates for large-scale $CO_2$ sequestration without competing with food crops. For example, species like switchgrass and miscanthus are not only efficient at sequestering carbon but are also well-suited for bioenergy production in lands that are unsuitable for conventional agricultural use. These plants are able to grow under low-input conditions, requiring minimal fertilizer and irrigation, making them both an economically and environmentally sustainable choice for carbon sequestration projects (3). Additionally, recent advancements in plant breeding and genetic engineering have made it possible to develop crop varieties that are specifically designed to enhance photosynthetic efficiency and carbon sequestration potential. Such innovations hold the promise of maximizing the carbon storage capabilities of plants without compromising their growth rates or adaptability (13).

**Biochemical Pathways of $CO_2$ Capture in High Photosynthetic Plants**

One of the most important enzymes involved in $CO_2$ sequestration in plants is Ribulose-1,5-bisphosphate carboxylase-oxygenase (RuBisCO). It is responsible for fixing atmospheric $CO_2$ into organic molecules during the Calvin cycle of photosynthesis, which ultimately leads to biomass accumulation and carbon storage in plant tissues. This process is especially relevant for high photosynthetic plants, which tend to have higher concentrations of RuBisCO and enhanced efficiency in carbon fixation. RuBisCO, however, is known for its dual activity: it can catalyze both carboxylation ($CO_2$ fixation) and oxygenation (photorespiration). The oxygenation activity reduces the overall efficiency of carbon fixation, as it leads to the release of $CO_2$ rather than its storage. Consequently, enhancing RuBisCO's carboxylase activity or minimizing its oxygenase function has been a significant focus in efforts to improve $CO_2$ sequestration capacity in plants.

**Advances in RuBisCO Optimization**

Recent research has explored both natural and genetic enhancements to RuBisCO's function, aiming to boost its carboxylation efficiency and reduce photorespiration. Studies have shown that some high photosynthetic plants, such as certain species of *Populus* and *Eucalyptus*, have evolved variations in RuBisCO structure that favor $CO_2$ fixation over oxygenation, thereby enhancing carbon sequestration potential. Additionally, genetic engineering approaches have been employed to optimize RuBisCO function in high-biomass plants, such as tobacco (*Nicotiana tabacum*), to serve as model organisms for $CO_2$ capture improvement (14). Several promising strategies developed since 2015 include the introduction of synthetic or modified RuBisCO enzymes, identified through comparative genomics of highly efficient photosynthetic organisms such as cyanobacteria and certain algae. By incorporating these optimized RuBisCO variants into terrestrial plants, researchers aim to increase photosynthetic efficiency and ultimately enhance carbon capture (15). Moreover, advances in CRISPR-Cas9 technology have enabled precise editing of RuBisCO genes to favor carboxylation. This approach holds potential to significantly improve $CO_2$ fixation rates, particularly in high photosynthetic plants with large biomass production. For example, in a study by South et al. [18], gene editing in *Nicotiana* resulted in modified RuBisCO enzymes with decreased oxygenation activity, leading to higher $CO_2$ sequestration and plant growth under controlled conditions.

**RuBisCO in C4 and CAM Plants**

While RuBisCO is present in all plants, its role varies depending on the photosynthetic pathway. In C4 plants, such as maize and sorghum, a spatial separation of $CO_2$ fixation and the Calvin cycle allows RuBisCO to operate in a high-$CO_2$ environment, thus reducing photorespiration and enhancing carbon fixation. CAM (Crassulacean Acid Metabolism) plants, which fix $CO_2$ at night, also exhibit improved RuBisCO efficiency by minimizing oxygen competition. Leveraging the mechanisms of RuBisCO in C4 and CAM plants could offer promising avenues for $CO_2$ sequestration in regions with extreme temperatures or low water availability (19). These advances demonstrate how RuBisCO plays a critical role in improving $CO_2$ sequestration efficiency, particularly in high photosynthetic plants. With continued research, optimizing RuBisCO could significantly contribute to phytoremediation-based $CO_2$ sequestration efforts.

## Plant Species for $CO_2$ Sequestration

Several plant species have been identified for their potential in effective $CO_2$ sequestration through the process of phytoremediation. These species are typically selected based on criteria such as high photosynthetic rates, rapid growth, and the ability to adapt to a range of environmental conditions. Plant selection for $CO_2$ sequestration must also account for additional factors such as biomass production, soil quality improvement, and long-term carbon storage.

### Trees and Woody Plants

#### *Poplar* (*Populus* spp.)

Poplar trees, including hybrids such as *Populus deltoides × Populus nigra*, have been widely studied for their $CO_2$ sequestration capabilities. Poplars are fast-growing, high-biomass species that exhibit both high photosynthetic efficiency and the ability to sequester large amounts of carbon. Their extensive root systems and significant aboveground biomass contribute to carbon storage over long periods. Moreover, poplar species are ideal for afforestation and reforestation projects, where long-term carbon storage is critical. Recent studies have highlighted the potential of poplar trees for large-scale carbon sequestration. For example, Gielen et al (20) emphasize the suitability of poplars for bioenergy and carbon farming initiatives, while Harris et al. (21) demonstrate that hybrid poplar plantations significantly enhance soil carbon storage alongside aboveground biomass accumulation. These features make poplars a strong candidate for mitigating atmospheric $CO_2$ levels through carbon sequestration.

#### *Eucalyptus* (*Eucalyptus* spp.)

*Eucalyptus* species, known for their rapid growth rates and high carbon uptake, are considered effective candidates for $CO_2$ sequestration, particularly in temperate and tropical climates. *Eucalyptus* trees have a short turnover rate of biomass and are capable of efficiently capturing carbon through both aboveground and belowground growth. Additionally, *eucalyptus* is well-suited to marginal and degraded soils, where it can contribute to both soil restoration and carbon sequestration. Sims et al. (22) highlight the potential of eucalyptus plantations in tropical regions for both bioenergy production and carbon sequestration. Their study underscores the need for sustainable management practices to maximize the environmental benefits of eucalyptus, as improper management can lead to negative impacts on local biodiversity. *Eucalyptus* thus remains a promising species, provided that its cultivation is carefully managed to ensure environmental sustainability.

#### *Willow* (*Salix* spp.)

*Willows* are another group of fast-growing woody species that play an important role in carbon sequestration. Known for their ability to thrive in riparian and wetland environments, willows sequester carbon in both their biomass and in the surrounding soil, particularly through their extensive root systems. In addition to their carbon storage capabilities, willows have been widely used in bioenergy and phytoremediation projects due to their high growth rates and biomass yields. Research by Hughes et al. (22) shows that willow plantations not only increase soil carbon storage but also improve ecosystem services such as water quality regulation and soil erosion control. Furthermore, willow species have shown great promise in agroforestry systems where carbon sequestration can be coupled with biomass production for energy.

### Grasses and Herbaceous Plants

#### Switchgrass (*Panicum virgatum*)

Switchgrass, a perennial C4 grass, is another promising species for $CO_2$ sequestration. This grass is known for its high photosynthetic efficiency and rapid growth, making it ideal for both carbon sequestration and bioenergy production. The deep and extensive root system of switchgrass contributes to soil carbon storage, which makes it particularly beneficial for enhancing soil organic matter in degraded or marginal lands. Its perennial nature also reduces the need for soil disturbance, which further helps to lock carbon in the soil. Sanchez et al. (23) emphasize the role of switchgrass in improving soil organic carbon content, with potential benefits for soil structure and water retention. Moreover, Zhao et al. (3) confirmed that switchgrass is a suitable candidate for carbon farming systems, where its high biomass yield and carbon fixation potential make it a valuable tool for climate change mitigation.

#### Miscanthus (*Miscanthus* x *giganteus*)

*Miscanthus*, a C4 grass species with a rapid growth rate, has been recognized for its significant biomass production and potential for carbon sequestration. *Miscanthus* can store carbon both in its aboveground biomass and in the soil, where its deep root system helps stabilize organic carbon. This species is particularly effective in temperate climates, where its high photosynthetic efficiency enables substantial carbon capture. *Miscanthus* also requires minimal fertilizer input and can grow on marginal lands, which further enhances its appeal as a sustainable option for $CO_2$ sequestration. Clifton-Brown et al. (24) report that *miscanthus* has one of the highest rates of carbon capture among bioenergy crops, with potential benefits for soil conservation and erosion control. Liu et al. (25) further demonstrate that *miscanthus* plantations contribute to long-term soil carbon storage while providing a renewable biomass source for bioenergy, making it a strong candidate for integrated carbon sequestration and energy production systems.

**Wetland Plants**

**Cattails (*Typha* spp.) and Reeds (*Phragmites* spp.)**

Wetland plants such as cattails (*Typha spp.*) and reeds (*Phragmites spp.*) are critical components of $CO_2$ sequestration strategies, particularly in wetland ecosystems. Wetlands are known to be highly effective carbon sinks due to their waterlogged conditions, which slow down the decomposition of organic material and allow carbon to be stored in the soil for extended periods. Cattails and reeds grow in these waterlogged environments, where they sequester carbon in both their biomass and the surrounding soil. These plants can play a significant role in carbon capture, particularly in coastal, riparian, and degraded wetland areas. Mitchell et al. (26) demonstrate that wetland plants significantly enhance carbon sequestration by increasing soil organic carbon levels, with particularly strong effects in coastal zones where wetlands are vulnerable to climate change. Similarly, Foley et al. (27) highlight the role of reeds in restoring disturbed wetlands and improving carbon storage in sediment, which contributes to both ecological restoration and long-term $CO_2$ sequestration.

## DISCUSSION

The potential of phytoremediation using high-photosynthetic plants for $CO_2$ sequestration represents a promising strategy for addressing global climate change. As atmospheric $CO_2$ levels continue to rise, driven by human activities such as industrial emissions, deforestation, and agriculture (17), the need for large-scale, cost-effective carbon capture methods has never been more urgent. While conventional carbon capture and storage (CCS) technologies are primarily focused on industrial emissions, biological carbon sequestration, through processes like phytoremediation, offers a natural and sustainable solution to removing $CO_2$ from the atmosphere. This discussion explores the key mechanisms involved in phytoremediation, the types of plants that show the greatest potential for CO2 sequestration, and the challenges and opportunities for scaling this technique in the fight against climate change.

## CONCLUSION

Phytoremediation using high photosynthetic plants offers a promising and sustainable approach to $CO_2$ sequestration. By leveraging the natural processes of photosynthesis, plants can capture and store atmospheric carbon in biomass and soils. While challenges remain in scaling this technique for large-scale $CO_2$ mitigation, advances in plant selection, genetic engineering, and land management practices hold significant promise for optimizing phytoremediation strategies. Integrating this approach into broader climate change mitigation efforts could contribute substantially to reducing atmospheric $CO_2$ levels and mitigating global warming.

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