Carbon Credit: Harnessing Green Solutions for Climate Mitigation

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Climate change is a serious global challenge with rising greenhouse gas emissions driving the need for effective carbon sequestration strategies. Carbon sequestration plants, such as fast-growing tree species, bioenergy plants, agroforestry systems, and blue carbon ecosystems, play a critical role in capturing and storing atmospheric carbon dioxide. Despite increasing interest, there is a lack of integrated reviews that connect plant-based sequestration mechanisms with emerging technologies and policy instruments such as carbon credits. This review explores the mechanisms of carbon sequestration in plants, emphasizing the contributions through aboveground and belowground biomass accumulation, soil carbon retention, and microbial interactions. Key plant species, including *Eucalyptus*, *Paulownia*, bamboo, and mangroves, have demonstrated high sequestration potential and are discussed. This article aims to synthesize current knowledge while identifying opportunities for enhancing carbon sequestration through biotechnology and policy. This review also highlights emerging biotechnological advancements, such as genetic modifications, to improve carbon uptake efficiency and growing potential of blue carbon ecosystems. Emerging digital tools such as AI-based monitoring and blockchain supported carbon credit tracking are discussed as complementary systems to improve data transparency, verification and trust in carbon markets. By aligning scientific innovation with policy and social engagement, carbon credit can serve as a key element for climate mitigation strategies.

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INTRODUCTION

Climate change is one of the world's biggest issues that is driven primarily by the accumulation of high amounts of greenhouse gases in the atmosphere, leading to rising global temperature and sea water levels, changes in weather patterns, and environmental degradation (Nunes 2023). The increment of carbon dioxide (CO_2) levels in the atmosphere is mainly caused by human activities, particularly deforestation, industrial emissions, and burning of fossil fuels (Petrov *et al.* 2023). Climate change directly threatens biodiversity, human livelihood, and food security. Effective strategy for climate mitigation including carbon sequestration, which is the process of capturing and storing atmospheric CO_2 by plants, is being explored as a sustainable and natural way to reduce CO_2 (Anwar *et al.* 2018).

Carbon credit is a concept that has been introduced to incentivize carbon sequestration and reduce emissions as a part of global climate policies (van der Gaast *et al.* 2018). It also promotes sustainable land management practices that can enhance biodiversity and ecosystem services (Anderson *et al.* 2017). They are integral to various climate mitigation strategies, including REDD+ (Reducing Emissions from Deforestation and Forest Degradation), which incentivizes countries to reduce emissions from deforestation and forest degradation by providing financial rewards for verified reductions in emissions (West *et al.* 2020). Carbon credits represent a tradable permit that allows an entity to emit a specific amount of CO_2 with the requirement that emissions are offset *via* carbon sequestration projects (Gupta 2024). This system enables countries and industries to neutralize the carbon footprint by investing in eco-friendly projects such as reforestation, afforestation, and nature conservation. Currently the carbon market is expanding across the globe, and the role of high-carbon sequestering plants is being recognized for the ability to provide long-term solutions for carbon storage (Fan *et al.* 2022). Malaysia's carbon credit market is still in its early stages, with efforts centered on establishing a well-structured trading platform through the Bursa Carbon Exchange (BCX). Initiated by Bursa Malaysia, BCX functions as a voluntary carbon market (VCM), allowing businesses to trade carbon credits to offset their greenhouse gas (GHG) emissions.

Carbon sequestration by plants is conducted through the process of photosynthesis in which plants absorb CO_2, release oxygen, and convert into biomass (Prasad *et al.* 2021). The CO_2 absorbed by plants is stored in plant tissues, roots, and soils, which significantly can reduce overall CO_2 concentration in the atmosphere (Basile-Doelsch *et al.* 2020). Forests, agroforestry systems, aquatic plants, and mangroves have been found to demonstrate high potential in capturing and storing carbon. Furthermore, perennial plants and deep-rooted species contribute to enhancement of soil organic carbon content and long-term carbon-retention (Peixoto *et al.* 2022). Recent studies have highlighted that a substantial portion of sequestered carbon exists in the form of stable soil organic matter, such as humic substances, which can persist for centuries and significantly enhance belowground carbon storage (Basile-Doelsch *et al.* 2020; Garcia *et al.* 2022).

Carbon credits are market-based instruments that represent the removal or reduction of one metric ton of CO_2 or its equivalent in other greenhouse gases (Awazi *et al*. 2025). Carbon credits are designed to incentive efforts to reduce emissions or enhance carbon sequestration by assigning a financial value to each ton of CO_2 mitigated (Salma *et al.* 2024). Entities such as companies, governments, or individuals can purchase carbon credits to offset their own emissions, thereby supporting climate mitigation projects like reforestation, renewable energy, and soil carbon enhancement (Senadheera *et al.* 2019). These credits can be traded in voluntary or compliance carbon markets, depending on regulatory frameworks. By placing a tangible economic value on carbon reduction, the carbon credit system aims to mobilize investment into environmental sustainability (Michaelowa *et al.* 2019).

Today, carbon credit has gained interest to overcome climate change, and carbon sequestration projects, such as reforestation and afforestation, have been promoted in many countries. Despite the popularity of carbon credit projects, several issues including sustainability, permanence, and economic viability have raised concerns (Hou *et al.* 2019; Grim *et al.* 2020; Cho *et al.* 2025). Moreover, the competition for land between carbon credit plantations and agricultural land causes ethical and practical concerns (Regan *et al.*

2020). According to Pan *et al*. (2022), the methodologies for measuring the amount of carbon sequestered in carbon offset projects are still lacking standardization, making it hard to ensure transparency and accountability. Hence, to consider carbon credit projects as a reliable strategy for climate mitigation, these issues need to be addressed.

The aim of this review article is to explore the importance of carbon credit in combating climate change by understanding the mechanisms of carbon sequestration, finding the suitable plant species for carbon credit plantations, and the challenges associated with carbon credit programs. The insight from this review article will be able to provide a deep understanding of the potential of the carbon credit program as a natural way to reduce carbon emissions.

CLASSIFICATION OF CARBON SEQUESTRATION PLANTS

Carbon sequestration plants refer to plant species that play a significant role in climate change mitigation by absorbing and storing CO_2 in soil and biomass (Elbasiouny *et al.* 2022). The growing interest in identifying and utilizing plant species with high sequestration potential is due to increasing recognition of carbon credit projects in global climate policies (Terrer *et al.* 2021). High sequestration plant species are integral to carbon offset projects to reduce carbon emissions, where organizations and governments invest in reforestation, afforestation, and sustainable agricultural practices. The efficiency of the plant to absorb CO_2 depends on several factors including growth rate, accumulation of biomass, root system, and ability to enhance carbon storage. In addition to carbon sequestration, plants contribute to conservation of biodiversity, stabilize soil, and improve microclimates (Jansson *et al.* 2021).

Carbon sequestration plants can be divided into forestry species, agroforestry plants, bioenergy crops, and aquatic vegetation. Each category has distinct applications and characteristics in carbon sequestration initiatives. Forest species are the backbone of many carbon credit programs as the trees can store carbon in woody biomass for a long period (Favero *et al.* 2020). Forests serve as the largest terrestrial carbon sink as forest trees are capable of absorbing and storing significant amounts of carbon throughout the tree lifespan. Studies have shown that forest ecosystems can sequester substantial amounts of carbon, with some estimates suggesting that they account for approximately 68 to 71% of carbon sequestration services globally (Lama *et al.* 2024). Forests are the critical component of global carbon sequestration strategies due to the ability of forests to act as long-term carbon reservoirs (Funk *et al.* 2019). In reforestation and afforestation projects, fast-growing species, such as *Eucalyptus*, *Paulownia*, and bamboo, are widely planted due to rapid accumulation of biomass and capability to absorb a high amount of CO_2 (Weber *et al.* 2019; Behera *et al.* 2020; Li *et al.* 2021a; Ghazzawy *et al.* 2024). The selection of tree species for afforestation and reforestation projects is crucial, as different species exhibit varying capacities for carbon storage (Miripanah *et al.* 2019).

Agroforestry is the integration of trees, perennial crops, and shrubs into agricultural systems that offers dual benefit by producing food with environmental sustainability (Raj *et al.* 2019). This approach could enhance carbon sequestration by improving soil organic carbon content and increment of biomass storage (Ghale *et al.* 2022). This practice not only increases biomass carbon storage but also improves soil health and biodiversity (Zheng *et al.* 2023). Moreover, other types of agroforestry techniques that can maximize carbon sequestration are alley cropping (crops are planted between wide rows of trees) and silvopasture systems (trees and grazing livestock coexist in the same area) (Jose and Dollinger 2019; Varsha *et al.* 2019). Agroforestry has advantages compared to conventional agriculture systems as agroforestry systems reduce greenhouse gas emissions associated with intensive farming practices, retains more organic matter in soil, and reduces degradation of soil (Gross *et al.* 2022). The presence of trees in agricultural systems can improve microclimates, leading to increased crop yields and further carbon sequestration potential (Flude *et al.* 2022). In addition, soil fertility could be enhanced by covering the soil with leguminous trees, such as *Gliricidia*, *Leucaena*, and fruit-bearing trees, will contribute to long-term carbon storage while providing economic benefits to farmers (Alamu *et al.* 2023). The interaction between trees and crops creates a synergistic effect that maximizes carbon capture while providing economic benefits to farmers.

Bioenergy crops are grown for carbon sequestration, biomass production, and biofuel generation. Bioenergy crops also act as alternative sources to fossil fuels (Wu *et al.* 2018; Babin *et al.* 2021). The most popular bioenergy crops grown are *Jatropha*, switchgrass, and miscanthus that have rapid growth rate and high photosynthesis efficiency, which allow substantial carbon uptake in a short time (Clifton-Brown *et al.* 2019; Moore *et al.* 2020; Cezario *et al.* 2023). Bioenergy crops contribute significantly to dynamic carbon cycling as carbon absorbed by crops for photosynthesis is released to the atmosphere after burning as biofuel. The key difference between fossil fuels and biofuel is the fossil fuels adding carbon to the atmosphere as the process releases the carbons that have been trapped for a long-time during combustion (Wang and Song 2020). In contrast, bioenergy maintains work on a short-term carbon cycle in which the crops absorb CO_2 during photosynthesis and release the same amount of carbon after combustion (Maschler *et al.* 2022). The efficiency of bioenergy crops to absorb carbon and sustainable land-use practices are the important elements in enhancing carbon sequestration potential and mitigating climate change.

Aquatic vegetations are essential carbon sinks in blue carbon sequestration (Himes-Cornell *et al.* 2018; Pham *et al.* 2019). There are several important aquatic vegetations, such as mangroves, salt marshes, and seagrass meadows, that efficiently store carbon in submerged sediments and are unsusceptible to disturbances such as wildfires and deforestation (Huxham *et al.* 2018; Drexler *et al.* 2021; Bao *et al.* 2022). Mangrove ecosystems are potent to sequester carbon, up to four times per unit area compared to terrestrial forests, which make them one of the most effective carbon sinks in the ecosystem (Hamilton and Friess 2018). In addition to carbon sequestration, strong and deep mangrove roots act as a coastal region's stabilizer, prevent soil erosion, and protect against storm surges (Karimi *et al.* 2022). Meanwhile, the accumulation of peat in seagrasses and wetland areas contribute to the carbon sequestration process and results in significant long-term carbon storage (Hao *et al.* 2024). Another valuable blue carbon storage is seagrass meadows which are a flowering plant that is powerful carbon sinks, absorbing and storing CO_2 in the biomass and sediments (Lin *et al.* 2023). The conservation and restoration of aquatic vegetation are critical for enhancing carbon sequestration and providing additional ecosystem services, such as coastal protection and habitat for marine life (Hagger *et al.* 2022).

MECHANISM OF CARBON SEQUESTRATION IN PLANTS

The plant is an important organism that plays a vital role in reducing CO_2 in the atmosphere by absorbing the CO_2 and storing it in plant biomass and soil. The carbon sequestration process occurs through multiple interconnected mechanisms and it is essential to understand the mechanisms to maximize the potential of vegetation in climate mitigation strategies.

One of the key mechanisms of carbon sequestration by plants is through accumulation of biomass that can be divided into aboveground and belowground biomass storage (Kumar *et al.* 2021). The aboveground biomass storage occurs in various plant organs, such as leaves, branches, stems, and trunks, where carbon can be stored for a long time (Eslamdoust and Sohrabi 2018). The largest aboveground carbon reservoirs on earth are forests, particularly tropical and temperate forests (Sun and Liu 2020). The fast-growing forest species, including *Eucalyptus* and *Paulownia*, are highly capable in absorbing CO_2 rapidly and these species are commonly used in afforestation projects (Cravino and Brazeiro 2021; Ghazzawy *et al.* 2024). Meanwhile, trees, such as redwood, mahogany, and teak, are capable of accumulating high amounts of carbon (Racelis *et al.* 2019; Watt and Kemberley 2022). Additionally, perennial crops like bamboo have fast-growth patterns and high annual carbon intake that has mainly contributed to biomass carbon storage (Devi and Singh 2024).

An equally important role in carbon sequestration is belowground biomass storage that is mainly conducted by the plant roots system. The carbons from the atmosphere are absorbed from the leaves, transported to the root systems and stored in the soil (Pausch and Kuzyakov 2018). The mangroves, leguminous trees, and prairie grasses are the examples of deep-rooted species that contribute to long-term sequestration by stabilizing carbon in subsoil layers (Richards *et al.* 2024). Grassland ecosystems are very effective for carbon retention, which can store up to 90% of the belowground biomass (Bai and Cotrufo 2022). Unlike forests that can lose carbon through deforestation or harvesting, grasslands retain the soil carbon belowground (Fossum *et al.* 2022). Meanwhile, extensive root systems of mangroves and wetland plants can trap organic matters in submerged sediments, preventing carbon loss and rapid decomposition (Balieiro *et al.* 2018).

In addition to aboveground and belowground biomass storage, soil is the largest terrestrial carbon reservoir that can hold more carbon than vegetation and atmosphere (Zhou *et al.* 2023). The decomposition of plant residues, such as fallen leaves, woody debris, and decaying roots, will convert into humus, which is a stable residue that can persist in soils for centuries and enrich the soil with organic carbon (Samenov *et al.* 2019). The exudation of sugars and organic acids from the roots could promote microbial activity and soil aggregates, which directly enhance soil carbon storage (Ma *et al.* 2022). The accumulation of soil organic carbon is enhanced by increased microbial growth and biomass turnover, emphasizing the complex interplay between plant and microbial processes in the carbon cycle (Prommer *et al.* 2020). Effective carbon sequestration relies on the health of soil microbial communities, as their activity facilitates the decomposition of organic matter, releasing vital nutrients that promote plant growth and further carbon uptake (Prommer *et al.* 2020). One of the factors that influence soil carbon accumulation is land management practices. Grassland and forests store more aboveground and belowground carbon due to agroforestry activity and cover cropping that enhance soil carbon retention (Meena *et al.* 2019; Bai and Cotrufo 2022). In contrast, unsustainable land practices, such as deforestation and excessive tillage, lead to acceleration of carbon loss and contribute to greenhouse gas emissions (Hu *et al.* 2021; Xing and Wang 2024).

The presence of mycorrhizal fungi and soil microbes are important in facilitating long-term carbon storage and stabilizing organic matter (Jeewani *et al.* 2021; Wu *et al.* 2024). The mycorrhizal fungi form a symbiotic interaction with the plant roots by transferring carbon into the soil and creating underground networks that will enhance the carbon sequestration capacity (Basiru and Hijri 2024). Arbuscular mycorrhizal fungi help to transform carbon into soil aggregates are commonly found in crops and grasses (Agnihotri *et al.* 2022). Meanwhile, ectomycorrhizal fungi contribute to long-term carbon storage by slowing the decomposition of organic matter and are mainly found in trees such as oaks and pines (Zak *et al.* 2019; Tunlid *et al.* 2022). The fungal mycelial network functions as an underground carbon highway that distributes carbon in the soil and improves soil structure (Touseef 2023). The efficiency of microbial carbon in the soil can be enhanced by the application of biochar and reduced tillage activity (Liu *et al.* 2020). Additionally, interaction between plant roots, mycorrhizal, and microbes enhances soil health and long-term carbon storage, which improves the self-sustaining carbon sequestration cycle (Bhattacharyya *et al.* 2022).

CONTRADICTIONS AND CONSENSUS IN CARBON SEQUESTRATION RESEARCH

Understanding the varied outcomes and interpretations from different studies on carbon sequestration is vital. The purpose of this comparative analysis is to find the best strategies and explain why different studies have come to different conclusions. This will improve the scientific basis for policy and practice (Hübner *et al.* 2021). Variations in study designs, geographical focus, species studied, and methodologies significantly impact findings. For instance, Basile-Doelsch *et al*. (2020) focused on keeping soil carbon in temperate forests, while Gupta *et al*. (2017) looked at tropical agroforestry systems. Both groups talk about different ways and rates of carbon sequestration. These differences underscore the need for regionally tailored strategies (Gupta *et al.* 2017; Basile-Doelsch *et al.* 2020). The effectiveness of bioenergy crops in carbon sequestration illustrates a significant area of debate. Despite some discrepancies, there is a consensus regarding the carbon sequestration capabilities of certain fast-growing tree species. The carbon sequestration capacity of trees is influenced by their size and growth rates, leading to differing estimates of carbon storage potential (Channalli *et al.* 2022).

However, a common misconception in interpreting forest carbon data is the assumption that the total carbon stored in the forest directly equates to active carbon sequestration. In reality, processes such as decomposition and oxidation are constantly at play, returning carbon to the atmosphere (Raza *et al.* 2023). A critical question is whether forest management can establish a "new normal" with consistently higher biomass levels sustained over time. For example, intensive breeding programs in the southeastern United States have resulted in tall, mature pine forests that currently exceed the demand for timber (Hausle *et al.* 2023). While these forests represent a temporary carbon sink, their long-term role is uncertain. As the trees reach old age, the replantation of these trees could significantly alter the sequestration trajectory (Xu *et al.* 2024). This illustrates the importance of considering forest life cycles and long-term and land-use planning when evaluating sequestration potential (Deng *et al.* 2022a).

Moreover, sequestration through biomass alone may not result in permanent carbon storage (Dynarski *et al.* 2020). If plant material is not harvested and used in long lasting products such as bioplastics, timbers or construction materials or transformed into stable forms like biochar, the carbon will eventually return to the atmosphere through natural decomposition (Infurna *et al.* 2023; Mutjaba *et al.* 2023; Kumar *et al.* 2025). Therefore, for biomass-based carbon sequestration to be effective, strategies must be adopted to ensure that carbon is retained over the long term, either through soil incorporation, durable product development or energy substitution (Garcia *et al.* 2022; Tripathi *et al.* 2024). This has led to growing interest in circular bioeconomy models where biomass is utilized in ways that lock carbon while providing economic benefits.

Recent technological advancements are beginning to bridge gaps identified in earlier studies. Technologies, such as AI-driven monitoring and blockchain, for verifying carbon credits are proposed by Prawitasari (2024) and Adigun *et al*. (2024) as a means to enhance transparency and reliability in carbon accounting. These innovations are seen as pivotal in reconciling some of the methodological concerns previously highlighted (Prawitasari 2024; Adigun *et al.* 2024). The contradictions and consensus outlined herein underscore a clear need for continued research into the long-term ecological and socio-economic impacts of carbon sequestration. Future studies should particularly focus on biodiversity impacts, ecosystem health, and the socio-economic ramifications of carbon credit projects on local communities (Nunes 2023). The research on carbon sequestration reveals a complex landscape of contradictions and consensus. While there is agreement on the fundamental role of vegetation and effective land management practices in enhancing carbon storage, significant debates persist regarding the effectiveness of different ecosystems, the implications of leakage, variability in sequestration rates, and the challenges of modeling. Addressing these contradictions through further research and improved methodologies will be essential for developing effective carbon management strategies and policies.

IMPORTANCE OF CARBON SEQUESTRATION PLANTS IN CARBON CREDIT PROGRAMS

Carbon sequestration plants play a crucial role in carbon credit programs by providing a mechanism for businesses and individuals to offset their carbon emissions through the purchase of carbon credits generated from the carbon storage capabilities of these plants. Climate change is one of the biggest issues in the world caused by rapid urbanization and a high number of populations that contribute to high CO_2 emission in the atmosphere. In combating climate change, carbon credit serves as a crucial tool in climate change mitigation policies and international agreements between the countries (Nsabiyeze *et al.* 2024). The carbon credit program is a market-driven mechanism designed to assign a monetary value to carbon sequestration and emission to reduce CO_2 concentration in the atmosphere and reduce greenhouse gas emissions (Avwioroko 2023; Jia and Wen 2024). One carbon credit represents one metric ton of CO_2 that has been prevented or removed from entering the atmosphere (Woo *et al.* 2021). Carbon credit programs rely on carbon sequestering plant species that are generated through the project including reforestation, afforestation, agroforestry, and blue carbon ecosystem (Sapkota and White 2020; Di Sacco *et al.* 2021).

The effectiveness of these programs hinges on the ability of various plant species to sequester carbon, as evidenced by studies demonstrating that factors, such as biomass and growth characteristics, significantly influence carbon storage potential (Rindyasturi *et al.* 2018). Forest ecosystems earn carbon credits based on their ability to absorb carbon, which is influenced by how they are managed and their biomass productivity (Jia and He 2023; Joshi and Garkoti 2025). The concept additionality is important, meaning carbon storage must go beyond a set baseline to qualify for credits, encouraging sustainable land management (Randazzo *et al.* 2023). Planting a mix of species in afforestation and reforestation projects can further boost carbon storage and biodiversity, making them more valuable for carbon credits (Schuster *et al.* 2014).

In moving towards net-zero emissions, global frameworks, such as Kyoto Protocol, Paris Agreement, and Reducing Emissions from Deforestation and Forest Degradation (REDD+), play an important role in regulating and promoting the carbon credit program (Espejo *et al.* 2020). In the carbon credit program, several plant species with high carbon sequestration potential have been identified. Moreover, the carbon credit program will also encourage more involvement of private sector participation in investment of reforestation and afforestation projects (Cho *et al.* 2025). The inclusion of plants with carbon sequestration potential in the carbon credit program will enable the developing countries with vast forest areas to earn benefit economically (Di Sacco *et al.* 2021). The carbon credit programs create financial incentives for sustainable land management ensuring ecosystems remain protected while sequestered and reducing CO_2 concentration in the atmosphere (Evans 2018; Blanc *et al.* 2019). In addition to carbon sequestration, plants in carbon species programs also contribute to ecological and socio-economic benefits including enhancing biodiversity, improving soil fertility and soil retention (Zheng *et al.* 2024).

Furthermore, emerging research demonstrates that carbon credit participation is not only environmentally beneficial but also financially strategic. Companies engaging in carbon credit programs can enhance their corporate financial performance, particularly when such participation is embedded within a broader framework of Corporate Social Responsibility (CSR). For example, Martielli *et al.* (2025) conducted an in-depth empirical analysis on the interplay between carbon credits, CSR strategies, and corporate governance. The study revealed that carbon credits serve not only as a tool for environmental accountability but also as a financial asset that positively moderates the relationship between climate mitigation efforts and firm profitability. Specifically, firms with robust CSR frameworks and proactive governance structures were found to benefit more significantly from carbon credit participation, as these elements enhanced both market perception and operational efficiency.

Similarly, a study by Salvi *et al.* (2025) indicated that integrating carbon credits into corporate climate action plans can contribute to improving financial outcomes by aligning environmental objectives with value creation. Carbon credits were shown to enhance transparency in emissions reporting and promote compliance with international standards, which in turn builds corporate legitimacy and market credibility. Moreover, firms engaging in such programs exhibited greater adaptability and resilience to climate-related financial risks. In addition, Salvi *et al.* (2025) emphasized that carbon credit integration is most effective when supported by strategic planning and cross-sectoral collaboration, positioning firms not only as climate leaders but also position themselves as resilient and viable entities, capable of thriving amid shifting regulatory frameworks and growing market demands for sustainability.

Therefore, carbon sequestration plants form the biological backbone of the carbon credit economy, bridging environmental goals with financial incentives. When implemented effectively, carbon credit programs not only contribute to reduce atmospheric CO_2 levels but also stimulate green investment, promote policy innovation, and encourage corporate. Hence, the carbon credit program is not only beneficial in climate change mitigation but also in fostering environmental sustainability, economic development, and social equity (Hariram *et al.* 2023).

CARBON CREDIT MARKETS AND POLICIES

The global carbon credit market has evolved as a key mechanism to mitigate climate change by providing economic incentives for reducing greenhouse gas emissions (Aldy and Halem 2024). The concept of trading carbon credits emerged as part of international climate agreements, enabling countries and industries to meet emission reduction targets through market-based mechanisms (Verma 2023). The development of these markets is largely influenced by global agreements, such as the Kyoto Protocol, Paris Agreement, and REDD+, which establish regulatory frameworks for carbon trading and emissions reduction (Kim *et al.* 2020; Morita and Matsutomo 2023).

Global Carbon Credit Trading Mechanisms

The Kyoto Protocol was adopted on 11 December 1997 and enforced beginning 16 February 2005, which was the first international treaty to introduce carbon trading mechanisms (Wang *et al.* 2019). It established three market-based mechanisms: Emission Trading System (ETS), Clean Development Mechanism (CDM), and Joint Implementation (JI) (Deng *et al.* 2022b). The ETS, also known as cap-and-trade, allowed industrialized countries to trade excess emission allowances. The CDM enabled developing countries to earn carbon credits by implementing emission reduction projects such as reforestation, renewable energy, and energy efficiency. The JI allowed industrialized nations to invest in emission reduction projects in other developed countries in exchange for credits (Deng *et al.* 2022b; Xu and Zhang 2022). However, the Kyoto Protocol had a lack of participation from major emitters and difficulties in enforcing emission targets (Maamoun 2019).

The Paris Agreement, adopted on December 12, 2015, and enforced on November 4, 2016, introduced Nationally Determined Contributions (NDCs), which require countries to set their own climate targets. This agreement emphasizes voluntary cooperation and market mechanisms through Article 6 that allows countries to trade carbon credits internationally (Mehling *et al.* 2019; Asadnabizadeh and Moe 2024). It encourages both developed and developing countries to participate and to invest in natural solutions like reforestation and blue carbon ecosystems (Oliveira *et al.* 2019; Seddon 2022). REDD+, a UN-backed program, is designed to reduce carbon emissions from deforestation and forest degradation in developing countries. It provides monetary incentives for forest conservation and sustainable land use practices, thereby leveraging forests as carbon sinks and enhancing biodiversity conservation (Sauls 2020; Wainaina *et al.* 2021). Table 1 provides a summary of Kyoto Protocol, Paris Agreement, and REDD+ programs.

Table 1. Evolution of Carbon Credit Programs

	Kyoto Protocol (1997)	Paris Agreement (2015)	REDD+
Objective	• First legally binding international agreement to reduce greenhouse gas emissions • Assigned emission reduction targets to developed countries • Introduced market-based mechanisms to achieve emission reduction cost-effectively	• Replace the rigid Kyoto targets with a more inclusive, global climate action framework • Limit global warming to well below 2 °C, with an aspirational goal of 1.5 °C • Increase participation from all countries, including developing nations	• Address emissions from deforestation and land use changes (responsible for ~15% of global CO_2 emissions) • Provide financial incentives for forest conservation, sustainable management, and reforestation
Mechanisms introduced	**Clean Development Mechanism (CDM)** • Developed countries invest in emission reduction projects in developing nations • Earn Certificate Emission Reductions, which can be used to meet their reduction targets **Joint Implementation (JI)** • Developed nations finance emission reduction projects in other developed nations • Earn Emission Reduction Units **Emissions Trading (ET)** • Countries with surplus emission allowances can sell to countries exceeding their allowed emissions • This created regulated carbon markets such as the EU Emissions Trading System	**Key Market Mechanisms (Article 6)** **Nationally Determined Contributions (NDCs)** • Each country sets its own emission reduction goals (voluntary but reviewed every 5 years) • Allows for bottom-up flexibility but lacks strict enforcement mechanisms **Article 6.2 – International Carbon Market Cooperation** • Enables bilateral trading of carbon credits between countries • A country exceeding its reduction target can sell credits to another country struggling to meet its goals **Article 6.4 – New Global Carbon Market** • Introduces a centralized carbon trading system overseen by the UN. • Allows both public and private sectors to participate in emission reduction projects. • A replacement for the Clean Development Mechanism (CDM) under Kyoto.	**Phases of REDD+** **Readiness Phase** • Countries establish governance structures and carbon accounting frameworks • Example: Developing monitoring systems for tracking deforestation rates **Implementation Phase** • Pilot projects begin, and countries start testing REDD+ strategies • Performance-based funding mechanisms are introduced **Results-Based Payments** • Countries receive payments based on verified reductions in deforestation rates • Funds come from international donors, carbon markets, or private investors • Example: A country reducing deforestation gets paid per metric ton of CO_2 avoided.

		Voluntary Carbon Offsetting • Allows businesses and organizations to purchase carbon credits to offset their emissions	
Challenges	• Limited participation from developing nations • Verification complexity • Market imbalances due to some countries had excess carbon credits, leading to price drops	• Risk of double counting: Ensuring emission reductions are not claimed by multiple entities • Non-binding nature of NDCs: No strict penalties for missing targets. • Market uncertainties: Many rules (especially for Article 6) are still being finalized	• Monitoring difficulties: Requires satellite imaging and ground verification • Land tenure conflicts: Unclear land ownership can lead to disputes over carbon credit revenues • Ensuring permanence: Protecting forests long-term to avoid emissions rebounding
Outcomes	• Foundation for international carbon markets • Stimulated early investments in clean energy and efficient projects • However, loopholes and over-crediting issues reduced its long-term effectiveness	• Encouraged broader participation from both developed and developing nations • Introduced market-based flexibility, making carbon trading more accessible • Strengthened the role of corporations and voluntary markets in climate action	• Integrated forests into global carbon markets, making them valuable assets • Provided economic incentives for developing nations to preserve forests • Supported biodiversity conservation and sustainable development

Policy Implications and Economic Viability

The implementation of carbon credit programs varies significantly across different regions, influenced by local economic conditions, regulatory frameworks, and environmental priorities. The EU's Emissions Trading System (ETS) operates on a cap-and-trade principle. To optimize this system, the EU could consider tightening the cap progressively and expanding coverage to more sectors (Beck and Kruse-Andersen 2020). As for the United States, California's cap-and-trade program demonstrates the potential of state-level initiatives. Integrating these programs into a federal framework could standardize measures and enhance market liquidity (Lessmann and Kramer 2024). China's national carbon trading scheme focuses initially on the power generation sector. More stringent verification processes and enhanced transparency could optimize this system (Zhang *et al.* 2023). Many developing countries face challenges such as lack of funding and technical expertise. International cooperation and financial support are crucial to enhance the effectiveness of their programs (Zhao *et al.* 2022).

To improve the economic viability and effectiveness of carbon credit programs, it is essential to strengthen regulatory frameworks, enhance market stability, promote international collaboration, and incentivize innovation. These measures would support more robust, transparent, and accountable carbon markets, attracting stable investments and promoting sustainable development globally.

PLANTS USED FOR CARBON CREDIT PROGRAMS

The selection of suitable plant species is the key factor to determine the effectiveness of carbon credit programs. Selection of plant species with high growth rate, adaptability in various environments, disease resistance, and high carbon sequestration capacity are the main factors of choosing the suitable plant species for carbon credit plantations (Di Sacco *et al.* 2021). Among the plant species, *Eucalyptus*, bamboo, *Paulownia*, and mangroves have gained attention due to its capability to absorb high amounts of CO_2 and stand out as highly effective species for carbon credit programs such as reforestation, afforestation, and agroforestry projects (Cameron *et al.* 2019; Pan *et al.* 2023; Ghazzawy *et al.* 2024; Luo *et al.* 2024).

Eucalyptus: A High-Yield Carbon Sequestration Tree

Eucalyptus is a fast-growing tree belonging to the family Myrtaceae with over 700 species (Shala and Gururani 2021). *Eucalyptus* species is widely known for its rapid growth, high quality of timber, high production of biomass, and high capability to sequester CO_2 (Fig. 1) (Behera *et al.* 2020). *Eucalyptus* is native to Australia and currently has been cultivated worldwide particularly in tropical, subtropical, and temperate regions (Queiroz *et al.* 2020). *Eucalyptus* is one of the most frequently used trees in carbon credit plantations that are planted for commercial forest, degraded land restoration, and production of bioenergy production (Tesfaye *et al.* 2020; Morales *et al.* 2023). *Eucalyptus* is an excellent candidate for long-term carbon storage due to its rapid growth and high wood density (Fairman *et al.* 2022). Additionally, *Eucalyptus* has deep root systems that contribute to carbon storage as they facilitate organic matter accumulation and enhance microbial activities in the rhizosphere (Silva *et al.* 2020). Furthermore, *Eucalyptus* trees can be integrated into agroforestry systems as windbreaks, improve soil stability, and provide shade for intercropped agricultural crops (Kaur and Monga 2021; Dissanayaka *et al.* 2024). In addition to carbon sequestration potential, *Eucalyptus* plantations provide economic and ecological benefits, such as paper production, construction, and biofuel industries (Nogueira *et al.* 2021; Tomé *et al.* 2021).

Fig. 1. A eucalyptus plantation showing uniform tree spacing and canopy structure, which has an important role in timber production, carbon sequestration, and ecosystem restoration

Bamboo: The Fast-Growing Carbon Sink

Bamboo is a fast-growing perennial woody grass that belongs to the family Poaceae, subfamily Bambusoideae, which comprises over 120 genera and 1600 species (Ramasubramanian *et al.* 2023). Bamboo is predominantly found in tropical and subtropical regions with major bamboo forests in China and India (Tewari *et al.* 2019; Dlamini *et al.* 2022). Bamboo is a unique type of grass that is highly efficient for carbon sequestration due to its rapid growth rate, continuous regenerative ability, and high production of biomass (Fig. 2) (Adu-Poku *et al.* 2023; Pang *et al.* 2025). Moreover, bamboo plants have dense root systems that allow bamboo to store large amounts of CO_2, improve soil fertility, and prevent soil erosion (Emamyerdian *et al.* 2020). In carbon credit plantations, notable bamboo species from the genus *Phyllostachys* spp. and *Bambusa* spp. have been widely planted due its capability in absorbing high amounts of CO_2, high soil carbon storage, and extensive root networks (Pan *et al.* 2025). Beyond its role in carbon sequestration, bamboo byproducts have been extensively utilized for paper production, construction, furniture, textiles, and bioenergy, making bamboo a valuable resource for sustainable industries (Guan *et al.* 2019; Rocky and Thompson 2020; Xu *et al.* 2022; Liang *et al.* 2023). In addition, biochar produced from bamboo biomass is applied to enhance soil fertility, increase soil carbon storage capacity, further amplifying its role in mitigation of climate change (Odega *et al.* 2023; Chaturvedi *et al.* 2024). Bamboo also is widely planted in land restoration or agroforestry projects to improve the degraded soil (Singh *et al.* 2020).

Fig. 2. A bamboo plantation with mature clumps and scattered culms, illustrating its dense growth pattern and potential for sustainable biomass production

Paulownia: The Oxygen Tree with High Productivity of Biomass

Paulownia is a fast-growing deciduous tree genus belonging to the family Paulowniaceae. Native to China, *Paulownia* species are cultivated worldwide and renowned for their various ecological, economic, and environmental benefits (Costea *et al.* 2021; Sławińska *et al.* 2023). *Paulownia* is referred to as the "oxygen tree" that has exceptional photosynthetic efficiency and rapid growth rate (Adach *et al.* 2020). The *Paulownia* tree is capable of absorbing double the amount of CO_2 compared to other plant species, making it suitable for carbon credit plantations (Ghazzawy *et al.* 2024). The large size of leaves contributes to high absorption of CO_2 and efficient photosynthesis capacity (Ghazzawy *et al.* 2024). *Paulownia* tree also has lightweight yet strong wood that has been utilized in multiple industries, such as construction, furniture, and bioenergy (Rodríguez-Seoane *et al.* 2020; Barbu *et al.* 2023; Huber *et al.* 2023). In addition, *Paulownia* trees can grow in poor and degraded soil. This species is useful in plantings because it enhances soil fertility and soil organic matter content (Woźniak *et al.* 2022). The deep root systems of *Paulownia* trees contribute to nitrogen fixation and groundwater conservation (Ren *et al.* 2024). Paulownia trees are increasingly being promoted in carbon credit plantations for reforestation and afforestation projects (Ghazzawy *et al.* 2024).

Mangroves: Blue Carbon Ecosystems for Coastal Carbon Storage

Mangroves are a group of salt-tolerant trees and shrubs that grow in coastal intertidal zones, particularly in subtropical and tropical regions (Quadros *et al.* 2021). The most common mangrove genera including *Rhizophora* spp., *Avicennia* spp., and *Sonneratia* spp., which can be grown in saline and waterlogged environments and among the most powerful plants in blue carbon ecosystems (Ngernsaengsaruay *et al.* 2024; Twomey and Lovelock 2025). Blue carbon ecosystems are capable of sequestering four times more carbon per unit area than terrestrial forests (Hamilton and Friess 2018). Mangrove forests can store carbon in aboveground biomass and carbon also remains trapped for centuries in thick layers of sediment beneath (Sasmito *et al.* 2020; Murdiyarso *et al.* 2021). Mangrove forests have multiple roles in ecosystems, such as absorbing CO_2 and protecting coastal areas from erosion, surges, and storms (Fig. 3) (Kearney *et al.* 2019; Temmerman *et al.* 2023). The anaerobic conditions in mangroves sediments slow down the process of organic matter decomposition that led to long-term carbon sequestration (Kida and Fujikate 2020). Currently, restoration and conservation of mangroves forests have become a key focus of carbon credit projects under blue carbon initiatives and REDD+ (Sidik *et al.* 2023).

Fig. 3. A mangrove forest with tidal waterways, showcasing the dense vegetation and intricate root systems that help prevent coastal erosion

LIMITATION OF CARBON CREDIT PLANTATIONS

As carbon credit plantations offer a promising solution for climate change mitigation, they also face several limitations that can affect the success of this program (Pan *et al.* 2022; Shrestha *et al.* 2022). It is important to address these limitations to ensure carbon credit plantations achieve the objectives in contributing to environmental and socio-economic benefits. One of the main challenges is land-use conflict with agricultural land (Froese and Schilli 2019). To carry out large-scale reforestation and afforestation projects for carbon credit, large land areas are needed, which can lead to conflict between land use for forest expansion and production of agriculture (van der Voorn *et al.* 2020; Li *et al.* 2021b). In many developing countries, especially in rural areas, land is mainly used for agriculture production for livestock grazing and subsistence farming and conversion of land to carbon credit plantation will threaten local economies and food security (Keenan *et al.* 2023).

Moreover, carbon leakage is another problem related to carbon credit plantations; Carbon leakage refers to the unintended displacement or release of carbon emissions outside of the designation carbon credit plantations area due to deforestation or shift in land use (Nielsen *et al.* 2021; Jakob 2021). In addition, carbon permanence, which refers to duration of sequestered carbon stored in biomass and soil is another major issue of carbon credit plantations (Regan *et al.* 2020). The stored carbon in the biomass and soil can be released into the atmosphere as forests and plantations are vulnerable to natural disasters such as drought and wildfires (Nunes *et al.* 2020; Psistaki *et al.* 2024). Furthermore, conversion of plantations into different land uses, abandoned or harvested, can cause the stored carbon to be partially or fully released into the atmosphere (Olorunfemi *et al.* 2022).

The carbon credit market can effectively function with the carbon sequestration in the plantations being measured, verified, and reported accurately. This process is complex and resource-intensive (Haya *et al.* 2020; Woo *et al.* 2021). It is hard to develop reliable methods for measurement of CO_2 sequestered as every plant species has variation of growth rates and CO_2 absorption potential (Nayak *et al.* 2019; Smith *et al.* 2020). The conventional monitoring methods, including biomass assessments and on-ground measurements, are time-consuming, labor intensive, and extensive fieldwork (Chave *et al.* 2019; Ma *et al.* 2024). Hence, introduction of current technologies, such as satellite imaging and remote sensing, have improved the scalability of carbon monitoring. However, quantification of underground carbon is still limited (Vaudour *et al.* 2022).

FUTURE PROSPECTS IN CARBON CREDIT PLANTATIONS

In moving towards revolutionizing carbon credit programs, carbon sequestration efficiency and monitoring accuracy could be achieved by implementing artificial intelligence, biotechnology, and remote sensing applications. Biotechnology *via* genetic application can be adapted for modifying the plant genetics to produce plants with higher growth rate, resilience, and carbon absorption potential (Cheng *et al.* 2019; Barati *et al.* 2021). In addition, advancement of synthetic biology field and clustered regularly interspaced short palindromic repeats (CRISPR) are extensively being explored to produce plants with higher adaptability to climate change and high carbon absorption capability (Massel *et al.* 2021; Zahed *et al.* 2021). Furthermore, advancement of remote sensing and artificial intelligence technologies has led to improvement of accuracy in the carbon sequestration monitoring process (Chen *et al.* 2019; Liu *et al.* 2021). In estimation of biomass and detection of deforestation trends, machine learning models, satellite imagery, light detection and ranging (LiDAR) scans, and drones are widely being used for accurate data collection (Abbas *et al.* 2020; de Almeida *et al.* 2025). Carbon credit integrity, such as carbon transactions transparency and preventing fraudulent claims, are further strengthened by using blockchain technology (Boumaiza and Maher 2024; Tsai 2025).

CONCLUSIONS

Carbon sequestration plants are vital for climate mitigation, sequestering CO_2, restoring ecosystems and supporting sustainable economies. Plant species, such as *Eucalyptus*, bamboo, *Paulownia,* and mangroves, contribute significantly through biomass accumulation and soil carbon storage. Meanwhile, agroforestry, bioenergy crops, and blue carbon ecosystems enhance sequestration efforts. However, challenges, such as land-use conflicts, carbon leakage, and verification difficulties hinder large-scale application. High costs and limited market access further restrict participation. This article contributes to the literature by offering an integrated classification of sequestration plant types across ecological systems, while bridging scientific, economic and policy considerations. Importantly, it emphasizes the need for converting plant biomass into long-lasting carbon pools such as lumber, biochar and soil organic matter. This moves beyond the conventional focus on biomass accumulation and highlights the necessity for permanence in carbon storage to meaningfully counteract fossil fuel emissions. In addition, this review also identifies a critical knowledge gap such as the lack of emphasis on biomass utilization pathways in carbon credit frameworks. It recommends that future strategies must incorporate ongoing biomass management programs that link sequestration with product-based carbon locking. Furthermore, it calls for stronger policies, advancement monitoring, and financial incentives to promote sustainable carbon credit projects. A holistic approach integrating scientific innovation, policy frameworks and market mechanisms are crucial. Strengthening verification, fostering public-private collaboration and expanding blue carbon markets will maximize the impact of carbon credit projects. Through prioritizing sustainability and equity, carbon credit plantations can be an effective climate action and a resilient future.

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