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REVIEW ARTICLE

# Carbon sequestration potential of eucalyptus-based agroforestry and cropping systems

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**Abstract**

Eucalyptus plantations and agroforestry systems have garnered significant interest due to their ability to capture carbon and mitigate climate change. This review assesses the carbon sequestration potential of eucalyptus-based systems, emphasizing their effectiveness in lowering atmospheric carbon dioxide ($CO_2$) levels. In India, eucalyptus plantations exhibit carbon sequestration rates between 9.62 and 11.4 Mg ha$^{-1}$ per year, with a total accumulation of up to 237.2 Mg C ha$^{-1}$ over their lifespan. Various factors, including plantation age, soil quality and management strategies, influence this potential. Older plantations have greater carbon storage capacity, making them vital for long-term mitigation efforts. In addition to monoculture plantations, agroforestry systems integrating eucalyptus, such as silvi-pastoral, agri-silvicultural and boundary plantations, provide a comprehensive approach to carbon sequestration. These systems not only enhance carbon accumulation in both biomass and soil but also offer economic and environmental advantages, such as improved soil health, biodiversity conservation and livelihood support for farmers. Short-rotation eucalyptus plantations and agroforestry models can capture up to 10 Mg C ha$^{-1}$ annually, contributing significantly to long-term carbon storage. Notably, eucalyptus species have also demonstrated potential for bio drainage in waterlogged areas due to their high transpiration capacity, though concerns regarding excessive water use have led to regulatory restrictions in certain Indian states. In regions facing land-use constraints, incorporating eucalyptus into agroforestry serves as a viable solution for sustainable carbon management. However, while eucalyptus plantations offer significant carbon sequestration benefits, their high water demand and potential groundwater depletion necessitate careful site selection, appropriate species choice and sustainable management to mitigate adverse effects. This review underscores the crucial role of eucalyptus plantations and agroforestry systems in global carbon sequestration initiatives. By increasing carbon storage in biomass and soil, these systems present an effective strategy for addressing climate change while delivering socio-economic and environmental benefits. Further research and the development of optimized management practices are needed to maximize their carbon sequestration potential while ensuring ecological sustainability.

**Keywords:** agroforestry systems; biochar; carbon sequestration; eucalyptus plantations; soil fertility

## Introduction

Eucalyptus (*Eucalyptus tereticornis*), commonly referred to as the forest red gum tree, safeda, or red iron tree, is among the most valuable hardwood timber species worldwide. It is primarily found in tropical and subtropical regions (1), though various species are also widely cultivated in temperate areas for shade or forestry purposes. This evergreen tree belongs to the Myrtaceae family and is the second most extensively planted hardwood species after pines, with eucalyptus plantations covering over 22 million hectares globally, of which approximately 13 million hectares are of industrial importance (2). Species such as *Eucalyptus camaldulensis* and *E. tereticornis* thrive in sandy loam to loam soils with a pH range of 6.0 to 7.5, in regions receiving 800 to 1000 mm of rainfall annually and at elevations up to 500 m above sea level. They are highly adaptable to diverse climatic and soil conditions, including warm to hot, sub-humid to humid environments and both fertile and degraded soils. Additionally, they can grow in saline or sodic soils, help manage excess water in waterlogged areas and are effective in restoring lands affected by soil erosion and low fertility.

A remarkable trait of eucalyptus, particularly *E. tereticornis*, is its utility as a biodrainage species, using high water uptake and deep rooting to control waterlogging and saline conditions. Physiologically, the species exhibits daily transpiration exceeding 30-56 L per tree and an annual average of 268 mm ha$^{-1}$ from 240 trees, surpassing mean annual rainfall in some semi-arid zones. Root systems can penetrate up to 2.8 m deep, reaching capillary fringe zones for efficient water absorption. In canal-irrigated, waterlogged areas of Haryana, strip plantations of clonal *E. tereticornis* lowered groundwater tables by 0.85 m in three years and improved wheat yields by 3.4 times in interspaces due to soil aeration, pH stabilization and better infiltration. This validates Eucalyptus' role as a bio-pump, offering a cost-effective and sustainable alternative to expensive sub-surface drainage systems (3). However, the same water-demanding nature that supports biodrainage can become problematic in fragile ecosystems. Unchecked proliferation in regions with declining groundwater levels has prompted bans or regulatory constraints in several Indian states. Therefore, site-specific planning, selection of suitable clones and integrated agroforestry approaches are essential to maximize carbon and hydrological benefits without compromising ecological stability. Approximately 700 species of eucalyptus are there, most of which are native to Australia. In India, more than 170 species, varieties and provenances have been tested (4). *E. tereticornis* originates from eastern Australia and southern New Guinea (5). *Eucalyptus globulus*, native to southeastern Australia, has spread and naturalized in various non-native regions, including other parts of Australia, Europe, Africa and the western United States (6). Across the country, eucalyptus plantations account for 20.2 % of the total plantation area (7), covering 2.5 lakh hectares nationally, with carbon sequestration rate ranging from 9.62 to 11.4 Mg ha$^{-1}$ (4).

Climate change, land degradation and desertification contribute significantly to the depletion of carbon in both soil and vegetation. The atmospheric $CO_2$ level has risen to 412 ppm, marking a 47 % increase since the pre-industrial era when it was approximately 280 ppm. Consequently, capturing atmospheric carbon has become a critical priority. Among fast-growing tree species, eucalyptus stands out for its rapid growth and high wood density, which make it particularly effective for carbon sequestration. Although eucalyptus trees, especially species like *E. pilularis*, exhibit strong apical dominance resulting in limited lateral branching and a narrower crown structure, this characteristic does not diminish their carbon sequestration potential. The vertical growth habit, characterized by concentrated foliage in the upper crown and reduced lower crown development, reflects a dominant central stem and contributes to efficient light interception and photosynthetic activity in the upper canopy layers (8). However, it is the substantial accumulation of woody biomass, primarily in the stem and roots, that accounts for the majority of carbon stored in eucalyptus plantations, rather than the extent of their foliage (9).

Research has shown that eucalyptus plantations can store considerable amounts of carbon, with estimates reaching up to 237.2 Mg C ha$^{-1}$ and a net sequestration rate of 12.7 Mg C ha$^{-1}$ yr$^{-1}$ (10). These values highlight the species' efficiency in carbon capture, which is largely independent of crown width or leaf area. However, sequestration potential varies based on species, soil quality, climate and management approaches. While research indicates that eucalyptus plantations can store substantial amounts of carbon, large-scale plantations must be assessed for potential environmental trade-offs. This study aims to review past research on the carbon sequestration potential of eucalyptus plantations and eucalyptus-based cropping systems, with the goal of synthesizing current knowledge, identifying knowledge gaps and guiding future research and sustainable land management practices to enhance climate change mitigation efforts.

## Factors affecting the carbon sequestration potential of eucalyptus

### Genetic factors

The carbon sequestration potential of eucalyptus is significantly influenced by genetic factors, as different species and hybrid clones exhibit varying growth patterns, biomass allocation strategies and environmental tolerances. (9, 11) indicated that different eucalyptus genotypes, including *E. gloni* (*E. nitens* × *E. globulus*), exhibited varying carbon allocation strategies between wood growth and leaf area expansion across seasons. This suggests that selecting appropriate genotypes can enhance growth in different planting environments. The introduction of genetically improved eucalyptus clones developed through breeding strategies such as clonal forestry, hybridization (e.g., *E. tereticornis* × *E. camaldulensis*) and marker-assisted selection can significantly boost productivity and enhance carbon sequestration capacity (12). For instance, hybrid clones of *Eucalyptus grandis* × *Eucalyptus urophylla* (e.g., GG100, I144, AEC1528) demonstrated markedly higher biomass and carbon accumulation than others under identical environmental conditions, confirming that genetic variation directly affects carbon stock accumulation through enhanced stem wood production (13). Similarly, studies have shown significant differences among eucalyptus clones (e.g., C-316, PE-7) in diameter, height and total carbon biomass, even under uniform effluent irrigation regimes, highlighting the genetic control of biomass production traits critical to carbon sequestration. Clonal forestry, especially when supported by rigorous breeding strategies such as hybridization and marker-assisted selection, can increase plantation productivity from 25-30 m$^3$ ha$^{-1}$year$^{-1}$ to 35-45 m$^3$ ha$^{-1}$year$^{-1}$, correlating directly with higher carbon storage (14). Furthermore, variations among eucalyptus species and clones influence their tolerance to salinity and waterlogging, impacting their biomass production and carbon sequestration efficiency (15). However, despite similar environments, studies in Sri Lanka showed no significant carbon stock differences between *E. grandis* and *Eucalyptus microcorys*, indicating that genetic expression may be masked under uniform silvicultural practices, emphasizing the importance of genotype-environment interaction in evaluating sequestration potential (16). Therefore, the deliberate selection and deployment of genetically superior eucalyptus clones is a pivotal strategy in maximizing carbon sequestration in plantation forestry.

### Nutrient availability and elevated $CO_2$

The carbon sequestration potential of *Eucalyptus* spp. is strongly influenced by both nutrient availabilities, particularly nitrogen (N) and phosphorus (P) and elevated atmospheric $CO_2$ concentrations. Under elevated $CO_2$ ($eCO_2$) conditions (up to 600 ppm), *E. globulus* showed enhanced growth and carbon content, especially when supplied with higher nitrogen levels. The maximum carbon concentration in plant tissues (52.37 ± 0.03 %) was recorded at 200 mg kg$^{-1}$ N under 600 ppm $CO_2$, reflecting a synergistic interaction. The response was attributed to improved photosynthesis, greater nitrogen uptake and increased biomass allocation to aboveground woody tissues (17). While these results are specific to *E. globulus*, it is important to distinguish them from findings on other species. For example, other studies (18-20) focused on different eucalyptus species, particularly *E. tereticornis* and on mature forest ecosystems. Though some physiological and ecological responses to *e*$CO_2$ and nutrient dynamics may be directionally similar, species-specific differences exist and should be acknowledged. Elevated $CO_2$ stimulates rhizosphere processes like increased root exudation and microbial activity which in turn accelerates nitrogen and phosphorus cycling. However, long-term productivity and carbon storage under *e*$CO_2$ are still constrained by nutrient limitations, especially phosphorus, in weathered soils. Deep soil layers under *e*$CO_2$ showed less decline in P availability, suggesting that deeper rooting and organic acid exudation may enhance nutrient acquisition (18). These insights come primarily from studies on *E. tereticornis* and may not directly extrapolate to all eucalyptus species. Although *e*$CO_2$ initially boosts N and P availability via microbial stimulation, these effects are not sustained long-term. Moreover, a "decoupling" of nutrient cycles was reported, meaning that essential elements like Ca, Mg and micronutrients no longer cycled in synchrony under *e*$CO_2$ conditions. This disrupted coordination may limit the efficiency of plant growth and ultimately carbon sequestration, despite increased $CO_2$ availability (19). Given that these results are derived from mature forest species such as *E. tereticornis*, their generalization to other species should be approached with caution. Elevated $CO_2$ (793 ppm) increased carbon accumulation in *E. tereticornis* foliage which manifested in higher C:N ratios, greater non-structural carbohydrates and increased phenolic compounds. However, under nutrient-deficient conditions, especially low nitrogen, these benefits were offset by reduced leaf quality and lower growth efficiency. Light intensity interacts with nutrient status and $CO_2$ levels, influencing carbon chemistry and biomass traits relevant to long-term sequestration (20).

**Age, rotation length, stand dimensions, spacing and density**

Carbon storage generally increases with tree age and size (diameter and height) (21, 22). Older eucalyptus plantations and larger trees tend to accumulate more biomass, leading to higher carbon sequestration potential. Greater stand density and older plantations result in increased biomass production and carbon storage (10, 23, 24). Total ecosystem carbon pools expand as eucalyptus plantations mature (25). However, higher tree densities and closer spacing promote biomass accumulation and carbon sequestration, however, as competition for resources intensifies, mortality rates may rise. Wider spacing can mitigate competition, enhancing overall tree growth (22, 26, 27). Plant biomass carbon in eucalyptus plantations increases with stand age, with tree biomass becoming the dominant carbon pool over time. However, soil organic carbon (SOC) initially increases after afforestation but then gradually declines with plantation age. The highest soil carbon storage was observed in younger stands (1-3 years old) and it decreased in older stands (4-8 years old) (25). Notably, older eucalyptus stands (>20 years) store substantially more carbon than younger stands (0-10 years and 10-20 years), primarily due to the cumulative biomass growth and structural development of mature trees, which significantly enhance above and below-ground carbon stocks (Table 1) (28). Extending rotation length can enhance carbon sequestration however, the mean annual increment of aboveground carbon may decline with longer rotations (16). As biomass accumulates over time, carbon sequestration potential rises (29, 30). However, intercropping eucalyptus with wheat becomes less effective as trees age due to increased competition (30). Higher stand density and basal area contribute to greater carbon storage (31). Additionally, large, mature trees, particularly in riparian areas with ample water availability, continue to accumulate significant biomass and sequester more carbon than smaller trees or those in denser stands (32). Optimizing rotation cycles (e.g., 12-15 years in subtropical regions) can maximize carbon sequestration in eucalyptus plantations. As stands age, the proportion of carbon stored in tree biomass increases, while SOC contribution may decline (33).

**Table 1.** Carbon stock and $CO_2$ sequestration potential of eucalyptus stands by age class (28)

| Age of eucalyptus stands | Carbon stock (Mg C $ha^{-1}$) | $CO_2$ sequestration (Mg $CO_2$ eq $ha^{-1}$) | Annual rate (Mg C $ha^{-1}$ $year^{-1}$) |
|---|---|---|---|
| 0-10 years | 39.66 | 200.38 | 4 |
| 10-20 years | 57.28 | 261.79 | 6 |
| >20 years | 85.46 | 397.87 | 9 |

**Biomass distribution and tree components**

The majority of total biomass and assimilated carbon in eucalyptus trees is stored in the stem or bole (~52-60 %), followed by the roots (~20-25 %), branches (~10-13 %) and leaves (~5-11 %) (24, 34), with woody structures such as the stem and roots serving as the primary carbon reservoirs due to their higher biomass and carbon storage capacity (9, 21). Eucalyptus plantations allocate a significant proportion of their biomass to aboveground woody components, leading to greater aboveground biomass carbon stocks compared to native forests (35).

**Litter**

Litter from eucalyptus plantations plays a crucial role in enriching surface soil carbon pools due to its recalcitrant compounds, with litter carbon input increasing as plantations mature (21, 22). Accumulation of litter on the forest floor over multiple rotations enhances forest floor carbon stocks (36). The high productivity of eucalyptus plantations results in greater carbon inputs to the soil through litterfall, thereby contributing to the long-term accumulation of SOC (35, 37).

**Environmental conditions**

Various environmental factors, including climate, rainfall, temperature, altitude and soil properties (such as depth and fertility), play a significant role in determining the growth and carbon storage capacity of eucalyptus plantations (10, 23, 38).

**Site quality**

Optimal site conditions, including fertile soil, adequate moisture and a favorable climate, enhance the growth and carbon sequestration potential of eucalyptus plantations. However, maintaining these conditions may require intensive management practices (9, 26). In contrast, nutrient-deficient soils at higher elevations can restrict productivity and carbon sequestration over successive rotations unless appropriate site improvement measures are implemented (16).

### Climate and seasonal variations

Eucalyptus plantations exhibited year-round carbon assimilation like Mediterranean forests, with higher carbon uptake during warmer months. However, stomatal closure due to summer water stress limited this uptake (39). Seasonal variations in temperature and water availability influenced carbon allocation, affecting the balance between wood growth and leaf area expansion in different eucalyptus genotypes (11).

### Drought and rainfall

During an extremely dry year, eucalyptus plantations acted as strong carbon sinks, though their carbon uptake capacity was lower than in wetter years. Extended periods of severe drought significantly reduced carbon sequestration over multiple years by decreasing leaf area, photosynthesis and water use efficiency. However, deep-rooted eucalyptus trees initially resisted moderate drought by tapping into soil water reserves (40). Water availability from rainfall, flooding and groundwater access positively affects growth rates and carbon sequestration in eucalyptus woodlands (32).

### Solar radiation and water vapor deficit

Monthly net ecosystem exchange (NEE) is the balance between $CO_2$ absorbed through photosynthesis and released via ecosystem respiration. NEE was primarily influenced by solar radiation and water vapor deficit. This highlights the relationship between carbon and water vapor exchanges, regulated by stomatal control in Mediterranean regions (39).

### Management practices

The seasonal pattern of carbon uptake shifted after tree felling, with increased uptake in summer. This change was attributed to the mature root system retained by the stumps and reduced aerial biomass, which improved water stress tolerance (41). Among different forest management approaches, conservation and protection forests tend to store more carbon than production forests (23). However, intensive management practices such as site preparation, burning residues and weed control can reduce SOC and understory vegetation carbon (UC) stocks over successive rotations (36). Sustainable management strategies including irrigation, fertilization and pruning can enhance biomass productivity and carbon sequestration (10). Additionally, practices like soil preparation, fertilization and intercultural operations can further improve growth, biomass accumulation and carbon sequestration potential (22, 26, 27). Intensively managed eucalyptus plantations, characterized by higher planting densities, shorter rotation cycles and cultural practices like fertilization and irrigation, can sequester greater amounts of carbon per hectare annually (42). Optimizing tree spacing, density and thinning practices can further maximize biomass growth and carbon uptake (29) (Fig. 1).

## Mechanism of carbon sequestration

Carbon sequestration, the process of capturing and storing atmospheric $CO_2$, is increasingly recognized as a critical strategy for mitigating climate change. Among various land-use strategies, eucalyptus-based cropping systems have garnered attention for their exceptional carbon storage potential, both above- and belowground. These systems integrate fast-growing eucalyptus species with agricultural crops, thereby enhancing carbon accumulation in biomass and soil.

### Rapid biomass accumulation and aboveground carbon storage

Eucalyptus trees are known for their rapid growth and high biomass yield, reaching harvest maturity in 10-12 years which is significantly faster than many softwoods which may require 40-75 years. This rapid growth enables eucalyptus plantations to sequester carbon 2.7-4.6 times more efficiently than commonly used softwoods, with estimates suggesting over 100 tons of carbon per hectare can be sequestered in just

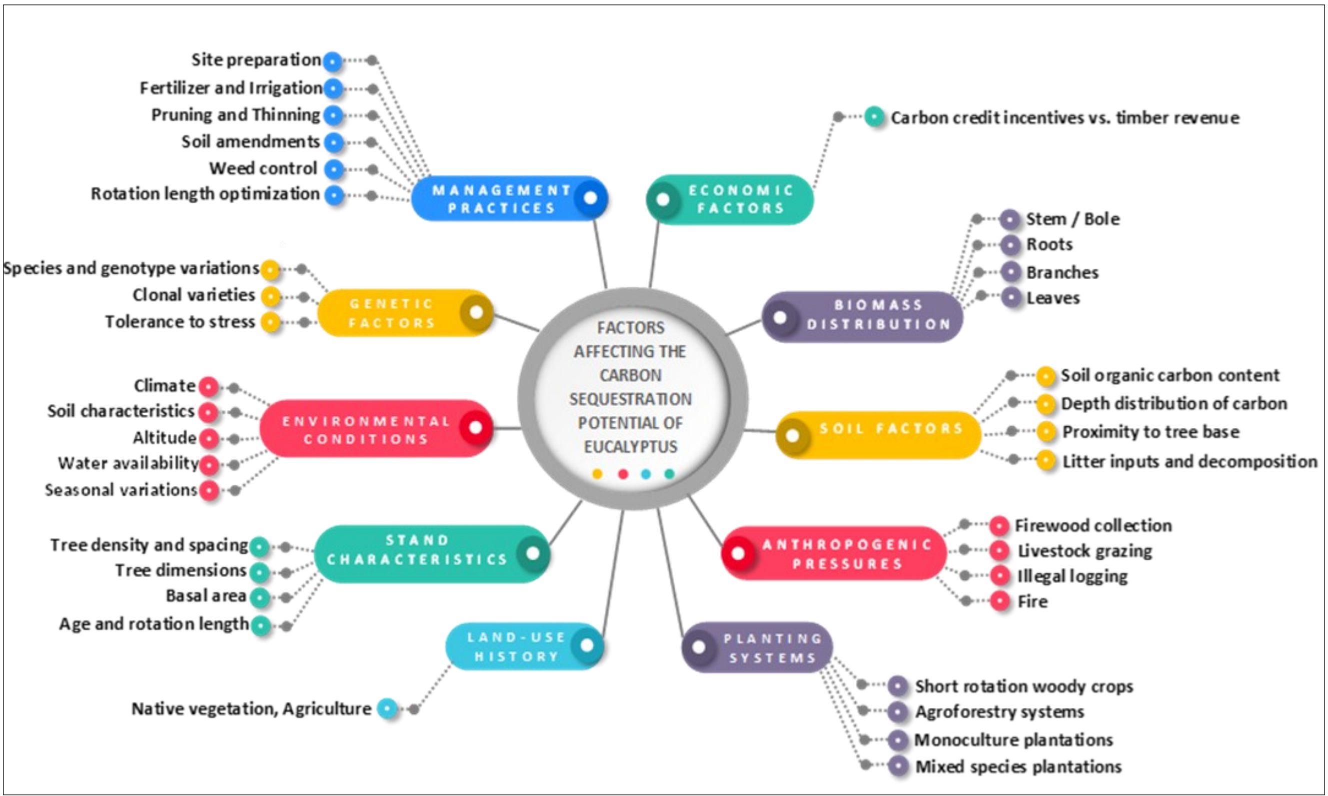


**Fig. 1.** Factors affecting the carbon sequestration potential of eucalyptus.

nine years (43). This aboveground carbon is stored in stems, branches and leaves and may remain sequestered for decades when used in durable wood products such as timber and furniture, delaying the release of carbon back into the atmosphere.

**Below-ground carbon sequestration through root sys*tems***

Equally important is the role of below-ground carbon storage. Eucalyptus trees possess deep and extensive root systems that contribute significantly to SOC pools. These roots deposit organic matter into the soil both during growth and after senescence through root turnover and decomposition. Studies indicate that approximately 40 % of total biomass carbon in eucalyptus systems can be stored below-ground (44). Root exudates further stimulate microbial activity, promoting soil aggregation and reducing carbon losses via microbial respiration (7, 45).

**Contribution of litterfall and organic residues**

Another critical mechanism in eucalyptus-based systems is litterfall, including shed leaves, bark and twigs, which contribute to soil organic matter (SOM). The decomposition of this organic material depends on microbial activity and climatic conditions, but typically results in gradual and sustained enrichment of the soil carbon pool (46). This litter decomposition leads to humus formation, a highly stable form of organic matter that aids in long-term carbon stabilization in soils.

**Soil microbial mediation of carbon dynamics**

Microbial communities play a pivotal role in regulating carbon dynamics within these systems. Through the decomposition of organic matter, microbes convert plant residues into stable forms of carbon that persist in soil. The ecological interactions between trees and soil microbes thus act synergistically to enhance carbon retention. Agroforestry systems that incorporate eucalyptus not only benefit from this microbial mediation but also from improved soil structure, increased moisture retention and reduced erosion. These effects collectively promote greater carbon inputs and minimize carbon losses (10).

**Eucalyptus biochar as a carbon sequestration strategy and reduction of greenhouse gas emissions**

Biochar enhances carbon sequestration through multiple synergistic mechanisms, offering a promising solution for sustainable agriculture and climate change mitigation. When applied to infertile sandy soils such as those in central and southern Florida, biochar improves soil structure, nutrient retention and water-holding capacity, thereby boosting the growth and biomass productivity of eucalyptus plantations. This results in greater above- and below ground carbon storage, while also helping to maintain or increase soil carbon stocks and counteracting the natural decline in SOC as plantations age. Moreover, biochar itself is a highly stable, carbon-rich byproduct of biomass pyrolysis that can persist in soils for hundreds to thousands of years, contributing significantly to long-term carbon sequestration. When combined with organically-based slow-release fertilizers, biochar further enhances nutrient availability and uptake, increasing plant growth and improving the efficiency of carbon capture (42). Additionally, eucalyptus-derived biochar enhances soil fertility and microbial function while reducing greenhouse gas emissions. It significantly improves soil enzymatic activity, such as β-glucosidase and urease, which are key indicators of carbon and nitrogen cycling (47). Application rates of 6.25 Mg $ha^{-1}$ in upland rice-sugarcane rotations have demonstrated sustained fertility improvements, making it especially beneficial for tropical agricultural systems. Furthermore, eucalyptus biochar reduces $CO_2$ and $N_2O$ emissions through physical and biological mechanisms. These include the adsorption of mineral nitrogen and shifts in microbial community structure, particularly the enhancement of $N_2O$-reducing organisms, thereby enhancing nitrogen use efficiency and decreasing the global warming potential of treated soils. Such dual benefits of carbon storage and emission reduction position eucalyptus biochar as a powerful tool for sustainable agriculture and climate change mitigation (48).

Thus eucalyptus-based cropping systems offer multiple carbon sequestration mechanisms, including rapid biomass accumulation, deep root contributions to SOC, microbial mediation, litterfall decomposition and biochar application. Together, these processes create resilient, multifunctional agroecosystems capable of enhancing soil health, increasing agricultural productivity and mitigating climate change. As global environmental pressures intensify, leveraging the carbon sequestration potential of eucalyptus systems will be essential for achieving sustainable land-use goals (Fig. 2).

## Carbon sequestration potential of eucalyptus plantations

**Impact of eucalyptus on soil carbon and management practices**

Eucalyptus plantations have demonstrated substantial carbon sequestration potential, with performance influenced by species, site conditions, management practices and stand age. However, their impact on soil carbon is complex and context dependent. In northeastern Argentina, the conversion of native grasslands to *E. grandis* plantations resulted in significant SOC losses, particularly in sandy and sandy-clay-loam soils. Soils with 75-95 % sand (sandy or loamy-sand) experienced a 23 % reduction in SOC, while soils with 50-60 % sand content (sandy-clay-loam or loam) showed even greater losses, up to 53 %. This decline was attributed to diminished litter input and rapid decomposition under short-rotation cycles that limited the time available for organic matter accumulation. Originally, grassland SOC levels in sandy soils were 21.5 Mg C $ha^{-1}$, which declined to 16.5 Mg C $ha^{-1}$ after three rotations. In sandy-clay-loam soils, SOC dropped sharply from 79.4 to 37.3 Mg C $ha^{-1}$, a loss of 42 Mg C $ha^{-1}$. Notably, the number of rotations had a compounding negative effect on SOC, whereas standage up to 12 years did not significantly enhance carbon storage due to the short duration between harvests. Among management strategies, coppice systems retained more SOC compared to those that were fully replanted after each rotation. Practices such as intensive site preparation, residue burning and short rotation periods were identified as key factors reducing the soil's carbon sequestration potential (49). While early plantation stages did not significantly enhance SOC due to inadequate litter accumulation, extending rotation length and integrating soil amendments like biochar improved carbon retention.


**Fig. 2.** Pathways of carbon sequestration in eucalyptus-based systems. Data sourced from [A, B] (25); [C] (88); [D] (89); [E] (90); [F] (4); [G, H] (73, 91, 92); [I] (55).

Short-rotation woody crops (SRWCs) of fast-growing eucalyptus cultivars such as *E. grandis* and its hybrid *E. grandis* × *E. urophylla* have sequestered up to 112.8 Mg C $ha^{-1}$ in six years and approximately 77-82 Mg C $ha^{-1}$ in 4-5 years, respectively, under optimized conditions in Florida. When used as windbreaks with biochar application, *E. grandis* sequestered 34 Mg C $ha^{-1}$ in just three years. Estimates of whole-system carbon allocation show that 78 % of the carbon in *E. grandis* was stored in aboveground biomass (mainly stem and crown), with 22 % in root biomass (42). Similarly, a six-year-old *E. tereticornis* plantation achieved a total carbon stock of 122.6 Mg C $ha^{-1}$, encompassing above- and belowground biomass and soil carbon. This translated to a $CO_2$ assimilation potential of 369.2 Mg $CO_2$ eq ha-, with an annual carbon sequestration rate of 12.9 Mg C ha-. Carbon concentration across different tree components ranged from 43 % to 46 %, with most biomass carbon stored in the stem (69.8 %), followed by roots (25.0 %), leaves (3.49 %) and twigs and fuelwood (2.30 %). SOC at a depth of 0-30 cm ranged from 21.2 to 22.8 Mg C $ha^{-1}$, representing a statistically significant ($p \leq 0.05$) 44.4 % increase in SOC compared to soil under a rice-wheat cropping system (34).

### *Carbon accumulation with plantation age*

As eucalyptus plantations matured, total ecosystem carbon (TEC) stocks consistently increased, ranging from 79.8 to 204.9 Mg C $ha^{-1}$. The plantations were categorized into three age groups: young (less than 6 years), middle-aged (6-15 years) and mature (over 16 years). Among these, mature plantations (older than 16 years) exhibited the highest TEC, reaching 204.9 Mg C $ha^{-1}$. SOC constituted the largest proportion of TEC, varying between 50.3 and 102.7 Mg C $ha^{-1}$ across the plantations. SOC levels increased as plantations aged, with older stands accumulating up to 102.7 Mg C $ha^{-1}$ in the top 100 cm of soil. SOC concentration decreased with depth, with the top 20 cm showing the highest levels, indicating significant accumulation near the surface (50) (Table 2). In younger plantations, biomass carbon increased rapidly from 10.66 Mg C $ha^{-1}$ at one year to 70.91 Mg C $ha^{-1}$ at five years, while total carbon content, including soil and biomass, rose from 30.48 to 94.46 Mg C $ha^{-1}$. SOC percentage also showed a modest rise with plantation age, from 0.56 % to 0.67 % over the same period (24). Peak soil carbon was observed around three years post-planting before gradually declining in older stands, indicating a transient benefit to SOC following afforestation. For example, one-year-old stands stored 112.9 Mg C $ha^{-1}$ in total ecosystem carbon, peaking at 203.8 Mg C $ha^{-1}$ in three years before decreasing to 162.7 Mg C $ha^{-1}$ in six- to eight-year-old stands. Biomass carbon storage followed a similar trajectory, with stem biomass accounting for 86.7 % of tree carbon in older stands, followed by roots (6.1 %), branches (5.0 %) and leaves (2.1 %) (25).

**Table 2.** Biomass carbon distribution across tree age groups (50)

| Tree age group | Carbon (Mg C $ha^{-1}$) | | |
|---|---|---|---|
| | Canopy tree layer biomass | Secondary biomass | Total biomass |
| Young (less than 6 years) | 27.3 | 2.1 | 29.5 |
| Middle-aged (6-15 years) | 68.5 | 6.4 | 74.8 |
| Mature (over 16 years) | 93.2 | 9.0 | 102.2 |

### Carbon sequestration in regional contexts and agronomic practices

In Indonesia's East Nusa Tenggara drylands, *E. urophylla* trees exhibited substantial variability in carbon content, from 6.34 to 184.76 kg per tree depending on tree diameter, with stems containing the most carbon (44.1 %), followed by branches and foliage (9). Across *E. tereticornis* plantations aged one to four years, total carbon stocks rose from 38.10 to 115.88 Mg C $ha^{-1}$ using biomass and carbon percentage methods. When the assumption method was used (50 % of biomass considered carbon), estimates were higher, ranging from 42.66 to 129.04 Mg C $ha^{-1}$ (21). A clear hierarchy of carbon content was found in tree biomass: stem > root > branch > leaf. Mulching emerged as a highly effective practice for enhancing carbon sequestration, particularly in saline soils. It significantly reduced soil salinity, evident from a drop in electrical conductivity from 13.9 ± 0.3 dS $m^{-1}$ in unmulched ridges to 3.54 ± 0.3 dS $m^{-1}$ in mulched ridges and boosted tree growth, biomass accumulation and soil health. After four years, trees established on mulched ridges sequestered 147.8 ± 18.4 Mg C $ha^{-1}$ in timber biomass, far surpassing their unmulched counterparts. Root biomass alone contributed around 30.2 % of this timber biomass, with mulched trees storing 74.6 % more root carbon than those in unmulched plots. Branch biomass carbon averaged 34.6 ± 3.1 Mg C $ha^{-1}$ -approximately 80.2 % higher in mulched ridges. Carbon sequestration in twigs and leaves, though about 3.7 to 3.9 times lower than in branches, was still markedly higher by around 61.1 % in mulched plots. Additionally, mulching enhanced SOC stocks, which ranged from 9.7 to 13.0 Mg C $ha^{-1}$ in mulched areas compared to 9.5 to 11.3 Mg C $ha^{-1}$ in unmulched ones (15).

### Comparison of eucalyptus with other agroforestry systems

In comparison to other agroforestry systems like cashew, neem, cocoa and *Populus*-based systems, eucalyptus-based systems consistently outperformed them in terms of total carbon stock and $CO_2$ sequestration potential. The total carbon stock in eucalyptus stands ranged from 54.65 ± 1.38 Mg C $ha^{-1}$ in plantations aged 10 years or younger to 108.51 ± 2.46 Mg C $ha^{-1}$ in stands over 20 years old. Correspondingly, $CO_2$ sequestration potential varied from 296.7 ± 1.98 Mg $CO_2$ eq $ha^{-1}$ to 859.33 ± 10.01 Mg $CO_2$ eq $ha^{-1}$, with most carbon stored in aboveground biomass. Carbon was also distributed in below-ground biomass, though to a lesser extent. Stand density and basal area were found to strongly influence total carbon stocks across the systems studied (31) (Table 3). Eucalyptus plantations, particularly *Eucalyptus saligna*, exhibit a strong and age-dependent carbon sequestration capacity, surpassing many traditional agroforestry systems and savannah ecosystems. Carbon stocks progressively increased with stand age, from 39.66 Mg C $ha^{-1}$ in young plantations (<10 years; 4 Mg C $ha^{-1}$ $yr^{-1}$), to 57.28 Mg C $ha^{-1}$in middle-aged stands (10-20 years; 6 Mg C $ha^{-1}$ $yr^{-1}$) and 85.46 Mg C $ha^{-1}$ in mature stands (>20 years; 9 Mg C $ha^{-1}$ $yr^{-1}$). These correspond to $CO_2$ sequestration rates of 14.66, 22 and 33 Mg $CO_2$ eq $ha^{-1}$ $yr^{-1}$, respectively. Total carbon stock in eucalyptus systems reached up to 234.5 Mg C $ha^{-1}$, significantly exceeding other agroforestry systems and savannah ecosystems. Aboveground carbon stocks ranged from 10.78 ± 3.03 Mg C $ha^{-1}$ in young plantations to 90.02 ± 26.27 Mg C $ha^{-1}$ in mature

**Table 3.** Variation in above- and below-ground biomass accumulation with age (31)

| Age of eucalyptus stands | Aboveground biomass (AGB) (Mg ha$^{-1}$) | Belowground biomass (BGB) (Mg ha$^{-1}$) |
|---|---|---|
| ≤10 years | 44.69 ± 0.98 | 9.96 ± 0.08 |
| 10-20 years | 58.67 ± 1.02 | 12.67 ± 0.13 |
| >20 years | 90.02 ± 3.51 | 18.49 ± 0.19 |

stands. Belowground biomass also contributed substantially, with root carbon stocks increasing from 2.84 ± 0.002 Mg C ha$^{-1}$ in savannah to 18.49 ± 0.19 Mg C ha$^{-1}$ in older eucalyptus plantations. The cumulative $CO_2$ sequestration in eucalyptus plantations was estimated at 956.82 Mg $CO_2$ eq ha$^{-1}$, with an economic value of \$9568.45 ha$^{-1}$, making them highly efficient carbon sinks relative to savannah (50.05 Mg $CO_2$ eq ha$^{-1}$). (28). In riparian ecosystems, *E. camaldulensis* (River red gum) sequestered an average of approximately 2.5 Mg C ha$^{-1}$ yr$^{-1}$ in aboveground woody biomass under favorable conditions of high rainfall and periodic flooding. In certain sites with healthy, widely spaced mature trees, carbon sequestration peaked at 8.96 Mg C ha$^{-1}$ yr$^{-1}$. Although diameter growth tended to slow with age, total biomass and carbon accumulation increased with tree size, highlighting the significance of mature and old-growth individuals as long-term carbon sinks. Trees with healthy crowns exhibited higher trunk diameter growth and greater sequestration potential than those in denser stands, where limited light access reduced growth rates. Additionally, trees in riparian zones outperformed those on adjacent floodplains in both growth and carbon storage, reinforcing the ecological value of spatial heterogeneity in these systems (32). For *E. grandis*, baseline aboveground carbon (AGC) stock was 175.91 Mg C ha$^{-1}$ over a 25-year rotation, with a mean annual increment of 7.04 Mg C ha$^{-1}$ yr$^{-1}$. Extending the rotation length (ERL) by 60 % led to a 15.5 % reduction in the annual increment, decreasing it to 5.95 Mg C ha$^{-1}$ yr$^{-1}$. Nevertheless, the long-term carbon sequestration benefit remained evident. Similar trends have been observed in *E. microcorys* plantations, where increasing rotation length enhances carbon sequestration potential (16) (Table 4). A 34-year-old *E. grandis* plantation accumulated a total ecosystem carbon (TEC) stock of 407 Mg C ha$^{-1}$, significantly exceeding that of adjacent degraded miombo woodlands, which held only 116 Mg C ha$^{-1}$. The net ecosystem production (NEP), indicating the rate of carbon sequestration at the ecosystem level, was 8.54 Mg C ha$^{-1}$ yr$^{-1}$. This high NEP was primarily driven by biomass accumulation, with increases in both above and belowground tree biomass contributing approximately 81 % of the total (35) (Table 5).

**High-performance eucalyptus plantations and case studies**

Studies from Punjab, India, showed that pure *E. tereticornis* plantations had 4-7 times the carbon sequestration potential of other agroforestry systems, such as *Populus deltoides* + *Triticum aestivum* (wheat) and *Tectona grandis* + *P. deltoides*. With a total biomass of 1311.82 Mg ha$^{-1}$ and a carbon stock of 654.91 Mg C ha$^{-1}$, these high-performance plantations sequestered carbon at an exceptional rate of 130.98 Mg C ha$^{-1}$ yr$^{-1}$ (27). More than 90 % of aboveground carbon storage was found in the tree bole (stem), while roots accounted for 23-33 % of the total carbon stock. Small branches, leaves and twigs contributed only about 2.9-3.3 % of the total. Over a 9- to 10-year rotation period, total carbon stocks varied depending on stocking density and irrigation practices, ranging from 34.6 Mg C ha$^{-1}$ at low stocking density to as high as 156.1 Mg C ha-1 under high stocking density with sewage irrigation and up to 151.9 Mg C ha$^{-1}$ under underground irrigation (51). On average, across a 9-year rotation, total carbon stocks (biomass + soil + wood products) in pure eucalyptus plantations reached 134 Mg C ha$^{-1}$, with biomass contributing approximately 41 Mg C ha$^{-1}$, with a net annual carbon sequestration rate of 6 Mg C ha$^{-1}$ yr$^{-1}$ (52). These variations highlight the significant influence of planting density and irrigation method on carbon sequestration potential in high-performance eucalyptus plantations. In agroforestry arrangements, planting density significantly influenced eucalyptus biomass accumulation and carbon sequestration. For instance, eucalyptus planted at a spacing of 6 m × 1 m in an agroforestry system achieved a total dry biomass of 59.5 Mg ha$^{-1}$ by five years of age, whereas denser block plantations at 3 m × 1 m spacing nearly doubled this, storing 113.59 Mg ha$^{-1}$ of utilizable biomass. In terms of carbon dynamics, *E. tereticornis* plantations showed a steady increase in carbon content from 38.10 Mg ha$^{-1}$ in one-year-old stands to 115.88 Mg ha$^{-1}$ in four-year-old stands. On average, eucalyptus sequestered carbon at a rate of 10 Mg ha$^{-1}$ yr$^{-1}$, with fast-growing tropical plantations reaching rates as high as 14 Mg ha$^{-1}$ yr$^{-1}$. These figures underscore the critical role of optimal spacing and plantation design in maximizing both biomass production and carbon sequestration potential in high-performance eucalyptus systems (53). Across all contexts, eucalyptus showed consistent capacity for rapid biomass accumulation and carbon sequestration, underscoring its strategic value in climate change mitigation and land restoration (Table 6 & 7).

**Table 4.** Effect of extension of rotation length on aboveground carbon accumulation in eucalyptus plantations (16)

| Extension of rotation length (ERL) | Increase in rotation length (years) | Increase in aboveground carbon (AGC) (%) | Increase in aboveground carbon (AGC) (Mg ha$^{-1}$) |
|---|---|---|---|
| ERL by 20 % | 5 | 13.7 | 24.03 |
| ERL by 40 % | 10 | 25.2 | 44.35 |
| ERL by 60 % | 15 | 35.2 | 61.95 |

**Table 5.** Comparison of carbon stocks in eucalyptus plantations and miombo woodlands biomass (35)

| Tree component | Carbon stocks (Mg ha$^{-1}$) | |
|---|---|---|
| | *E. grandis* plantations | Miombo woodlands |
| Aboveground biomass | 202.5 | 17.9 |
| Belowground biomass | 58.7 | 8.6 |
| Soil organic carbon (0-50 cm) | 138.8 | 87.3 |
| Litter layer carbon | 6.6 | 2.6 |

**Carbon sequestration potential of eucalyptus based cropping systems**

Studies suggest that pure eucalyptus plantations generally have higher carbon sequestration potential than eucalyptus-based agroforestry systems due to greater tree density. Integrated livestock-forestry systems sequester less carbon than pure eucalyptus stands due to methane emissions from cattle. For instance, a monoculture eucalyptus plantation sequestered 510 Mg $CO_2$ ha$^{-1}$ over eight years without thinning, whereas an integrated livestock-forestry system

**Table 6.** Biomass carbon stock across eucalyptus species under different locations, ages and spacings

| Location | Species | Age (Years) | Spacing (m) | Tree Density (trees ha$^{-1}$) | Stem carbon (kg tree$^{-1}$) | Branch carbon (kg tree$^{-1}$) | Leaf carbon (kg tree$^{-1}$) | Bark carbon (kg tree$^{-1}$) | Root carbon (kg tree$^{-1}$) | Total biomass carbon (kg tree$^{-1}$) | Total biomass Carbon (Mg C ha$^{-1}$) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| India (Mettupalayam, Tamil Nadu) | *E. tereticornis* | 1 | 1.5 × 1.5 | 4444 | 1.08 | 0.42 | 0.26 | - | 0.55 | 2.31 | 10.25 | (21) |
| | | 2 | | | 3.16 | 1.20 | 0.73 | - | 1.83 | 6.92 | 30.75 | |
| | | 3 | | | 6.03 | 1.66 | 1.35 | - | 3.63 | 12.67 | 56.31 | |
| | | 4 | | | 8.57 | 2.84 | 2.10 | - | 4.98 | 18.49 | 82.16 | |
| Brazil | *E. grandis* | 7 | 2.0 × 1.0 | 4450 | 41.9 | 1.89 | 1.75 | - | 10.87 | 56.4 | 251.1 | (81) |
| | | | 2.0 × 1.5 | 2967 | 84.0 | 3.44 | 3.20 | - | 19.17 | 110.2 | 327.1 | |
| | | | 3.0 × 1.0 | 2967 | 55.1 | 2.26 | 2.02 | - | 14.32 | 73.7 | 218.7 | |
| | | | 3.0 × 1.5 | 1978 | 67.9 | 2.83 | 2.53 | - | 19.93 | 93.1 | 184.2 | |
| India (Kurukshetra, Haryana) | *E. tereticornis* | 6 | 3.6 × 3.0 | 925 | 74.71 | 2.52 | 3.78 | - | 26.81 | 107.82 | 100.6 | (34) |
| India (Punjab) | *E. tereticornis* | 3 | 1.5 × 1.5 | 4444 | 21.44 | 19.04 | 4.18 | 4.16 | 4.01 | 52.83 | 234.78 | (27) |
| | | 4 | | | 43.19 | 37.64 | 9.07 | 7.89 | 5.25 | 103.04 | 457.91 | |
| | | 5 | | | 68.76 | 45.36 | 14.55 | 11.45 | 7.25 | 147.37 | 654.91 | |
| India (Haryana) | *Eucalyptus* sp. | 8 | 3 × 3 | 1111 | 106.13 | 11.55 | 5.13 | - | 31.06 | 153.87 | 166.29 | (82) |
| | | | 6 × 1.5 | | 67.11 | 9.70 | 3.85 | - | 20.98 | 101.64 | 112.88 | |
| | | | 17 × 1 × 1 (Paired row) | | 199.61 | 21.52 | 7.66 | - | 36.62 | 140.23 | 155.80 | |
| Brazil | *E. urograndis* | 5.5 | 3 × 3 | 1111 | 25.5-64.8 | 1.76-3.98 | 0.59-2.78 | - | 2.58 – 12.22 | 30.55 – 81.16 | - | (83) |
| Indonesia (Timor Island, East Nusa Tenggara | *E. urophylla* | 23 | - | 182 | 184.89 | 44.07 | 8.79 | - | 45.23 | 287 | 52.25 | (84) |

**Table 7**. Aboveground biomass and carbon stock of different eucalyptus species under varying spacing and locations

| Location | Eucalyptus species | Spacing (m) | Tree density (trees ha$^{-1}$) | Age (Years) | Stem carbon (Kg tree$^{-1}$) | Branch carbon (Kg tree$^{-1}$) | Leaf carbon (Kg tree$^{-1}$) | Total aboveground carbon (Kg tree$^{-1}$) | Total biomass (Kg tree$^{-1}$) | Total biomass (Mg ha$^{-1}$) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| India (Tamil Nadu) | *E. camaldulensis* | 3 × 3 | 1111 | 6 | 33.56 | 2.8 | - | 36.36 | 72.72 | 80.79 | (85) |
| | | 3 × 2 | 1666 | | 25.33 | 2.45 | - | 27.78 | 55.56 | 92.61 | |
| | | 3 × 1.8 | 1851 | | 22.59 | 2.25 | - | 24.84 | 49.67 | 91.98 | |
| | | 3 × 1.65 | 2020 | | 20.97 | 1.95 | - | 22.92 | 45.84 | 92.60 | |
| | | 3 × 1.5 | 2222 | | 22.28 | 1.6 | - | 23.88 | 47.76 | 106.12 | |
| | | 3 × 1.35 | 2469 | | 20.07 | 1.35 | - | 21.42 | 42.84 | 105.78 | |
| | | 3 × 1 | 3333 | | 15.84 | 1.2 | - | 17.04 | 34.08 | 113.59 | |
| Tacuarembó, Uruguay | *E. benthamii* | 3 × 1.5 | 2220 | 6.25 | 41.75 | - | - | - | 83.50 | 104.2 | (86) |
| | *E. benthamii* | 3 × 0.5 | 6660 | | 27.95 | - | - | - | 55.90 | 212.6 | |
| | *E. dunnii* | 3 × 1.5 | 2220 | | 55.85 | - | - | - | 111.7 | 130.3 | |
| | *E. grandis* | 3 × 1.5 | 2220 | | 48.65 | - | - | - | 97.3 | 111.2 | |
| Paysandú, Uruguay | *E. benthamii* | 3 × 1.5 | 2220 | 6.33 | 45.0 | - | - | - | 90 | 166.1 | |
| | *E. benthamii* | 3 × 0.5 | 6660 | | 16.8 | - | - | - | 33.6 | 174.9 | |
| | *E. dunnii* | 3 × 1.5 | 2220 | | 50.4 | - | - | - | 100.8 | 187.7 | |
| | *E. dunnii* | 3 × 0.5 | 6660 | | 18.55 | - | - | - | 37.1 | 198.1 | |
| | *E. grandis* | 3 × 1.5 | 2220 | | 46.95 | - | - | - | 93.9 | 159.3 | |
| Brazil | *E. urograndis* | 1.15 × 3 | 2564 | 3 | 27.97 | 6.19 | 2.74 | 36.9 | 45.56 | 116.99 | (87) |
| | | 1.75 × 3 | 1754 | | 29.49 | 6.45 | 3.03 | 38.97 | 57.36 | 100.63 | |
| | | 2.35 × 3 | 1333 | | 30.16 | 6.65 | 3.38 | 40.19 | 63.11 | 84.08 | |
| | | 2.95 × 3 | 1075 | | 31.72 | 7.14 | 3.73 | 42.59 | 70.68 | 75.96 | |
| | | 3.55 × 3 | 901 | | 32.94 | 7.48 | 3.99 | 44.41 | 74.93 | 67.48 | |
| | | 4.15 × 3 | 775 | | 33.73 | 7.71 | 4.17 | 45.61 | 78.27 | 60.65 | |
| | | 4.75 × 3 | 680 | | 34.56 | 7.96 | 4.29 | 46.81 | 81.90 | 55.69 | |
| | | 5.35 × 3 | 606 | | 35.66 | 8.26 | 4.52 | 48.44 | 84.38 | 51.10 | |
| | | 5.95 × 3 | 546 | | 36.91 | 8.59 | 4.68 | 50.18 | 91.79 | 50.13 | |
| | | 6.55 × 3 | 498 | | 37.75 | 8.86 | 4.8 | 51.41 | 103.26 | 51.45 | |
| Indonesia (Timor Island, East Nusa Tenggara province) | *E. urophylla* | - | - | 24 | 5.96-181.25 (Mean: 52.38) | 0.23-4.38 (Mean: 1.71) | 0.14-3.47 (Mean: 1.43) | 6.34-184.76 (Mean: 55.51) | 127 | - | (9) |

sequestered only 129 Mg $CO_2$ ha$^{-1}$ (54). However, total SOC was lower in eucalyptus plantations (174 Mg ha$^{-1}$) compared to a silvopastoral system with eucalyptus and *Urochloa decumbens* grass (195 Mg ha$^{-1}$) and well-managed pasture (260 Mg ha$^{-1}$) (55).

Agroforestry systems with wheat and rice had lower carbon sequestration than pure eucalyptus plantations due to reduced tree density. A pure eucalyptus block plantation sequestered 90.6 Mg C ha$^{-1}$, while agroforestry systems sequestered 22.8, 13.5 and 9.5 Mg C ha$^{-1}$ depending on tree spacing. Despite lower carbon sequestration rates, agroforestry systems offer additional benefits such as crop yields, making them more suitable for small landholders (56). A forest area predominantly consisting of eucalyptus had the highest aboveground biomass (129.08 Mg ha$^{-1}$) and carbon stock (64.54 Mg C ha$^{-1}$). In comparison, an agroforestry system with crops such as maize, sorghum and berseem intercropped with *E. camaldulensis* and *Bombax ceiba* over 25-30 years had 81.00 Mg ha$^{-1}$ of biomass and 40.50 Mg C ha$^{-1}$ of carbon stock (57).

Some research suggests that eucalyptus-based agroforestry systems can sometimes achieve higher carbon sequestration. Pure eucalyptus plantations had a sequestration potential of 2.18 Mg C ha$^{-1}$ yr$^{-1}$, while eucalyptus in agroforestry systems sequestered between 2.18 and 13.86 Mg C ha$^{-1}$ yr$^{-1}$. However, the agricultural components of these systems contributed relatively lower sequestration rates, ranging from 0.01 to 0.60 Mg C ha$^{-1}$ yr$^{-1}$. Additional carbon sequestration from the agricultural component and soil carbon pool may enhance overall sequestration in agroforestry compared to pure eucalyptus stands (58). Intercropping with legumes like red gram and green gram improved SOC levels compared to pure eucalyptus plantations (59). Complex, multi-strata agroforestry systems with diverse species exhibited the highest carbon sequestration rates (60). Homestead agroforestry with high crop diversity increased soil carbon sequestration relative to monoculture eucalyptus plantations (61).

Carbon sequestration potential varies depending on the cropping system. Pure eucalyptus plantations sequestered 54.11 Mg ha$^{-1}$, while eucalyptus-based agroforestry systems sequestered between 56.57 and 59.92 Mg ha$^{-1}$. The highest sequestration was observed in eucalyptus + pigeonpea (59.92 Mg ha$^{-1}$), followed by eucalyptus + paddy-wheat (57.48 Mg ha$^{-1}$), eucalyptus + moong-wheat (57.27 Mg ha$^{-1}$) and eucalyptus + soybean-mustard (56.57 Mg ha-$^{1}$) (62). Additionally, eucalyptus + pigeonpea agroforestry had the highest sequestration rate (42.71 Mg ha$^{-1}$ yr$^{-1}$) compared to other intercrops and pure eucalyptus plantations (22.11 Mg ha$^{-1}$ yr$^{-1}$) (63). Further studies indicate that some eucalyptus-based agroforestry systems can achieve greater overall sequestration. Agroforestry systems combining eucalyptus with sugarcane, wheat and fodder sorghum had 13-22 % higher total organic carbon (TOC) stocks compared to monocropped sugarcane (64). Eucalyptus intercropped with *Cymbopogon* species had 33.3-83.3 % higher SOC than pure eucalyptus stands (65). Similarly, eucalyptus grown with fodder-wheat rotation had 70.6 % greater SOC and eucalyptus combined with citrus showed a 30.2 % SOC increase compared to sole cropping at a depth of 0-15 cm (66). Among agroforestry models, eucalyptus + spider lily had the highest carbon sequestration potential at 47.87 Mg ha$^{-1}$ (67).

Carbon sequestration potential in eucalyptus hybrid + wheat boundary plantation was 7.90 Mg C ha$^{-1}$ year$^{-1}$ (68). The total $CO_2$ equivalent carbon stock was higher under the wheat -*E. tereticornis* agroforestry system (62.77 to 66.47 Mg ha$^{-1}$) compared to wheat crop alone (9.68 to14.85 Mg ha$^{-1}$) (69). Under 4-year eucalyptus (*E. tereticornis*) + wheat agroforestry system, Permanganate Oxidizable Carbon (POXC) was statistically higher by 4.40 % than sole wheat crop and SOC was 6.30 % higher than sole wheat crop (70). *E. tereticornis* boundary plantation sequestered 0.84 Mg C ha$^{-1}$ year$^{-1}$. For a pure eucalyptus stand, aboveground biomass of 21.22 Mg ha$^{-1}$ and carbon stock of 10.52 Mg C ha$^{-1}$were reported (71). In the silvi-silvi mixed forestry system consisting of *E. camaldulensis* and *P. deltoides*, the total aboveground biomass carbon stock was 34.46 Mg C ha$^{-1}$),with eucalyptus alone contributing 16.92 Mg C ha$^{-1}$ (72). Eucalyptus trees, planted in strip plantations interspaced with wheat, sequester 15.5 Mg C ha$^{-1}$during the 5 year and 4 month rotation (3) (Fig. 3, Table 8).

## Effects of agroforestry systems on soil health

Agroforestry systems, particularly homestead agroforestry with diverse crop combinations, exhibited greater levels of SOC and SOM compared to monoculture croplands or orchards, thereby contributing directly to enhanced carbon sequestration in soils (61). The eucalyptus + wheat agroforestry system enhanced soil MBC, POXC (labile carbon fraction) and SOC stock in comparison to a sole wheat crop, indicating improved carbon storage

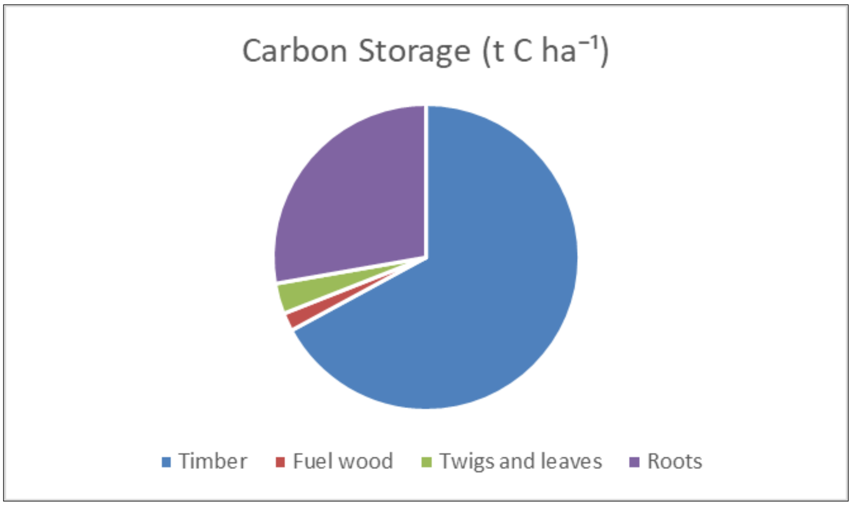


**Fig. 3.** Component-wise carbon storage. Data sourced from Ref. (3).

capacity under integrated systems (70). Increased SOC, carbon pools, water-soluble carbon and MBC were recorded at various soil depths, further demonstrating the vertical distribution and sequestration of carbon in the soil profile (64-66). Agroforestry systems also exhibited lower soil bulk density and greater SOC content and stock than sole crop systems, reflecting improved soil structure, porosity and long-term carbon stabilization through soil aggregation (62). The presence of trees in agroforestry systems contributed to enhanced soil aggregation, higher SOC levels, increased available soil moisture and reduced soil erosion, all of which support the physical mechanisms of carbon retention in soils (58). Additionally, the steady-state infiltration rate was notably higher in fields with eucalyptus (8.3 mm $h^{-1}$) compared to those without (5.1 mm $h^{-1}$), indicating better soil physical properties that facilitate organic matter decomposition and SOC accrual (3).

Compared to non-planted control fields, agroforestry systems resulted in reduced soil pH, electrical conductivity and bulk density while improving SOC content, thus promoting a favorable environment for carbon stabilization in the soil matrix (56). The eucalyptus + spider lily agroforestry system demonstrated increased SOC, as well as higher levels of available nitrogen, phosphorus and potassium than other systems, supporting both fertility and carbon enrichment (67). Furthermore, greater concentrations of nitrogen, phosphorus, potassium and micronutrients such as zinc, manganese and copper were reported in agroforestry systems (64), which enhance microbial activity and organic matter decomposition, key drivers of SOC formation. The eucalyptus + wheat agroforestry system led to increased soil MBC, often described as creating "islands of fertility" due to its role in enhancing nutrient cycling and SOC buildup (70). Agroforestry systems featuring nitrogen-fixing tree species, along with nutrient cycling from litter fall, contributed to soil nutrient replenishment and long-term fertility improvement, while simultaneously increasing soil carbon stocks (61). These systems promote soil fertility through leaf litter decomposition, nutrient cycling and carbon sequestration. Seasonal variations in soil nutrients, particularly nitrogen, phosphorus and potassium, were observed, with higher levels recorded after the rainy season due to decomposition and mineralization processes that also enhance SOC levels (72). Agroforestry thus plays a vital role in enhancing soil physical and chemical properties, contributing not only to soil fertility but also to terrestrial carbon sequestration (58). Greater SOC, nitrogen, phosphorus and potassium content in agroforestry systems compared to croplands further confirms their dual benefit in improving soil fertility and storing atmospheric carbon in stable soil pools (57).

## Future thrust

The future of eucalyptus-based cropping systems in carbon sequestration lies in improving soil carbon stabilization, enhancing microbial interactions and optimizing biochar applications. One of the key research areas is increasing SOC sequestration through conservation practices such as reduced tillage, organic mulching and biochar incorporation (10, 73). These techniques can significantly enhance long-term carbon retention in soil, reducing $CO_2$ emissions and improving soil fertility. Additionally, deep-rooted eucalyptus species contribute to subsoil carbon sequestration, which remains stable over longer periods due to reduced microbial decomposition and environmental disturbances (74).

Another promising area of future research is the role of soil microbial communities in stabilizing organic matter and enhancing carbon sequestration. Prominent among these are arbuscular mycorrhizal fungi (Glomeromycota), ectomycorrhizal fungi (Basidiomycota, Ascomycota) and ericoid mycorrhizal fungi, which contribute to carbon retention through extensive hyphal networks, necromass scaffolding and exudate-mediated formation of mineral-associated organic matter (75). The application of biochar derived from eucalyptus biomass offers another long-term carbon sequestration strategy. Biochar has been shown to improve soil structure, enhance water retention and provide stable carbon pools that have persisted for centuries. Future studies will focus on optimizing biochar production techniques and determining the most effective application rates to maximize its impact on carbon sequestration and soil fertility (76, 77).

Deep soil carbon sequestration through extensive eucalyptus root systems is another area of interest. Unlike many annual crops that primarily store carbon in surface soils, eucalyptus has the potential to sequester carbon in deeper layers, making it less susceptible to microbial respiration and degradation. Future research will focus on quantifying deep soil carbon pools and developing improved land management strategies to enhance root biomass contributions to SOC storage. The integration of eucalyptus into agroforestry and mixed cropping systems presents additional opportunities for carbon sequestration. Agroforestry systems that combine eucalyptus with leguminous crops or perennial vegetation have been shown to increase soil carbon stocks through continuous organic matter inputs and improved soil structure. Comparative studies suggest that such integrated systems sequester more carbon than monoculture plantations, making them a sustainable strategy for both carbon mitigation and soil conservation.

As climate change continues to impact global ecosystems, climate-resilient management strategies will be critical in ensuring the continued efficiency of eucalyptus-based carbon sequestration. Future research on eucalyptus carbon sequestration should focus on how drought-resistant clones store carbon, especially in roots and soil. Studies should explore the link between water-use efficiency and carbon storage, long-term sequestration trends and soil-plant interactions. Comparing monoculture plantations with agroforestry systems can offer insights into sustainable carbon storage. Additionally, understanding non-stomatal photosynthesis limitations and using carbon isotope discrimination (Δ13C) as an indicator could help refine carbon sequestration assessments. However, leveraging these traits effectively requires a deeper understanding of how different genotypes physiologically respond to drought. Measuring net photosynthesis and stomatal conductance are useful, non-stomatal factors such as limitations in RuBisCO activity and electron transport also play a significant role in determining drought responses. Although Δ13C has been

**Table 8.** Carbon sequestration potential of eucalyptus-based systems across different countries and management practices

| Eucalyptus species | Country | Age | Impact on carbon sequestration | Reference |
|---|---|---|---|---|
| *E. urophylla* × *E. grandis* clone H13 | Brazil | 8 years | 510 Mg $CO_2$ $ha^{-1}$ in monoculture; 129 Mg $CO_2$ $ha^{-1}$ in integrated livestock-forestry system | (54) |
| Eucalyptus hybrid (*E. grandis* × *E. urophylla*) | Brazil | 8 years | SOC stock under<br>i) Eucalyptus plantation: ~174 Mg $ha^{-1}$<br>ii) Silvopastoral systems (Eucalyptus hybrid + *U. decumbens*): ~195 Mg $ha^{-1}$ | (55) |
| *E. tereticornis* | India (Haryana) | 6 years | Pure plantation (block): 90.6 Mg C $ha^{-1}$<br>Agroforestry (strip plantations):<br>1 m × 1 m spacing: 22.8 Mg C $ha^{-1}$<br>1 m × 2 m spacing: 13.5 Mg C $ha^{-1}$<br>1 m × 3 m spacing: 9.5 Mg C $ha^{-1}$ | (56) |
| *E. camaldulensis* | Pakistan | 25-30 years | Pure forest land:<br>Aboveground biomass: 129.08 Mg $ha^{-1}$<br>C-stock: 64.54 Mg $ha^{-1}$<br>Agroforestry (Eucalyptus + maize, sorghum and berseem in rotation):<br>Aboveground biomass: 81.00 Mg $ha^{-1}$<br>C-stock: 40.50 Mg $ha^{-1}$<br>Below-ground biomass (at 0-20 cm):<br>Forest land: 14.09 Mg $ha^{-1}$<br>Agroforests: 11.78 Mg $ha^{-1}$<br>SOC:<br>Forest land (0-20 cm): 6.84 Mg $ha^{-1}$<br>Agroforestry (0-20 cm): 5.75 Mg $ha^{-1}$<br>SOC decreases with depth in both systems | (57) |
| *E. tereticornis/E. camaldulensis* | India | 2-6 years | Agroforestry: 13.86 Mg C $ha^{-1}$ $yr^{-1}$ (*E. tereticornis* at 320 trees $ha^{-1}$, 2 years)<br>Pure plantation: 2.18 Mg C $ha^{-1}$ $yr^{-1}$ (*Eucalyptus* spp., 6 years)<br>Soil C sequestration up to 3.98 Mg C $ha^{-1}$ $yr^{-1}$ reported | (58) |
| *E. tereticornis* clone ITC-3 | India (Karur, Tamil Nadu) | 8 months | Red gram intercropping had the highest SOC (7.00 g C $kg^{-1}$) followed by green gram (6.90 g C $kg^{-1}$).<br>Tree alone had the lowest SOC (6.60 g C $kg^{-1}$)<br>Available N, P, K were also highest with red gram, indicating better nutrient cycling and potential for carbon buildup in the soil. | (59) |
| *E. tereticornis* | India | Not specified | *E. tereticornis* in silvopastoral systems accumulated 6.92 Mg biomass $ha^{-1}$ $year^{-1}$<br>Total carbon storage in such systems ranges from 1.89-3.45 Mg C $ha^{-1}$<br>Eucalyptus used in boundary plantations along with crops like wheat also contributed to significant carbon storage<br>These systems help in both SOC build-up and aboveground biomass storage | (60) |
| *E. camaldulensis* | Bangladesh (Dinajpur) | 3-23 years | Cropland agroforestry under eucalyptus recorded the highest SOC (1.60 %) and SOM (2.75 %) among systems. Orchard had the lowest (SOC 0.32 %)<br>SOC and SOM increased with stand age.<br>SOC increased from 0.31 % at 3 years to 1.99 % at 23 years. | (61) |
| *Eucalyptus* sp. | India (Jabalpur, Madhya Pradesh) | Not specified | Eucalyptus + pigeonpea agrisilviculture system sequestered 59.92 Mg $ha^{-1}$ $CO_2$<br>SOC stock under this system: 16.33 Mg $ha^{-1}$<br>SOC content: 0.81 % (mean across 0-45 cm depth)<br>Soil bulk density: 1.339 $g/cm^3$ (mean) | (62) |

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|---|---|---|---|---|
| *Eucalyptus* sp. (Clone) | India (Jabalpur, Madhya Pradesh) | 5 years | Eucalyptus + pigeonpea (agroforestry): 42.71 Mg $ha^{-1}$ $yr^{-1}$<br>Sole eucalyptus plantation: 22.11 Mg $ha^{-1}$ $yr^{-1}$<br>Maximum total biomass production: 21.26 Mg $ha^{-1}$ $yr^{-1}$ in eucalyptus + pigeonpea agrisilviculture system<br>Highest carbon stock: 11.64 Mg $ha^{-1}$ $yr^{-1}$ under eucalyptus + pigeonpea<br>Carbon sequestration potential (other systems):<br>Eucalyptus + paddy-wheat: 39.18 Mg $ha^{-1}$ $yr^{-1}$<br>Eucalyptus + moong-wheat: 34.96 Mg $ha^{-1}$ $yr^{-1}$<br>Eucalyptus + soybean-mustard: 31.63 Mg $ha^{-1}$ $yr^{-1}$ | (63) |
| *E. tereticornis* | India (Kurukshetra, Haryana) | 6 years | Eucalyptus based agroforestry system had 22 % greater TOC stock in March and 13 % greater in September compared to monocropped sugarcane | (64) |
| Eucalyptus hybrid | India | Not specified | SOC 33.3-83.3 % higher with *Cymbopogon* sp. Intercrop | (65) |
| *E. tereticornis* | India (Punjab) | 15-20 years (Third rotation of 7 years each) | Eucalyptus + fodder-wheat rotation had 70.6 % higher SOC than sole fodder-wheat<br>Eucalyptus + citrus had 30.2 % higher SOC than sole citrus<br>Eucalyptus litterfall contribution was upto 1.39 Mg $ha^{-1}$ $year^{-1}$<br>Eucalyptus based agroforestry system showed higher SOC, total nitrogen, microbial biomass carbon (MBC) and water-soluble carbon than sole cropping system and fallow land | (66) |
| Eucalyptus + spider lily | India (Navsari, Gujarat) | 6 years | Highest total carbon sequestration at 47.87 Mg $ha^{-1}$<br>Woody component: 42.9 Mg $ha^{-1}$<br>Intercrops: 4.97 Mg $ha^{-1}$<br>SOC: 0.82 % (Highest) | (67) |
| Eucalyptus hybrid | India (Uttarakhand) | 9 years | 7.90 Mg C $ha^{-1}$ $yr^{-1}$ in eucalyptus hybrid + wheat boundary plantation<br>$CO_2$ mitigation potential: 52.63 Mg $CO_2$ $ha^{-1}$ total mitigation | (68) |
| *E. tereticornis* | India (Jabalpur, Madhya Pradesh) | 4 to 5 years | $CO_2$ stock (eucalyptus tree only): 224.18-230.86 Mg $ha^{-1}$ (pooled average across treatments over two years)<br>$CO_2$ stock (wheat crop): 9.68-14.85 Mg $ha^{-1}$ (depending on weed control treatment)<br>$CO_2$ stock (Total agroforestry system - eucalyptus + wheat + weeds): 62.77-66.47 Mg $ha^{-1}$ (pooled across treatments)<br>Agroforestry system stored significantly more carbon compared to sole wheat cropping | (69) |
| *E. tereticornis* | India (Kurukshetra, Haryana) | 4 years | Compared to sole wheat crop, eucalyptus + wheat agroforestry system had:<br>6.30 % higher SOC, 4.40 % higher POXC, 12.3 % higher MBC, 29.3 % higher soil carbon stock<br>POXC increment across soil profile: 43 % higher than sole wheat crop<br>MBC increment across soil profile: 36.6 % higher than sole wheat crop | (70) |
| *Eucalyptus* sp. (unspecified) | India (Uttarakhand) | Not specified | Aboveground biomass: approximately 21.22 Mg $ha^{-1}$<br>Carbon stock: approximately 10.52 Mg C $ha^{-1}$<br>Carbon sequestration rate: about 0.84 Mg C $ha^{-1}$ $year^{-1}$<br>Eucalyptus sequesters less carbon compared to *Dalbergia sissoo* and *P. deltoides* but contributes significantly in agroforestry systems | (71) |
| *E. camaldulensis* + *P. deltoides* | India (Uttarakhand, Tarai region) | 3 years (Both eucalyptus and poplar) | Total aboveground bioimass<br>Eucalyptus + Poplar: 34.46 Mg C $ha^{-1}$;<br>Eucalyptus contribution: 16.92 Mg C $ha^{-1}$ | (72) |
| *E. tereticornis* (strip plantation) | India (Haryana) | 5 years and 4 months | Total carbon sequestered was 15.5 Mg $ha^{-1}$ (Timber: 10.4 Mg $ha^{-1}$, Fuelwood: 0.3 Mg $ha^{-1}$, Twigs/leaves: 0.5 Mg $ha^{-1}$, Roots: 4.3 Mg $ha^{-1}$<br>Raising strip-plantations of eucalyptus (4 % of total agricultural land) in waterlogged areas of Haryana could sequester 1.33 Mg additional carbon annually | (3) |

**Note:** Mg = Megagram (1 Mg = 1 metric ton); $CO_2$ = Carbon dioxide; SOC = Soil organic carbon; SOM = Soil organic matter; TOC = Total organic carbon; POXC = Permanganate-oxidizable carbon; MBC = Microbial biomass carbon. Values are reported as given in respective studies.

proposed as a potential indicator, its application may be constrained by the lack of consistent responses, particularly among tolerant and moderately sensitive genotypes, which did not show clear or uniform changes in Δ13C under drought conditions. In some cases, carbon acquisition may have been too limited to influence isotope signatures, further challenging the reliability of Δ13C as a standalone indicator (78). Furthermore, advancements in carbon monitoring and modeling will play a key role in quantifying the sequestration potential of eucalyptus-based systems. The integration of remote sensing, AI-based modeling and blockchain technology will enhance the accuracy of carbon tracking, making it easier to verify and monetize carbon credits associated with eucalyptus plantations.

By utilizing satellite imagery and machine learning algorithms, land managers will be able to optimize carbon sequestration strategies and participate in global carbon trading markets (79, 80). Overall, the future of eucalyptus-based cropping systems in carbon sequestration is promising, with a focus on improving soil carbon stabilization, microbial interactions, biochar applications and deep soil carbon storage. These strategies will not only enhance climate change mitigation efforts but also improve soil health, agricultural productivity and ecosystem resilience. As global carbon reduction targets become more ambitious, eucalyptus-based agroforestry and cropping systems will play an increasingly vital role in sustainable land management and long-term carbon sequestration.

## Conclusion

Eucalyptus plantations and agroforestry systems offer substantial potential for carbon sequestration, making them effective tools for climate change mitigation. In India, the carbon sequestration capacity of eucalyptus plantations increases with age, reaching up to 237.2 Mg C ha$^{-1}$, with annual sequestration rates between 9.62 and 11.4 Mg ha$^{-1}$ year$^{-1}$, as documented in a 2023 study. Agroforestry systems that integrate eucalyptus, such as silvopastoral, agrisilvicultural and boundary plantations, further enhance carbon sequestration while also providing economic and environmental advantages. These systems can sequester up to 10 Mg C ha$^{-1}$ year$^{-1}$ in short-rotation eucalyptus plantations and agroforestry setups, with long-term carbon storage potential in both biomass and soil. Optimizing carbon sequestration in eucalyptus plantations and agroforestry systems depends on key factors such as species selection, soil conditions, climate and management practices. This review highlights the importance of promoting eucalyptus -based plantations and agroforestry as sustainable forestry practices, emphasizing their dual benefits-economic returns and a significant role in climate change mitigation through carbon sequestration. Further research, coupled with the adoption of best management practices, can maximize their carbon sequestration potential, supporting global efforts to combat climate change and enhance environmental sustainability.

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## Authors' contributions

VR wrote original manuscript; SK conceptualized the manuscript and reviewed the manuscript; PKT, TS and KP reviewed the manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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