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REVIEW ARTICLE

Enhancing biomass production in multifunctional agroforestry: A review of strategies and benefits

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Abstract

The decline in the global forest area has increased the demand for timber and forest products, necessitating sustainable forestry practices. Agroforestry integrates trees with crops and livestock, offering multifunctional benefits including soil improvement, biodiversity conservation and climate change mitigation. This review explores agroforestry's diverse roles, emphasizing biomass production enhancement through optimized planting methods, nutrient management and water conservation. It highlights the environmental, economic and social benefits of agroforestry while addressing sustainable land use. Agroforestry enhances soil quality through improved nutrient cycling and biodiversity. Researchers indicated that agroforestry practices reduce the soil temperature (3.37-9.25 %) and increase the soil moisture considerably (10-20 %). They also reduce the soil erosion by 50 % thus stabilizing soil structure. An increase in soil organic carbon (40 %), nitrogen storage (13 %) and accessible nitrogen and phosphorus (46 % and 11 %) availability was also reported by many. In pest management, it considerably reduces flies (38 %), pollen beetles (57 %), wheat stem sawflies (37 %) and aphid damage by 13 % while increasing farm income. Agroforestry represents a viable strategy for sustainable land management, food security and ecological restoration. Tailored models can improve economic returns, environmental sustainability and climate resilience. Further research should refine best practices and integrate advanced technologies to maximize the benefits.

Keywords: agroforestry system; carbon sequestration; nutrient management; soil health; water management

Introduction

Trees and their products, such as paper, timber and plywood, continue to play an essential role in human life, making their sustainable management crucial for future needs. The demand for forest products will likely increase threefold by 2050 due to shifting consumption trends and a growing population (1). At the same time, global forest area declined from 4.28 to 3.99 billion ha^{-1} between 1990 and 2015 (2). This decline can be addressed through agroforestry, an approach that integrates trees into agricultural landscapes. Agroforestry has been practiced since the early days of land cultivation (3) and has been recognized as a sustainable technique for more than 50 years (4). Agroforestry is a multifunctional approach that involves integration of trees and shrubs with crops or livestock. In India, various agroforestry systems are adopted, which are influenced by the diverse climatic conditions throughout the country (5). India faces significant challenges such as population pressure, deforestation and land degradation, which make sustainable agroforestry practices crucial (3). The rapid expansion of agriculture, urbanization and industrial development has led to the depletion of forest cover, increasing the need for integrated land-use strategies. Agroforestry offers a viable solution by balancing economic productivity with environmental conservation, ensuring sustainable land management while addressing resource constraints (6). Based on the structure and utility, agroforestry can be grouped into silvi-pasture, agri-silvi-pasture, horti-pasture, agro-silviculture, agri-horticulture and agri-silvihorticulture-systems (6, 7). To effectively domesticate and improve agroforestry species, it is essential to identify and quantify the variations in traits between individual trees that contribute to improving the quality of products including fruits, pulp and timber (7).

Agroforestry has broad applications and considerable potential in improving soil conservation, nutrient cycling, soil fertility, productivity and carbon sequestration (8). It also facilitates water and soil conservation while providing ecosystem services, that enhance economic stability, timber, food, shade and income generation (9). Agroforestry systems help to promote soil health and fertility by altering the soil's physical, chemical and biological properties, therefore enhancing nutrient cycling (10). The diverse microbial communities in the agroforestry system play a crucial role in various nutrient cycles and promote mineralization (10, 11). This system also serves as a valuable habitat for soil macrofauna, which in turn improves soil health and quality and reduces contaminants (11). Furthermore, it provides a natural approach to insect pest management by offering food and shelter for natural enemies, like beneficial insects and birds that prey on insect pests (12). While prior reviews focus primarily on carbon sequestration, this work integrates nutrient management, biodiversity and socio-economic benefits, highlighting a more holistic approach to agroforestry. Hence, this review discusses the importance and ecosystem services of various agroforestry systems and strategies to enhance their sustainable production.

2. Agroforestry systems

Agroforestry systems are characterized by the integration of shrub and tree species with agricultural and animal components, arranged in a spatially and temporally diverse manner (13). The complexity of these systems depends on interactions between climate and tree species (14). This system has been followed for the past 1300 years (9) and worldwide, 1.6 billion ha of land have room for agroforestry management, mostly in tropical and subtropical regions (15). The estimated area of natural forest in India is 873705 km^2, which accounts for 26.6 % of the total geographical area, while the area inhabited by trees outside the forest, as in agroforestry, is 103585 km^2, accounting for 3.15 % of the country's total geographical area (16). The most widespread adoption of agroforestry systems is observed in the southern, eastern and northern regions of India because of the high rainfall and agro-biodiversity, while the lowest numbers were practiced in the Indo-Gangetic region (Fig. 1). The commonly practiced agroforestry systems in India are silvi-pasture, horti -pasture, agri-silvi-pasture, agri-horticulture, agri-silviculture and agri-silvi horticulture systems, are varying according to agro-climatic zones.

2.1. Types of agroforestry systems

The agri-horticulture system, also known as the food-cum-fruit system, integrates fruit trees such as custard apple, sapota, guava, pomegranate and mango with short-duration arable crops like pulses. It is the second most widely practiced agroforestry system in India (6).

The agro-silvi-horticulture system combines horti-silviculture and agri-silviculture systems by incorporating horticultural plant species into the agri-silviculture system to provide consistent revenue to farmers in addition to cultivating crops during the early stages and silviculture species in the later stages, which ensures long-term productivity and arrests land degradation (17, 18). The silvi-pasture system involves the combined cultivation of tree crops with grasses, primarily practiced enhancing feed supply to animals, timber, fuel wood and soil fertility (19). In India, *Leucaena leucocephala* and *Gliricidia sepium* are the commonly cultivated tree species under this system (20).

The horti-pasture system integrates fruit trees such as guava, amla (*Phyllanthus emblica*), custard apple and ber with fodder grasses like *Panicum antidotale*, *Cenchrus setigerus*, *Cenchrus ciliaris*, *Chloris gayana* and *Dichanthium annulatum*, along with legumes such as *Macroptilium atropurpureum* and *Stylosanthes scabra*. This is a widely practiced system in semiarid and arid regions of India (21). The agri-silvi-pasture system involves the integration of grasses and crops with woody tree components on a single piece of land, commonly in the humid tropical highlands, aiming at food production, soil conservation, fodder and fuel provision, potentially involving a tree-livestock crop mix with green-leaf manure and wood-hedgerow for grazing (22). The major agroforestry systems under various agro-climatic regions of India are listed below (Table 1).

3. Functions of agroforestry systems

Agroforestry systems (AFS) promote sustainable land management and agriculture by improving soil health, biodiversity and climate resilience. By integrating trees with crops, agroforestry enhances soil health through nutrient cycling and erosion control for improved water retention and utilization. It also promotes the conservation of biodiversity and habitats of natural pests and plays a vital role in carbon sequestration. The major functions are described below:

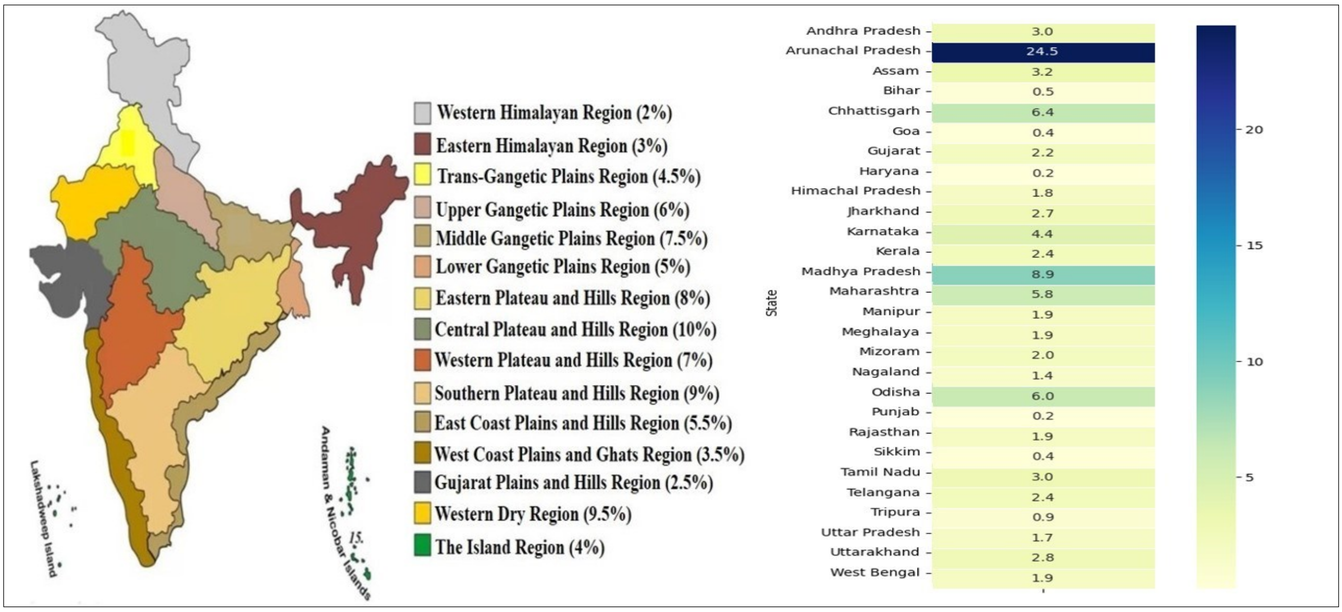

Fig. 1. Area occupied by agroforestry under different zones in India (Forest Survey of India, 2021).

Table 1. Major agroforestry systems under various agro-climatic regions of India

Agroforestry System	Agro-climatic Region	Crops/Trees	References
Agri-horticulture	Western Himalayan Region	*Ocimum sanctum* (Tulsi) + *Prunus armeniaca* (Apricot), *Ocimum sanctum* (Tulsi) + *Prunus persica* (Peach)	(8)
Silvi-pasture	Eastern Himalayan Region	*Morus alba* (Tree fodder) + *Setaria anceps* grass (Green forage)	(123)
Agri-silviculture	Lower Gangetic Plains Region	*Eucalyptus tereticornis* + Wheat + Rice	(124)
Agri-silviculture	Middle Gangetic Plains Region	*Tectona grandis* + Sorghum/Groundnut	(125)
Agri-silviculture	Upper Gangetic Plains Region	*Dalbergia sisso* + Mustard	(125)
Agri-silviculture	Trans-Gangetic plains Region	*Populus deltoides* + Wheat/Potato/Turmeric	(126)
Agri-silviculture	Eastern Plateau and Hills Region	*Albizia procera* + Wheat	(125)
Agri-silviculture	Central Plateau and Hill Region	Acacia + Greengram + Mustard	(124)
Agri-silviculture	Western Plateau and Hills Region	*Ailanthus excelsa* + Cowpea + Mustard	(8)
Silvipasture	Southern Plateau and Hills Region	*Leucaena leucocephala* + *Gliricidia sepium* + *Stylosanthes hamata* (Grass)	(127)
Horti-silviculture	East Coast plains and Hills region	*Acacia mangium* + Pineapple	(127)
Agri-silvi-horticulture	West Coast Plains and Ghats Region	*Artocarpus heterophyllus* (Jack fruit) + *Acacia auriculiformis* + Black pepper	(124)
Silvo-aromatic	Gujarat Plains and Hills Regions	*Melia dubia* + Lemon grass	(128)
Silvipasture	Western Dry Region	Ailanthus + *Panicum antidotale* / *Cenchrus ciliaris* (Fodder)	(124)
Horti-pasture	The Island Regions	*Cocos nucifera* (Coconut) + *Calliandra calothyrsus* (Dry forage)	(127)
Agro-silvi-horticulture	Arid and Semi-arid Zones	Multipurpose trees, fruit trees, crops	(125)
Agri-horticulture system	Indo-Gangetic Plains	Guava, pomegranate, mango, pulses, vegetables	(125)
Horti-pasture system	Semi-arid and Arid Regions	Fruit trees, pasture species	(127)
Agri-silvi-pasture system	Dry lands and Marginal Land	Crops, trees, pasture	(125)

3.1. Improves soil properties

Soil properties including physical, chemical and biological characteristics, define soil health and productivity by influencing the plant growth, water regulation and ecological balance. Agroforestry systems, by integrating trees and shrubs into agricultural lands, improves the soil physical, chemical and biological properties through various mechanisms which were described below:

3.1.1. Physical properties: Tree roots enrich soil, enhance soil structure, limit nutrient leaching and enable nutrient pumping from deeper soil layers (23). Land with tree crops experiences reduced tillage, which helps protect soil aggregates, while tree roots promote the formation of larger soil aggregates (24). However, the extent of this effect depends on tree species, terrain and soil moisture content (25). Various agroforestry systems improve soil health through their synergistic effects, such as crop cover, limited tillage, crop rotation and balanced nutrient management (26). In Bangladesh, jackfruit-based agroforestry systems have shown significant improvements in soil physical properties by lowering soil temperature (3.37-9.25 %) and increasing soil moisture by 10-20 % (27). These systems also reduce soil erosion by 50 % and enhance soil structure by increasing infiltration rates and soil macro aggregate stability (28).

3.1.2. Chemical properties: Tree integration in agricultural fields influences soil parameters, such as pH, cation exchange capacity and nutrient availability (29). Trees help in maintaining a stable soil pH by supplementing organic matter and releasing organic acids during litter decomposition, thus facilitating nutrient mineralization and availability (30). Tree leaf litter nourishes the surface soil with nutrients for crop growth, reduces the quantity of fertilizers needed and thereby improves the economic returns. Additionally, agroforestry systems help in pumping nutrients from deeper layers, which ensures efficient resource sharing between trees and other components (31). The quantum of nutrients added to the soil depends on tree species and their seasonal litter fall (32). However, litter decomposition rate is lesser in temperate regions than in tropical regions (33). It increases soil organic carbon content by 40 %, nitrogen storage by 13 % and accessible nitrogen and phosphorus also (46 % and 11 %, respectively). Additionally, it reduces soil acidity by increasing the soil pH (28).

3.1.3. Biological properties: Soil beneath tree canopies harbours higher microbial biomass and increased the mineralizable nutrients, such as nitrogen, phosphorus, potassium and calcium, as compared to soil in open agricultural fields (34). The rhizosphere of tree species supports diverse microbial communities, which play a crucial role in nutrient transformation under agroforestry systems, enhancing soil fertility more effectively than seasonal cropping alone (35). Biological nitrogen fixation (BNF) also has an inevitable role in enhancing environmental security and soil health since many nitrogen fixers are associated naturally with the tree crops (36), thereby enriching the soil nitrogen pool that serves as a nutrient source for the crop and grass component of the system. Tree integration with field crops also includes animals, which supplement the organic matter and nutrients (37). Among the agroforestry systems, silvi-pasture is the most effective strategy for restoring soil fertility because of its diversity in components *viz*., cattle, crops and trees and the interdependent link between these components that benefits each other (31, 38). Alley cropping systems also significantly influence soil biological properties by enhancing enzyme activities and microbial functional diversity in soil (39).

3.2. Biodiversity

Biodiversity refers to the variety of life at all levels, encompassing genetic, species and ecosystem diversity, including microorganisms, animals and plants within a given ecosystem. It plays a critical role in maintaining ecosystem functions and services, such as nutrient cycling, pollination and pest control (40). Agroforestry systems have greater potential than conventional monoculture farming for diversifying soil organisms, as they provide a habitat for various animals and microbiota (25). The vast variety of soil microbial communities, along with macrofauna, plays vital roles in nutrient cycling, mineralization, chemical degradation and overall maintenance of soil fertility and health (41). Furthermore, it reduces soil-borne diseases by fostering microbial competition that suppresses pathogenic populations (42).

Agroforestry enhances biodiversity and ecosystem connectivity by linking microbial, plant and animal species, thereby facilitating reproduction and genetic diversity (43). It serves as a sustainable alternative to slash-and-burn agriculture and provides habitats for various birds, animals and microorganisms that support nutrient cycling and biogeochemical processes (40). Biodiversity conservation is crucial for maintaining ecosystem sustainability and productivity. Additionally, agroforestry supports traditional farming practices while contributing to sustainable development goals (44). Some studies have demonstrated the significant benefits of biodiversity conservation for the environment and human well-being, such as improved soil fertility, enhanced carbon sequestration and increased resilience to climate change (45, 46). Biodiversity in agroforestry offers a wide range of essential benefits, including both nonmaterial (cultural heritage, ecological knowledge and aesthetic value) and material (food, timber and medicinal plants) and supports environmental governance (47). This positively contributes to agriculture through pest control, pollination and fostering long-term adaptability to disturbances and environmental changes (44), thereby contributing significantly to social and economic progress (47).

The interaction between trees and soil in agroforestry contributes to sustainable agricultural productivity by supporting soil microhabitats that promote biodiversity (Table 2). It also provides shelter for birds and animals (25). In return, this system enriches soil organic matter and enhances biological components, improving moisture retention and nutrient uptake by trees and crops (43). In southern Brazil, integration of native pine and oak species has enhanced the diversity of bird species like Rufous-collared Sparrow (*Zonotrichia capensis*), Chestnut-capped Blackbird (*Chrysomus ruficapillus*), Golden-collared Macaw (*Primolius auricollis*), Southern Beardless-Tyrannulet (*Camptostoma obsoletum*) and Green-barred Woodpecker (*Colaptes melanochloros*) (48). A coffee-based agroforestry system with local indigenous tree species in Mount Elgon increases the population of native tree species like *Ficus albizia* (49) and traditional native species like *Leucaena leucocephala* and *Calliandra houstoniana* in Guerrero, Mexico, contribute to soil fertility and biodiversity are also conserved with the help of home gardens (50). In Mbalmayo, cocoa and banana-based agroforestry system supports the conservation of diverse wildlife, including ungulates and bats (51).

3.3. Pest management

Pest management is a critical aspect of sustainable agriculture, aiming to minimize crop damage caused by pests and diseases while reducing reliance on chemical pesticides (44). Several components of an agroforestry system have pest-repellent properties, thus reducing pest and disease damage (52). Agroforestry promotes natural pest management by supporting beneficial insects and birds, reducing pesticide dependence (53). Additionally, some tree species have insecticidal properties, which reduce the damage caused by insects (54). For instance, the apple trees grown under agroforestry have lesser insect pest infestation than in monoculture systems due to the occurrence of natural enemies of insect pests (52). Carabid beetles, key predators and weed seed consumers, thrive under tree rows during winter, contributing to year-round pest and weed control. Agroforestry systems provide habitats for ground beetles, which prey on smaller insects and form part of a diverse food web supporting birds, small mammals, reptiles and amphibians (55). Root flies were significantly reduced to 38 % as compared to arable fields in agroforestry systems. The presence of pollen beetles and wheat stem sawflies declines by 57 % and 37 %, respectively, in agroforestry systems. In Nottinghamshire, UK, the practice of an apple-based silvoarable system reduced the aphid damage by 13.0 % when compared to mown under storeys and increased the farm income up to 231.02 GBP per hectare (56, 57).

3.4. Carbon sequestration

Agroforestry systems not only fulfil the demands of people and raw materials for small-scale forest-based industries but also enrich the soil with carbon. These systems contribute to both short-term carbon pools through labile soil organic carbon (SOC) derived from decomposing leaf litter and root exudates and long-term carbon storage through recalcitrant woody biomass and stable soil organic compounds (28). While labile SOC fractions cycle relatively quickly and provide immediate benefits to soil fertility, the recalcitrant carbon forms can persist for decades to centuries, offering more permanent climate change mitigation benefits through their extended residence time in the ecosystem (45, 46).

Carbon sequestration is crucial for climate change mitigation, as it removes atmospheric CO_2, from and stores it in long-term sinks such as soils and tree biomass (Fig. 2). Through photosynthesis, trees convert CO_2 into organic carbon, storing it in leaves, stems, branches and roots (58). Carbon sequestration efficiency varies among agroforestry systems and is influenced by factors such as tree species, ecosystem type and environmental conditions (Fig. 3). It demonstrates that increasing the tree species density by 10 units per hectare enhanced the above-ground biomass carbon by 0.8 Mg C ha^{-1} and 1.76 Mg C ha^{-1}, respectively (59). Different agroforestry

Table 2. Biodiversity improvements following the introduction of agroforestry systems

Study Region	Crops	Shannon Diversity Index		References
		Before	After	
Europe	Mixed	1.80	2.45	(129)
Uganda	*Coffea arabica*	2.50	3.10	(49)
Bangladesh	Mixed native species	1.70	2.20	(130)
Portugal, Brazil	Mixed native species	1.60	2.40	(131)
Southeast Asia	Mixed crops and trees	0.70	0.90	(132)

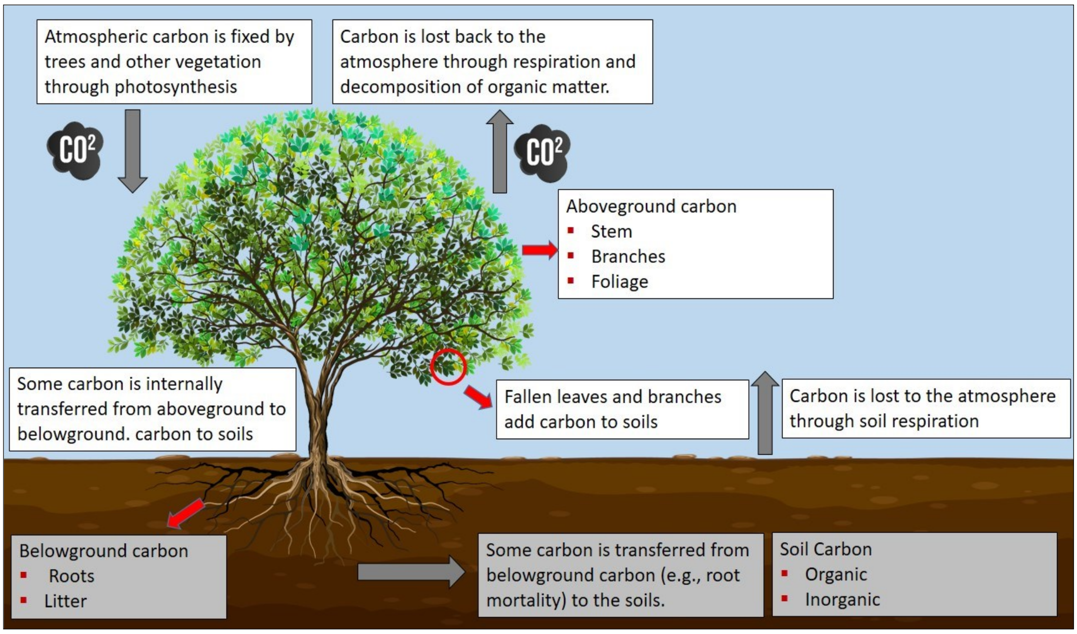

Fig. 2. Carbon sequestration under tree crop.

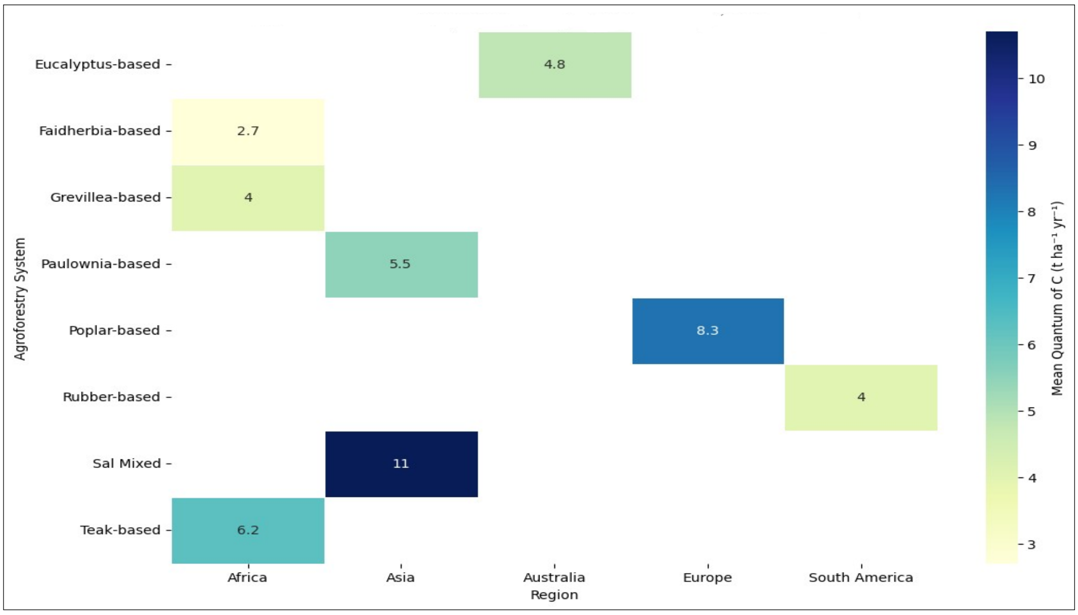

Fig. 3. Quantity of carbon sequestration under various agroforestry systems in different regions.

systems demonstrate varying carbon storage potentials and tropical ecosystems generally showing higher sequestration rates due to its rapid growth and high biomass accumulation (60). Agroforestry practices have shown substantial potential for carbon storage, with estimates ranging from 1.5 to 3.5 Mg C ha^{-1} $year^{-1}$ in tropical regions (61). Agri-silvicultural systems demonstrate higher carbon sequestration potential when compared to mono-cropping and the carbon storage varying between 23.61 and 34.49 t C ha^{-1}. In terms of soil organic carbon (SOC) intercropping of trees with crops has shown significant enhancement and the increase in SOC was 33.3-83.3 % under fast-growing species like *Populus deltoides* and *Eucalyptus* hybrid systems, which sequester carbon rapidly but come with significant ecological implications (62). Traditional systems like *Prosopis cineraria* have demonstrated a 50 % increase in SOC through leaf litter contribution. Many research indicates that silvi-pastoral systems accumulate from 5.41 to 8.6 t ha^{-1} $year^{-1}$ of biomass, with carbon storage ranging from 1.89 to 3.45 t C ha^{-1} (63). These findings emphasize that proper nutrient management in agroforestry systems significantly enhances the carbon sequestration potential while providing additional environmental and economic benefits. Tree roots contribute significantly to soil carbon storage through decomposition and exudation of organic matter (64, 65), while tree canopies influence soil organic matter decomposition rates by modifying microclimates (65). Diverse ecosystems with multiple tree species typically exhibit higher carbon sequestration potential as compared to monoculture plantations (59), highlighting the importance of biodiversity in enhancing ecological resilience and carbon storage capacity.

3.4.1. Organic fertilizers : Organic farming practices significantly enhance carbon sequestration through multiple mechanisms. Increased application of organic inputs through composts, cover crops, crop residues and animal manure contribute substantially to soil organic matter build-up (61). The integration of trees in agricultural systems, along with appropriate nutrient management strategies, has shown significant potential for enhancing carbon sequestration (66). Reduced soil disturbance through minimal tillage in organic farming helps preserve soil structure and prevents organic matter breakdown, enabling long-term carbon accumulation (67). Organic farming supports diverse and active soil microbial communities that break down organic matter into stable forms, improving carbon storage, soil fertility, water retention and overall soil health while helping climate change mitigation (66).

Grewia optiva-based agroforestry systems significantly improved the biomass carbon density (106.11 Mg ha^{-1}) and carbon sequestration rates (6.64 Mg ha^{-1} yea^{-1}) when compared to mono-cropping systems. Organic fertilizers, particularly farmyard manure (FYM), positively influenced the soil organic carbon content through improved soil physicochemical properties and enhanced microbial activity. Application of organic amendments led to better carbon accumulation in both biomass and soil pools as compared to inorganic fertilizers. Tree density plays a crucial role in carbon sequestration, with closer spacing (10 m × 1 m) leading to higher carbon storage capacity than wider spacing configurations (68). The significance of various agroforestry systems, with carbon sequestration potential ranging from 0.29 to 15.21 Mg ha^{-1} $year^{-1}$ (69). These results suggest that optimizing tree spacing can significantly enhance the carbon storage capacity of agroforestry systems.

Organic manures play a vital role in agroforestry systems like silvopasture, riparian buffers and alley cropping by enhancing soil organic carbon (SOC) and nutrient cycling (70). These systems integrate organic materials like farmyard manure (FYM), crop residues, compost and biochar, which improve soil structure, water retention and microbial activity. The leaf litter from trees like *Acacia* and *Eucalyptus* in riparian buffers contributes significantly to SOC and nutrient availability. Applying FYM at 10-20 tons per hectare and biochar at 5-10 tons per hectare annually provides a slow but sustained release of nutrients (62). These practices are effective in sequestering 12-31 tons of carbon per hectare per year in a silvopasture systems, primarily in soil and tree biomass. Organic inputs also reduce greenhouse gas emissions, making them a sustainable solution for soil fertility and carbon storage in agroforestry systems (71). In silvopasture and riparian buffer agroforestry systems, inputs such as leaf litter, farmyard manure (FYM) and crop residues play a crucial role in improving soil organic carbon (SOC) and fertility. These practices enhance the microbial activity, nutrient cycling and soil structure, leading to long-term carbon storage. In poplar -based agroforestry systems, SOC increased up to 83 % as compared to monocropping systems (72). Silvopasture systems with species like *Albizia* and *Leucaena* sequestered 6.72 tons of carbon per hectare annually by outperforming natural grasslands (73).

3.4.2. Inorganic fertilizers: The judicious application of inorganic fertilizers enhances biomass production and carbon fixation in agroforestry systems such as alley cropping, multistory cropping and windbreaks. These systems benefit from rapid nutrient availability of urea, single super phosphate and muriate of potash, which improve soil fertility and plant growth (74). This approach maximizes nutrient use efficiency during critical crop growth stages. Such practices not only increase the crop yields but also enhance SOC through biomass incorporation and reduced soil erosion. Inorganic fertilization in alley cropping has been shown to sequester up to 27 ± 14 tons of CO_2 per hectare annually, emphasizing the importance of balanced inorganic fertilizer application in agroforestry (75).

Water-soluble fertilizers (WSFs) play a crucial role in improving nutrient use efficiency and promoting sustainable practices in agroforestry systems (76). Fertigation, a technique where WSFs are applied through drip irrigation system, enhances the nutrient availability and synchronization with tree and crop nutrient demands. This method is particularly effective in increasing the efficiency of nutrient uptake, reducing nutrient losses through leaching and improving water productivity (77). Fertigation practices in agroforestry have shown significant improvements in tree growth, biomass production and overall agroforestry system productivity (78). The split application of N:P:K fertilizers (125-250 g per seedling) in hybrid *Eucalyptus* crop showed enhanced growth and biomass accumulation (79). Similarly, fertigation in teak plantations on medium black soil significantly increased the tree height, diameter, basal area and volume (80). Moreover, application of WSFs through fertigation optimizes nutrient delivery during critical crop growth stages, reduces the environmental impact by minimizing nutrient runoff and leaching while improving the economic returns of agroforestry systems by promoting faster crop growth rates and higher yields, thereby significantly contributing to sequestration of atmospheric carbon.

3.4.3. Integrated nutrient management : Integrated nutrient management (INM) and conservation agriculture (CA) practices enhance carbon sequestration while improving soil health across various agroforestry systems. INM integrates organic and inorganic inputs to optimize nutrient use efficiency and carbon sequestration in agroforestry systems like silvopasture and riparian buffers (58). Conservation agriculture practices such as push-pull polyculture and parkland agroforestry combined with proper nutrient management significantly increased the soil organic carbon levels, particularly in topsoil (0-30 cm, 81). The study reports that conventional tillage practices resulted in 23.6-35.3 % lesser soil organic carbon as compared to conservation approaches (81). Carbon sequestration in agricultural systems, particularly in cocoa agroforestry, has emerged as a better strategy for climate change mitigation while maintaining agricultural productivity. INM approaches not only improve carbon sequestration but also help in reducing greenhouse gas emissions. INM led to 11-24 % reduction in N_2O emissions from lowland rice (82). The effectiveness of these practices varies across different agro-ecosystems, with temperate regions showing more pronounced benefits when compared to tropical and subtropical regions (83). Long-term research shows that combining conservation practices with integrated nutrient management practices enhance carbon sequestration rates (0.3-0.76 Mg ha^{-1} yea^{-1}) across various geographical regions (84). Recent research on 47 cocoa agro-forests in Brazil found that these systems stored an average of 55 Mg C ha^{-1}, with shade trees contributing 93 % of total carbon stock (85).

However, farms that regularly applied with organic or inorganic fertilizers achieved yields above the global average of 500 kg ha^{-1} without compromising carbon storage. Notably, farms maintaining 53 % shade coverage and at least 68 shade trees per hectare achieved optimal carbon stocks of 65 Mg ha^{-1}.

The research demonstrated that sustainable intensification through proper nutrient management could enhance productivity while maintaining significant carbon reserves. The study emphasized that the type of fertilization (organic *vs.* inorganic) was less critical than the consistency of application, with approximately 65 % of fertilizing farms using chemical fertilizers, 27 % using organic fertilizers and 8 % implementing an integrated nutrient management approach combining both methods. These findings highlight the potential for balancing agricultural productivity with ecosystem services through appropriate nutrient management strategies.

Integrated nutrient management (INM) in poplar-based agroforestry systems has shown significant potential in improving soil health and carbon sequestration. For example, intercropping turmeric with poplar trees resulted in a total carbon sequestration of 436.47 Mg ha^{-1} under 4 × 4 m spacing, highlighting the importance of spatial arrangement in carbon storage. Notably, the research found positive correlations between soil biological properties and organic carbon content, suggesting that organic and integrated nutrient management practices effectively enhance both soil health and carbon sequestration potential in agroforestry systems (86). Silvopasture systems benefit from improved microbial activity and reduced nutrient losses, while riparian buffers enhanced the nutrient cycling and SOC stabilization. INM practices in silvopasture systems sequestered 15-35 tons of carbon per hectare annually, while riparian buffers under INM significantly reduced the soil erosion and stabilizes 40 % more carbon than conventional systems (58). Hence INM represents a sustainable, balanced approach for best nutrient management and climate mitigation (Fig. 4).

4. Strategies to enhance biomass production

Enhancing biomass production in agroforestry systems is essential for achieving sustainable land management and optimizing multiple ecosystem services. Maximizing biomass production in agroforestry requires effective nutrient management strategies that enhance growth, yield and system sustainability.

4.1. Nutrient management

Nutrient management in agroforestry is a critical factor that directly affects system productivity and overall economic viability. The timing and placement of nutrients during early and late growth stages of the crop determine whether tree-crop interactions are facilitative or competitive. Addition of organic manures significantly improved the yield, dry matter production and oleoresin content of ginger and turmeric as compared to conventional fertilization method (87). A comparative examination of various nutrient sources such as nitrogen, phosphorus, potassium (NPK: 200 kg ha^{-1}), poultry manure (PM), magnesium fertilizer (20 kg ha^{-1}) and their combinations revealed that use of NPK + 20 kg Mg ha^{-1} has improved the turmeric rhizome yield by 13.6 %. Similarly, other conventional approaches, use of 100 % NPK + 5 t vermicompost produced the best outcome in terms of plant height and cob production in maize (88). The maximum grain yield, starch content and crude protein content in maize were recorded with the addition of vermicompost at 5 t ha^{-1} along with 75 % RDF (89). For linseed and poplar, applying 125 % of recommended farmyard manure (FYM) led to higher plant growth and yield (90). In pea, a combination of 100 % Zn and 50 % of the recommended N, P and K significantly increased the number of pods per plant (19.53), seeds per pod (6.20) and pod yield (77.67 q ha^{-1}) (91). Furthermore, combined application of 50 % prescribed nitrogen and *Pongamia* cake to turmeric plants has shown greater fresh rhizome production (43.94 t ha^{-1}, (92)). Integrated nutrient management practices in paddy and wheat with *Casuarina equisetifolia* based agroforestry system recorded higher grain yield (93). Planting brinjal in an interspacing of 3 × 2 m in teak showed maximum growth and yield with 100 % RDF (100:50:50 NPK ha^{-1}). Darjeeling tea production achieved the highest yield when supplemented with 50 % recommended nitrogen and vermicompost (21). These studies highlight the importance of tailored nutrient management strategies to enhance biomass production and crop yields in diverse agroforestry systems.

4.2. Soil health management

Organic manures and biofertilizers play a vital role in preserving and improving soil health, which is essential for sustainable agriculture operations. These amendments enhance soil physical properties by improving structure and water retention, boost biological activity through diverse microbial communities and contribute to overall ecosystem health by promoting nutrient cycling and carbon sequestration.

4.2.1. Organic manures: Organic manures supply essential nutrients stimulating microbial processes that enhance nutrient availability in soil (94). These materials modify the microclimate, stimulate soil fauna and flora, influence moisture regimes and regulate root-zone temperature (25). Fresh organic matter acts as a nutrient source, promoting the

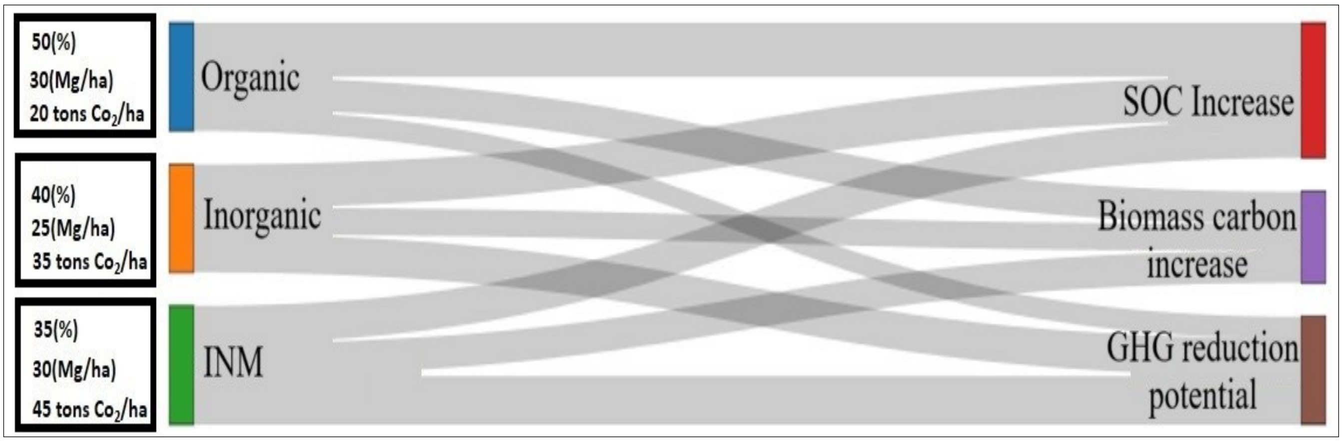

Fig. 4. Carbon sequestration under different nutrient management in agroforestry system.

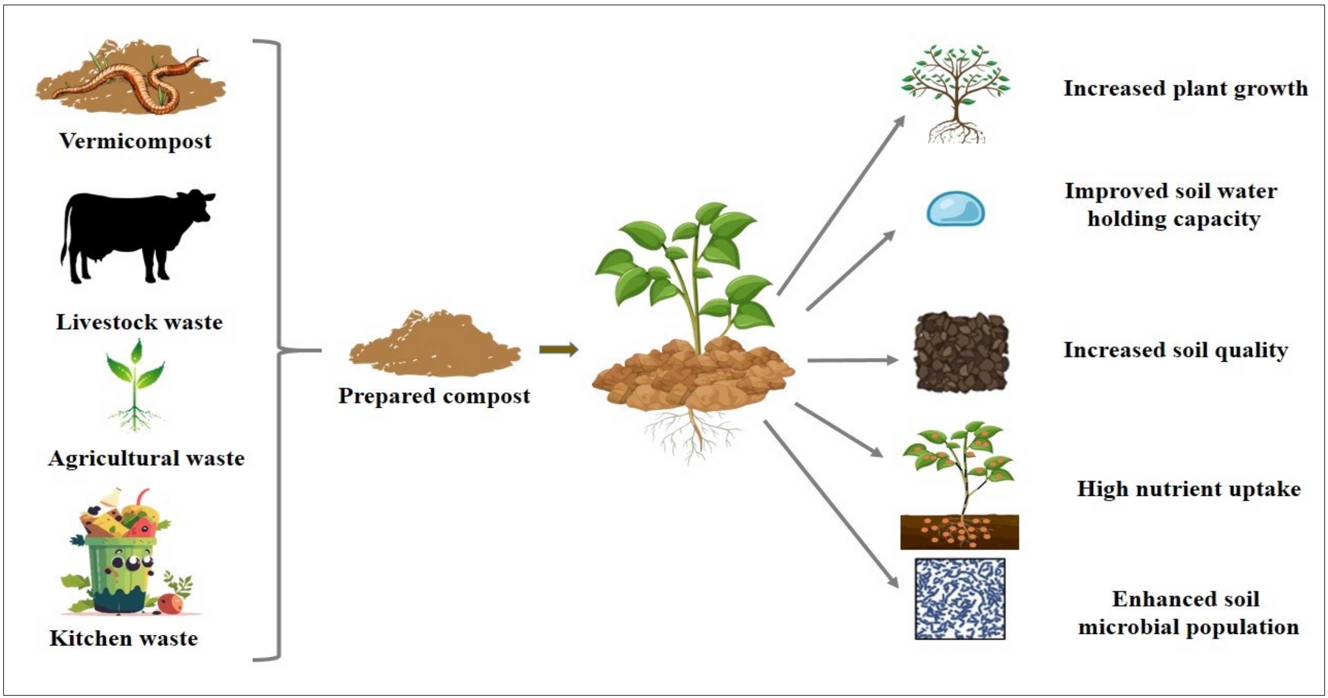

Fig. 5. Impacts of organic manures on soil health.

growth and activity of diverse microorganisms in soil (95). Fig. 5 depict the impacts of organic manures on soil health. Organic fertilizers provide slow-release nutrients that align with plant uptake patterns, though they require bulkier application compared to inorganic alternatives. Microbial biomass refers to total living microbial community in soil, plays an important role in nutrient cycling and soil fertility. The application of organic manures enhances microbial populations, including beneficial mycorrhizal fungi and nitrogen-fixing bacteria (96). By increasing the mycorrhizae, nitrogen-fixing bacteria and growth-promoting substances in soil, it helps to improve the crop performance (97).

Addition of organic materials such as sawdust, crop residues and bark compost to agricultural soils improved the growth and vitality of Scots pine (*Pinus sylvestris*) plantations; among these, bark composts were most effective in enhancing shoot growth, needle biomass and needle length as compared to those in control plots (98). The application of 20 g of vermicompost and 20 g of poultry manure per tree to *Melia dubia* seedling has significantly improved various growth parameters, like root length, root diameter, shoot length, root-to-shoot ratio, seedling dry weight and chlorophyll content in plants due to enhanced nutrient uptake and soil microbial interactions (99). These amendments also increased the seedling survival rates (88-92 %) and plant height by 4-7 cm when compared to control treatments in pine plantations (100). The improvement is likely due to better nutrient availability and enhanced microbial interactions in the rhizosphere. Microbial populations in *Melia dubia*-foxtail millet-based agroforestry systems under organic nutrient management practices have reported that application of organic manures such as FYM, vermicompost and poultry manure combined with panchagavya and vermiwash foliar sprays after 60 days, had the greatest bacterial, fungal and actinomycete populations in the *Melia dubia* and foxtail millet-based agroforestry system (101). The use of organic multipurpose fertilizer (OMF) in *Acacia crassicarpa* seedlings reduced the occurrence of major diseases such as *Fusarium* wilt, *Xanthomonas* leaf blight and leaf spot disease caused by *Phaeotrichoconis* or *Pestalotiopsis* (102). In Casuarina, biochar and manure addition enhanced the soil phosphorus and nitrogen availability, resulting in improved seedling height and collar diameter as compared to control. The combination of 20 % biochar and 10 % manure had the greatest effect on phosphorus availability and seedling height and seedling quality (102).

4.2.2. Inorganic fertilizers: Inorganic fertilizers are concentrated sources of important nutrients in an easily available form for plants (103). However, these concentrated nutrient sources can be lost through leaching, volatilization, or runoff if not properly applied (104). Furthermore, proper inorganic nutrient management practices are found to increase the nutrient use efficiency and economic yield of many agroforestry systems. Application of NPK fertilizers in older longleaf pine stands on poor sandy soils helps in augmentation of higher biomass production and farm income (105). Pine grown in wider spacing of 2.5 × 5.0 m also shows increased seedling growth by the addition of 50 kg nitrogen per hectare (106).

In a teak-groundnut-based agroforestry system, application of 50 kg urea ha^{-1} significantly increased the tree height, diameter and groundnut yields by 20-30 % (107) and in a poplar-based alley-cropping system, supplementation of 80 kg ammonium nitrate and urea ha^{-1} increased the intercrop yields of wheat, barley and rapeseed by 15-20 % as compared to monoculture systems (108). Phosphorus fertilization in Eucalyptus plantings increased the wood volume and biomass production by NPK uptake (109, 110). Application of diammonium phosphate (DAP) at 60 kg ha^{-1} in leguminous tree -maize-based systems increased the maize yields by 35 % and increased the synergistic effect of phosphorus fertilization and nitrogen fixation by leguminous trees, as evidenced by increased nodule formation (111). Single superphosphate (SSP) applied at 50 kg ha^{-1} to the mango-vegetable agroforestry system increased the fruit yield by 25 % and vegetable yield by 30 % (27). In shea-millet-based parkland systems, application of ammonium nitrate at 60 kg ha^{-1}

increased the millet yields by 25 % and soil nitrogen levels because of associated leguminous trees (110). Application of 80 kg potassium sulphate per ha improves the quality of olive oil and intercrops yield up to 15-20 % in olive tree-based systems (108).

Potassium fertilization significantly influences tree growth, fruit production and intercrop yields in agroforestry systems. In acai palm-based systems, applying 40 kg triple superphosphate ha^{-1} increased the acai fruit yield by 30 % and boosted the productivity of intercrops such as beans and corn by 25 % (111). Application of 90 kg muriate of potash per ha increases the growth of poplar trees and enhanced 20 % wheat and rice yields in poplar-wheat and poplar-rice-based systems (27). The beneficial effects of potassium fertilizers in enzyme activation, water regulation and carbohydrate transport, collectively improve plant vigour and productivity. In banana-coffee systems, application of muriate of potash (MOP) at 100 kg ha^{-1} significantly increases the banana yields by 20 % and coffee bean quality and quantity by 15 % (111). Fig. 6 provides an overview of the impact of inorganic fertilizers on yield improvements across different agroforestry systems, highlighting the role of nitrogen, phosphorus and potassium fertilization in enhancing productivity.

4.2.3. Bio-fertilizers: Bio-fertilizers play a crucial role in integrated nutrient management by enhancing soil productivity, sustainability and environmental preservation in agriculture. It offers eco-friendly and cost-effective alternatives to chemical fertilizers, serving as a renewable source of plant nutrients (112).

Recent reports have indicated that bio-fertilizer application has significantly reduced the nematode reproduction and migration in *Pinus pinaster* (59, 113). Additionally, it prevented water loss and chlorophyll degradation while inducing the biosynthesis of phenolic compounds in tolerant *Pinus pinea*. They also observed that application of bio-fertilizers is a potential, sustainable and cost-effective strategy for managing pine wilt disease. Other studies also reported that, application of 10 g of *Azospirillum*, *Azotobacter and* phosphate-solubilizing bacteria (PSB) consortia per seedling has released growth compounds which increased root length, shoot length, root-shoot ratio, collar diameter, leaf number, total length, biomass production and Dickson's quality index in *Melia dubia* (99, 114). Application of *Frankia* and phosphorus-solubilizing bacteria (PSB), either alone or in combination, had a positive impact on the growth and nutrient uptake by *Casuarina junghuhniana* seedlings (115).

A study on the growth-promoting effects of a microbial consortium comprising a nitrogen-fixing bacterium (*Agrobacterium* sp. CGC-5), an arbuscular mycorrhizal fungus (*Claroideoglomus* sp. PBT03) and an actinobacterium (*Kitasatospora* sp. TCM1-050) on teak seedlings at nursery stage showed increased growth and development (116). At the same time, inoculating *Acacia auriculiformis* seedlings with a selected microbial consortium (*Bacillus coagulans* + *Trichoderma harzianum* + *Azotobacter chroococcum* + *Scutellospora calospora*) in the nursery has significantly improved their growth and nutrient uptake (Table 3). Furthermore, these inoculated plants planted in wastelands exhibited 52 % greater growth than un-inoculated plants after six years of planting (117).

4.3. Planting methods in multifunctional agroforestry

Effective planting methods in agroforestry are essential for maximizing the benefits of integrating trees into agriculture landscapes. Various techniques are used to optimize land use, enhance soil fertility, reduce erosion and improve overall productivity.

Alley cropping: This method involves planting trees or shrubs between rows of crops or grasses to improve light transmittance, reduces erosion and increased the soil fertility through leaf litter decomposition (118).

Boundary planting: In this approach, trees are planted around the edges of agricultural fields to serve as windbreaks, mark property line and minimize soil erosion (119).

Contour planting: This widely practiced method is designed for sloped or hilly terrain, where trees and crops are planted along the natural contours of the land. It helps prevent soil erosion, improves water infiltration and enhances moisture retention (120).

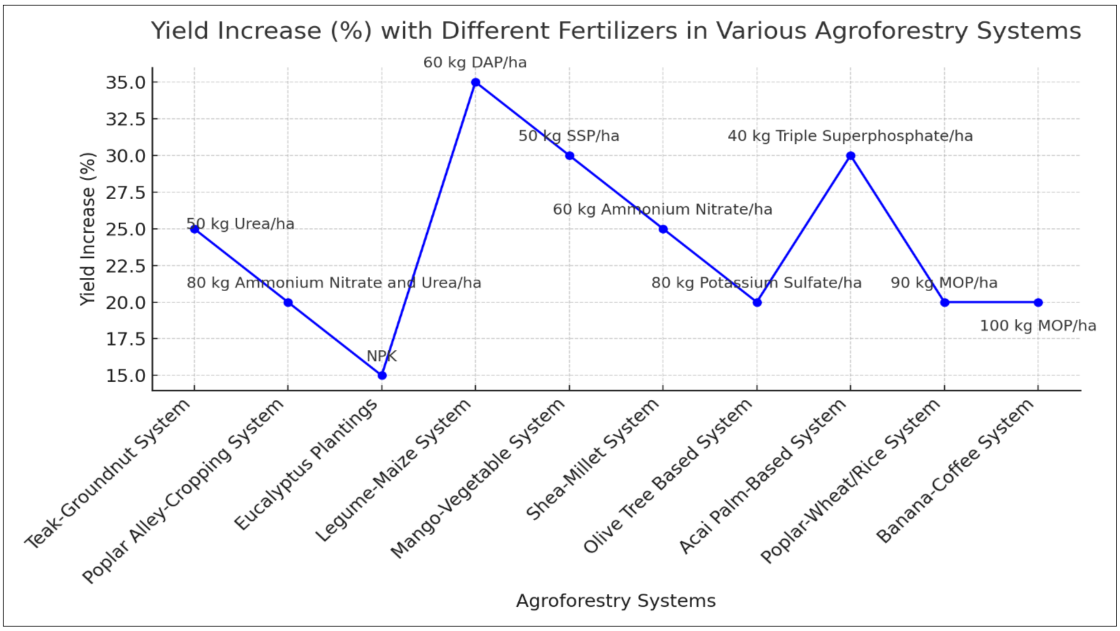

Fig. 6. Impact of inorganic fertilizers on yield of crops under various agroforestry systems.

Table 3. Impacts of different fertilizer management practices on tree crops

Approaches	Sources	Crop	Observation	References
Inorganic	Urea	Pine	Increased seedling growth parameters	(105)
	NPK	Longleaf pine	Increased wood growth and pine straw production cost effective	(13)
	Phosphorus	Eucalyptus	Increased wood volume (16-66 %) and NPK uptake, decreased understory biomass	(17, 18)
Organic	Bark compost	Scots pine	Improved shoot growth, needle biomass and length	(98)
	Vermicompost	Teak-based agroforestry	Improved soil fertility and productivity	(133)
	Farmyard Manure (FYM), Compost, Green Manure, Vermicompost	Various crops	Improved microbial processes, nutrient availability and soil health	(94, 95, 97)
Biofertilizers	Biofertilizer (*Azotobacter*, *Azospirillum*, PSB)	*Melia dubia*	Increased seedling height, collar diameter, leaf number, total length, biomass production and Dickson's quality index	(116)
	Microbial consortium	Teak, *Acacia auriculiformis*	Promoted growth development and nutrient uptake	(116, 117)
	Rhizobium, *Azospirillum*, *Azotobacter*, *Phosphate-Solubilizing Bacteria (PSB)*, *Mycorrhiza*, *(AMF)*	Various crops	Enhanced soil productivity, sustainability and environmental preservation	(112, 113)
INM	NPK + Vermicompost	Sandalwood, Swietenia, *Melia dubia*	Improved growth parameters and biomass accumulation, chlorophyll content and seedling quality index	(97, 106)
	Vermicompost, Poultry manure, FYM	*Melia dubia*	Improved root length, root diameter, shoot length, root-to-shoot ratio, seedling dry weight and chlorophyll content in plants. Increase bacterial, fungal and actinomycetes population in soil	(99, 101)
	AM, Rhizobium, Lime, Mustard oil cake	*Acacia mangium*	Improved growth, root development and nutrient uptake	(117)

Shelterbelts: grasses, shrubs and trees are planted perpendicular to the prevailing wind to protect crops from wind damage and prevent soil erosion (47).

Scattered tree planting: Trees are randomly distributed across crop fields to provide shade and improve microclimate conditions, benefiting crop growth and biodiversity (47).

Taungya system: This traditional agroforestry method integrates forestry and agriculture, allowing farmers to grow crops during the early stages of tree establishment. This system generates income during the initial non-productive phase of tree growth (121).

Integrated taungya system: Similar to taungya system, but once tree canopies are close, grazing animals are introduced in place of agricultural crops, optimizing land use efficiency (47).

Strip method: trees and crops are planted in alternating strips, which helps reduce wind erosion and maintain soil stability (122).

Conclusion

Agroforestry systems intentionally integrate trees, crops and/or livestock in the same land-use system to obtain sustainable farm income throughout the year, where the selection of trees depends upon the environmental conditions of the area. It satisfies various economic needs through income diversification and provides solutions for global challenges in climate change, food security and environmental degradation by incorporating trees and shrubs into agricultural landscapes. It also provides a wide range of benefits like enhanced soil health, water management, biodiversity, pest management, nutrient cycling and carbon sequestration. These systems directly contribute to SDG 13 (Climate Action) through carbon sequestration and climate resilience and SDG 15 (Life on Land) by promoting biodiversity and preventing land degradation. Despite its long history, agroforestry's full potential remains underutilized. Hence, the collection and coordination of efforts are required across research, extension, breeding programs, integrated management strategies and supportive policies to promote the widespread adoption of agroforestry. Agroforestry is also a sustainable strategy for better land-use management that helps in balanced food production, environmental protection and economic growth, which in turn ensuring food security and conserving natural resources for future generations.

Future perspectives

This review highlights several future directions for biomass enhancement and strategies in agroforestry systems. Improved practices of assessment, mapping methodologies for precise assessment of agroforestry systems are needed. Breeding programs must also be conducted for domesticating agroforestry species with desirable traits. Through sporadic research nutrient management practices are available, optimizing doses for augmenting the biomass production and efficiency of crops needs further investigation. Agroforestry's potential in climate change, carbon sequestration and development of resilience strategies has been studied by many researchers. However, the short- and long-term effect on agroforestry system services still needs to be studied in detail. Investigations on soil health, erosion control and water use efficiency are crucial for soil and water conservation. Biodiversity conservation efforts need to include assessments of species richness, habitat connectivity and ecosystem services. Promoting agroforestry systems is an important strategy for sustaining the livelihood of farm families and this requires continuous and consistent research efforts particularly in areas such as market access value chain development and adoption of climate-resilient species.

Authors' contributions

SK helped in collecting literature, investigation, analysis & interpretation, writing - original draft preparation; TC assisted with conceptualization, supervision, visualization, writing, reviewing and editing; SS, KTP and MM carried out writing, reviewing and editing.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no competing interests.

Ethical issues: None

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