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Integrated Nutrient Management Practices in Agroforestry

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ABSTRACT

Agroforestry is a transformative land-use strategy that integrates trees, crops, and livestock into cohesive systems, promoting sustainability through enhanced environmental, economic, and social outcomes. By blending diverse plant and animal species, agroforestry systems foster ecological balance and resilience, supporting biodiversity, soil health, and water conservation. Proper management of these resources, particularly soil, water, and biodiversity, is crucial for maximizing both ecological and economic benefits. Effective soil management enhances nutrient cycling and improves soil structure, ensuring long-term productivity. Integrated Nutrient Management (INM) combines organic and inorganic fertilizers to boost soil fertility and plant health, promoting growth while maintaining environmental integrity. The success of INM relies on factors such as soil characteristics, climate, and plant species, all influencing its effectiveness in agroforestry systems. These variables impact nutrient dynamics, necessitating adaptive management practices. Moreover, socio-economic factors such as land tenure, farmer knowledge, and market access influence the adoption and success of INM practices. Therefore, understanding the local context and incorporating these elements into agroforestry planning is essential for maximizing its benefits. The integration of efficient resource management with INM in agroforestry systems is vital for achieving long-term sustainability, ensuring food security, and promoting environmental conservation. Agroforestry optimizes nutrient use and promotes plant synergy, offering sustainable solutions to global challenges like climate change and food security.

KEYWORDS: Biochar, biodiversity, cost, INM, sustainable food production

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1. INTRODUCTION

Agroforestry fosters sustainable land use by integrating trees, crops, and livestock, providing environmental, economic, and social advantages. It boosts biodiversity, enhances soil health, and combats climate change through carbon sequestration and reduced greenhouse gas emissions, promoting a more resilient and productive ecosystem. (Muchane et al., 2020; Sollen-Norrlin et al., 2020; Pantera et al., 2021). Economically, agroforestry offers farmers diversified income streams, increasing resilience to market volatility and crop failures. It also enhances productivity by optimizing resource utilization, creating a more stable and profitable farming system while reducing dependence on single crops. (Sarvade et al., 2014a; Sarvade et al., 2014b). Socially, agroforestry enhances food security by offering a diverse range of food and raw materials. It also empowers rural communities by promoting sustainable land management practices, fostering local resilience and supporting the well-being of households through improved livelihoods and resource access. (Sarvade and Singh 2014, Sarvade et al., 2014c). Additionally, agroforestry is essential for water conservation, combating soil erosion, and rehabilitating degraded lands. It serves as a key element in sustainable agricultural systems, effectively balancing ecological health with the needs of human communities by fostering long-term environmental stability and resource management. (Sarvade et al., 2019a, Willmott et al., 2023).

Effective resource management in agroforestry is vital for optimizing ecological and economic outcomes. By strategically managing resources like soil, water, and biodiversity, these systems boost productivity, improve soil quality, and strengthen climate resilience, ensuring long-term sustainability and enhancing both environmental and economic benefits. (Fahad et al., 2022). In agroforestry, effective resource management ensures a harmonious balance between trees, crops, and livestock, enhancing beneficial interactions while minimizing competition. Well-managed systems help reduce soil erosion, improve water retention, and increase nutrient cycling, leading to more sustainable and productive agricultural landscapes that support both environmental health and farming productivity. (Muhie, 2022). Strategic resource management in agroforestry can also play a crucial role in mitigating climate change impacts by sequestering carbon and providing habitats for diverse species (Jose 2009). Ultimately, integrating these management practices is essential for ensuring long-term sustainability, food security, and environmental conservation. (Sarvade and Singh, 2014, Sarvade et al., 2014c).

INM in agroforestry systems is a holistic approach that integrates organic and inorganic nutrient sources to optimize soil fertility and plant productivity, while maintaining ecological balance (Paramesh et al., 2023). By leveraging the synergistic effects of trees, crops, and occasionally livestock, this method enhances nutrient cycling, improves soil health, and promotes agricultural sustainability. Agroforestry systems, which combine agricultural and forestry practices, offer a unique platform for implementing INM. These systems, from simple configurations like alley cropping and silvi-pasture to more complex structures such as multistrata systems and forest gardens, each present distinct benefits and challenges for nutrient management, making INM a key component of successful agroforestry practices (Nwaogu and Cherubin, 2024).

Soil characteristics, including fertility, pH, and organic matter content, are vital in determining nutrient availability and cycling within an agroforestry system (Gerke, 2022; Sarvade et al., 2014d). Climate factors, particularly rainfall and temperature, affect nutrient leaching, uptake, and the efficiency of fertilizer applications (Wang et al., 2024). The plant species composition, especially the interactions between trees and crops, also plays a significant role in nutrient dynamics. For instance, nitrogen-fixing trees enhance soil fertility (Kim and Isaac, 2022). Additionally, management practices such as organic amendments, proper fertilizer application, and mulching are crucial for optimizing nutrient use and reducing losses (Ahmed et al., 2024).

Socio-economic factors, such as farmers' knowledge, access to resources, and market incentives, play a significant role in the adoption and effectiveness of INM practices (Feliciano, 2022; Rizzo et al., 2024). Moreover, supportive policies, institutional frameworks, and environmental factors like ecosystem conservation further influence the successful implementation of INM in agroforestry systems (Cheikh et al., 2014; Sarvade et al., 2014d). Achieving effective nutrient management requires a customized approach that accounts for the specific interplay of these factors in each agroforestry system, ensuring both sustainable productivity and responsible environmental management.

2. NEED OF INM IN AGROFORESTRY

Researching Integrated Nutrient Management (INM) in agroforestry is essential due to the challenges posed by over-reliance on chemical fertilizers (Chejara et al., 2021; Thakur et al., 2023). Excessive use of chemical fertilizers can lead to soil degradation, diminished organic matter, and long-term fertility issues, as they often supply a narrow spectrum of nutrients (Das et al., 2022; Sarvade and Singh, 2014; Sarvade et al., 2019a; Selim, 2020). Additionally, chemical fertilizers can result in environmental problems like nutrient runoff, which contributes to water pollution and eutrophication (Akinnawo, 2023). In contrast, INM embraces organic practices like composting and cover cropping, which enhance soil health by improving structure, boosting organic matter, and promoting beneficial microbial activity (Shrivastava et al., 2018; Thakur et al., 2021). This holistic approach balances nutrient availability, mitigates environmental risks, and supports sustainable agricultural practices (Wu and Ma, 2015). By combining both organic and inorganic inputs, INM overcomes the limitations of chemical fertilizers, fostering more resilient, productive, and environmentally sustainable agroforestry systems.

3. KEY PRINCIPLES OF INM IN AGROFORESTRY SYSTEMS

3.1. Diverse nutrient sources

Integrated Nutrient Management (INM) utilizes a variety of nutrient sources to optimize soil fertility and boost crop productivity, ensuring the long-term sustainability of agricultural systems. By combining organic inputs like compost, manure, and green manure with inorganic fertilizers, INM enhances nutrient availability while minimizing environmental harm (Wu and Ma, 2015). Organic amendments improve soil structure, stimulate microbial activity, and provide slow-release nutrients, while inorganic fertilizers deliver a quick supply of essential nutrients at critical growth stages (Suhaibani et al., 2020). This diverse nutrient approach enhances nutrient use efficiency and reduces dependency on chemical fertilizers, lowering the risk of soil degradation and pollution (Krasilnikov et al., 2022). Additionally, incorporating biological nitrogen fixers, crop residues, and agroforestry components further enriches the nutrient pool, creating a balanced and resilient agro-ecosystem that supports sustainable farming practices (Martens, 2001; Valenzuela, 2023).

3.2. Efficient nutrient recycling

INM plays a vital role in fostering efficient nutrient recycling within agroforestry systems, ensuring that essential nutrients are consistently replenished and effectively used. By integrating practices such as organic matter incorporation, crop residues, and green manure, INM strengthens natural nutrient cycling processes, returning nutrients to the soil from plant and animal residues (Lei et al., 2022). This approach not only preserves soil fertility but also reduces the reliance on external inputs, cutting production costs and minimizing environmental impacts (Wu and Ma, 2015). Additionally, practices like crop rotation and the inclusion of leguminous plants help fix atmospheric nitrogen, benefiting other crops and reducing nutrient loss through leaching and erosion (Koudahe et al., 2022). The holistic nature of INM ensures nutrient recycling within the system, supporting soil health, long-term agricultural productivity, and decreased dependence on synthetic fertilizers (Mohite et al., 2024; Sande et al., 2024).

3.3. Soil health enhancement

Integrated Nutrient Management (INM) plays a critical role in enhancing soil health by promoting a balanced and sustainable approach to nutrient supply (Pandao et al., 2024). A key aspect of INM's impact is the incorporation of organic matter, such as compost, manure, and green manure, which enriches the soil with vital nutrients and improves its physical properties (Tahat et al., 2020; Koninger et al., 2021). Organic matter increases water retention, improves soil structure, and supports beneficial microorganisms essential for nutrient cycling and soil fertility (Gerke, 2022). As organic materials decompose gradually, they release nutrients over time, ensuring a steady supply that supports crop growth without causing nutrient leaching (Pathariya et al., 2022; Haydar et al., 2024). This gradual nutrient release contrasts with the rapid nutrient availability from chemical fertilizers, which can disrupt soil microbial communities and cause imbalances (Chi et al., 2018). INM practices like crop rotation, cover cropping, and incorporating nitrogen-fixing plants, such as legumes, further improve soil health (Garg, 2007; Scavo et al., 2022). These practices reduce pest and disease cycles, minimize soil erosion, and enhance soil structure by maintaining year-round plant cover. Legumes, in particular, naturally enrich the soil with nitrogen, reducing the need for synthetic fertilizers and minimizing the risk of soil acidification (Akinnifesi, 2007). Furthermore, INM encourages the use of bio-fertilizers and other biological inputs that support soil microbial activity, facilitating the breakdown of organic matter and nutrient release (Mahmud et al., 2021). By integrating these diverse practices, INM not only enhances soil fertility and agricultural productivity but also fosters the long-term resilience and sustainability of agricultural ecosystems (Indira et al., 2023).

3.4. Adaptive management

INM and adaptive managements are closely intertwined, forming essential pillars for sustainable agriculture. Adaptive management within INM focuses on dynamically adjusting nutrient management practices based on ongoing data from the ecosystem (Lin, 2011). This flexible approach accounts for varying factors like climate, soil health, and crop requirements. For instance, farmers may alter fertilizer use or crop rotations based on soil test results, pest pressures, or changing weather patterns (Liu et al., 2016; Yu et al., 2022). Such adaptability ensures the efficient application of nutrients, enhances soil health, and minimizes environmental impacts (Shah and Wu, 2019). By incorporating adaptive management, farmers can increase both productivity and ecological sustainability, creating resilient agricultural systems that respond to shifting conditions while preserving long-term soil and environmental health (Lin, 2011; Liu et al., 2016; Yu et al., 2022).

4. BENEFITS OF INM IN AGROFORESTRY SYSTEMS

INM in agroforestry systems intricately connects soil, plants, and the environment, cultivating a system based on diversity and harmony. As illustrated in Figure 1, one of the primary advantages of INM is its capacity to restore soil fertility through the strategic integration of organic and inorganic nutrient sources (Paramesh et al., 2023; Kumar et al., 2024). In agroforestry, the coexistence of trees and crops creates a dynamic synergy that promotes efficient nutrient cycling (Sarvade et al., 2014d). Organic matter from fallen leaves, pruned branches, and decaying roots enriches the soil, releasing nutrients gradually in sync with plant growth cycles (Usman et al., 2000). Nitrogen-fixing trees play a pivotal role by capturing atmospheric nitrogen and making it available to crops, enhancing soil fertility (Sarvade et al., 2014c; 2014d). This ongoing exchange of nutrients fosters a rich and resilient soil environment, capable of supporting a variety of plant life over time, while reducing the need for synthetic fertilizers and minimizing their environmental impact (Tahat et al., 2020; Krasilnikov et al., 2022).

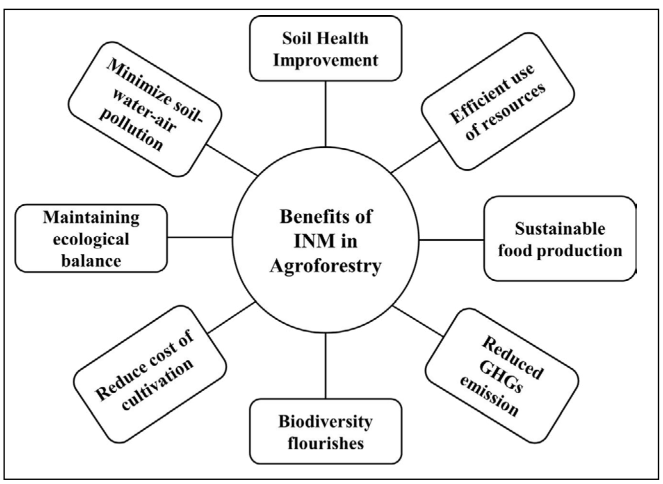

Figure 1: Benefits of integrated nutrient management in agroforestry

In agroforestry systems, INM not only enhances soil health but also fosters a resilient ecosystem where biodiversity thrives (Sarvade et al., 2019a; 2019b). The thoughtful integration of trees and crops creates a multi-layered environment, where deep-rooted trees access nutrients from deeper soil layers and make them available to shallow-rooted crops (Sarvade et al., 2014d). This layered nutrient cycling optimizes resource use and strengthens the system's ability to withstand external stresses like droughts and pest infestations. The diversity of plant species in agroforestry systems attracts a wide range of beneficial organisms, from pollinators to soil microbes, all contributing to maintaining ecological harmony (Bentrup et al., 2019; Pawar et al., 2014; Thakur et al., 2015). This biodiversity serves as a natural defense against pests and diseases, reducing the need for chemical treatments and increasing the overall resilience of the system (Sarvade et al., 2016; Gupta et al., 2015). Economically, INM in agroforestry provides farmers with diversified income streams, yielding not just crops, but also timber, fruits, and other forest products (Singh et al., 2015). By reducing chemical inputs and boosting the productivity of both trees and crops, INM makes agroforestry a sustainable, ecologically balanced, and economically profitable farming practice (Muhie, 2022; Sarvade et al., 2016; Sarveswaran et al., 2023; Tahat et al., 2020).

5. INTEGRATED NUTRIENT MANAGEMENT (INM) PRACTICES IN AGROFORESTRY

Integrated Nutrient Management (INM) in agroforestry employs a combination of organic and inorganic fertilizers, alongside natural biological processes, to sustain soil fertility and boost productivity (Figure 4). Below are several key INM practices implemented within agroforestry systems:

5.1. Use of organic amendments

In agroforestry, incorporating organic amendments such as compost and animal manure is vital for boosting soil health and ensuring long-term sustainability. These inputs enhance soil organic matter, improving moisture retention, soil structure, and mitigating erosion (Fahad et al., 2022; Sarvade et al., 2014d). They also promote microbial activity, improving nutrient availability and reducing soil-borne diseases (Sarvade et al., 2019a; 2019b; Panth et al., 2020). Compost and manure release essential nutrients slowly, diminishing the need for synthetic fertilizers and minimizing environmental harm (Goldan et al., 2023). Another important practice is green manuring, which involves growing and incorporating cover crops into the soil (Sharma et al., 2023). Leguminous cover crops, in particular, fix nitrogen and enhance soil fertility, texture, and moisture retention (Sarvade et al., 2014d). Green manures also help control weeds and prevent erosion, playing a key role in maintaining soil health and ecological balance within agroforestry systems (Sharma et al., 2023; Aulakh et al., 2024).

5.2. Use of biofertilizers (micro inoculants)

Biofertilizers play a crucial role in agroforestry by enhancing soil fertility and promoting sustainable land management practices. These natural products, which include beneficial microorganisms such as mycorrhizal fungi, rhizobia, and blue-green algae, help improve nutrient availability, increase soil organic matter, and boost plant growth. Their classification is represented in figure 2. In agroforestry systems, where diverse tree and crop species are cultivated together, biofertilizers contribute to the establishment of a balanced ecosystem by facilitating nutrient cycling and reducing the dependency on chemical fertilizers (Egamberdiyeva, 2007). Mycorrhizal fungi establish mutualistic associations with tree roots, improving phosphorus absorption, while rhizobia bacteria fix nitrogen from the atmosphere, boosting soil fertility and benefiting neighboring plants. (Maharana et al., 2018, Sarvade et al., 2014d). Additionally, biofertilizers support soil structure and health, leading to increased resilience against pests and diseases. By integrating biofertilizers into agroforestry practices, farmers can achieve improved crop yields, maintain soil health, and foster environmental sustainability, ultimately creating more productive and resilient agroforestry systems (Saha et al., 2023).

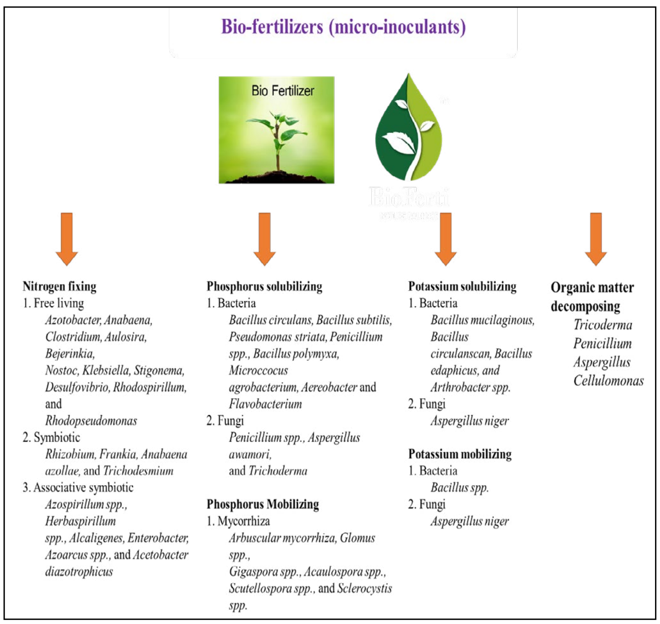

Figure 2: Classification of bio-fertilizers

5.3. Incorporation of nitrogen-fixing trees and shrubs

Integrating nitrogen-fixing trees and shrubs, such as *Acacia*, *Gliricidia*, and *Sesbania*, into agroforestry systems significantly boosts soil fertility and crop productivity. These plants convert atmospheric nitrogen into forms usable by other plants, enriching the soil and decreasing reliance on chemical fertilizers (Peoples et al., 1995; Abd-Alla et al., 2023). Their deep root systems help stabilize the soil, prevent erosion, and enhance water infiltration, while providing shade that benefits understory crops by regulating temperature and conserving moisture. In addition to improving soil health, these trees offer valuable resources like fuelwood and fodder, support biodiversity, and contribute to the sustainability and self-sufficiency of agroforestry systems (Sarvade et al., 2016; Sarvade et al., 2014d) (Table 1).

Table 1: Atmospheric N_2 fixation potential of agroforestry trees (Sarvade et al., 2014d)

Sl. No.	Tree species	N_2 fixation capacity
1.	*Leucaena leucocephala* (Lam.) de Wit.	100–500 kg N ha^{-1} $year^{-1}$ in pure stands 75–100 kg N ha^{-1} $year^{-1}$ in hedgerow intercropping systems
2.	*Sesbania rostrata*	500 kg N ha^{-1} $year^{-1}$
3.	*Faitherbia albida*	20–60 kg N ha^{-1} $year^{-1}$
4.	*Acacia senegal*	
5.	*Tephrosia vogelii*	150 kg N ha^{-1} $year^{-1}$
6.	*Sesbania sesban*	50-100 kg N ha^{-1} $year^{-1}$
7.	*Gliricidia sepium*	
8.	*Albizia lebbek*	
9.	*Acacia mangium*	
10.	*Casuarina equisetifolia* L.	60-110 kg N ha^{-1} $year^{-1}$
11.	*Acacia mearnsii De Wild.*	200 kg N ha^{-1} $year^{-1}$
12.	*Erythrina poeppigiana* (Walp.) Cook	60 kg N ha^{-1} $year^{-1}$
13.	*Gliricidia sepium* (Jacq.) Kunth ex Walp.	13 kg N ha^{-1} $year^{-1}$
14.	*Inga jinicuil*	35-40 kg N ha^{-1} $year^{-1}$
15.	*Indigofera tinctoria* L.	79 kg N ha^{-1} $year^{-1}$

5.4. Mulching

In agroforestry, applying organic materials such as crop residues, straw, and leaves as mulch is an essential practice for promoting soil health and enhancing productivity (El-Beltagi et al., 2022). Mulch helps retain moisture, reduce evaporation, prevent erosion, and preserve soil structure. As it decomposes, it enriches the soil with organic matter and nutrients, reducing the need for synthetic fertilizers (Sarvade et al., 2019a; 2019b). Additionally, mulch helps suppress weeds, minimizing competition for resources (Nwosisi et al., 2019). Living mulch, such as clover or vetch, offers further advantages, including moisture conservation, weed control, erosion prevention, and fertility improvement through nitrogen fixation and organic matter addition (Iqbal et al., 2020). It also provides forage for livestock, enhances biodiversity, and increases the system's resilience to extreme weather events. Both mulch types support the creation of a more sustainable, productive, and ecologically balanced agroforestry system (Wilson and Lovell, 2016).

5.5. *Composting and vermiculture*

On-farm composting and vermiculture are effective, sustainable methods for improving soil health and boosting productivity in agroforestry systems (Oyege and Balaji, 2023). Composting transforms organic waste such as crop residues and animal manure into nutrient-rich compost, enhancing soil structure, moisture retention, and microbial activity, while reducing dependency on synthetic fertilizers (Sayara et al., 2020). This practice also supports environmental conservation by reducing waste and minimizing greenhouse gas emissions (Mathlouthi et al., 2024). Vermiculture, which uses earthworms to convert organic materials into vermicompost, further enhances soil fertility (Rehman et al., 2023). Vermicompost improves nutrient availability, soil structure, and supports beneficial microbes, making it a vital component of agroforestry systems (Saha et al., 2022). Together, these practices help create a self-sustaining, eco-friendly system by recycling nutrients, promoting long-term soil health, and increasing productivity (Saha et al., 2022; Rehman et al., 2023; Oyege and Balaji, 2023).

5.6. *Biochar application*

Incorporating biochar into agroforestry systems offers substantial improvements in soil health and fertility (Alkharabsheh et al., 2021). As depicted in Figure 3, biochar, produced through the pyrolysis of organic materials, enhances both the physical and chemical properties of soil. It boosts nutrient retention, increases soil pH, and promotes the growth of beneficial microbes (Zheng et al., 2018). Its porous structure helps retain vital nutrients, reducing the frequency of fertilizer applications and creating a favorable environment for plant development (Khan et al., 2023). Furthermore, biochar aids in long-term carbon sequestration, supporting climate change mitigation while fostering sustainable soil management and improved productivity in agroforestry systems (Ayaz et al., 2021).

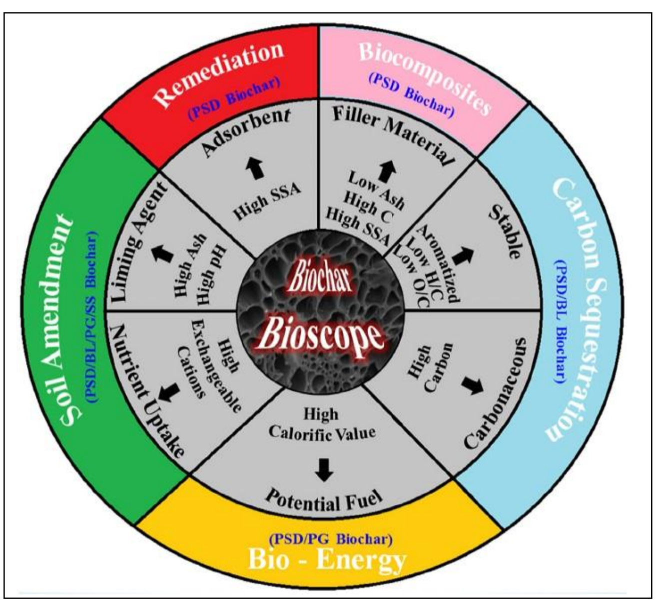

Figure 3: Applications of biochar based on their properties (Srinivasan et al., 2015)

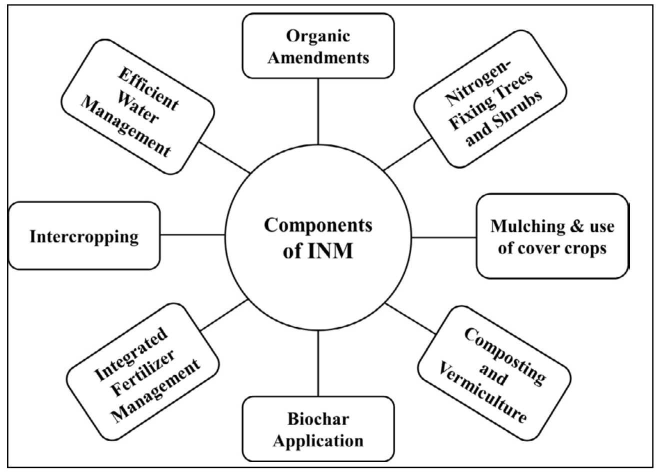

Figure 4: Components of the integrated nutrient management

5.7. *Integrated fertilizer management*

Integrated Fertilizer Management (IFM) plays a pivotal role in agroforestry by optimizing nutrient utilization and ensuring environmental sustainability. By combining organic fertilizers like compost and manure with inorganic ones, IFM addresses the specific needs of diverse plant species and soils (Sande et al., 2024). Soil testing helps tailor fertilizer applications, minimizing waste and environmental impact (Krasilnikov et al., 2022). Cost-effective solutions are crucial for smallholder farmers, and capacity building is vital for successful implementation (Singh et al., 2015; Chambers et al., 2020). IFM practices aim to reduce issues like soil acidification and nutrient leaching, fostering long-term soil health and productivity (Al-Shammary et al., 2024).

5.8. *Intercropping*

Intercropping, an essential practice in Integrated Nutrient Management (INM) within agroforestry, improves soil fertility and resource efficiency by growing a diverse range of crops together. This method enhances nutrient uptake, reduces competition, and strengthens soil health and resilience (Moreira et al., 2024). It also mitigates risks like pest infestations and soil degradation by fostering beneficial organisms and promoting biodiversity (Toker et al., 2024). Leguminous intercrops, in particular, fix nitrogen naturally, reducing the need for synthetic fertilizers and cutting input costs (Peoples et al., 1995; Sarvade et al., 2014d; Abd-Alla et al., 2023). Additionally, the presence of trees and shrubs offers shade and protection, further ensuring the stability and productivity of the agroecosystem (Sarvade et al., 2014c; 2014d; Fahad et al., 2022; Thakur et al., 2023).

5.9. Use of cover crops

Cover crops play a crucial role in Integrated Nutrient Management (INM) within agroforestry, boosting soil health and nutrient cycling (Paramesh et al., 2023). They help protect the soil from erosion, enhance soil structure, and increase organic matter, which reduces nutrient leaching and runoff (Patkowska et al., 2016). Leguminous cover crops are particularly valuable as they fix atmospheric nitrogen, lowering the need for synthetic fertilizers and promoting cost-effective, sustainable farming (Sarvade et al., 2014d). These crops also enhance nutrient cycling by scavenging residual nutrients, improving soil texture, and supporting biodiversity (Quintarelli et al., 2022). Furthermore, they contribute to natural pest control, increase water infiltration, and support root development, ensuring long-term productivity and sustainability in agroforestry systems (Adetunji et al., 2020).

5.10. Efficient water management

Effective water management is essential for Integrated Nutrient Management (INM) in agroforestry, as different plant species such as trees, shrubs, and crops have varying water demands. Key techniques include mulching to conserve moisture, regulate temperature, and control weed growth, along with the use of water-efficient irrigation methods like drip systems or micro-sprinklers to reduce evaporation and runoff (El-Beltagi et al., 2022). Additionally, integrating rainwater harvesting practices further conserves water and minimizes reliance on external water sources (Judeh et al., 2022). By understanding and addressing the specific water needs of each plant species, these practices enhance water use efficiency, promote plant health, and increase the resilience of agroforestry systems, ultimately ensuring their long-term sustainability and productivity (Rolo et al., 2023).

5.11. Soil testing

Soil testing plays a critical role in understanding soil health and nutrient levels, providing farmers with the information needed to customize fertilization practices for different plant species. This approach improves nutrient use efficiency while minimizing waste (Islam et al., 2023). Through regular soil testing, deficiencies, nutrient imbalances, and signs of degradation can be identified early, allowing for more precise applications of fertilizers and amendments, thereby supporting long-term soil health and productivity (Tahat et al., 2020; Das et al., 2022). Moreover, soil tests provide valuable insights into soil microbial activity, enabling the adoption of practices that support beneficial microorganisms. Ultimately, soil testing is an essential tool for sustainable nutrient management, ensuring continued soil vitality and enhanced productivity in agroforestry systems (Bargaz et al., 2018; Paramesh et al., 2023).

6. SYNERGISTIC IMPACT OF INM ON TREE-CROP GROWTH, YIELD, AND SOIL HEALTH

The studies summarized in Table 2 highlight the significant advantages of Integrated Nutrient Management (INM) practices, which combine organic and inorganic nutrient sources to optimize crop productivity while maintaining soil health. By blending chemical fertilizers with organic amendments such as compost, farmyard manure, and bio-fertilizers, INM enhances nutrient availability, improves nitrogen fixation, and stimulates microbial activity in the soil. These practices not only increase crop yields but also improve nutrient use efficiency and water retention, fostering more sustainable farming systems. Moreover, the integration of organic and inorganic inputs reduces reliance on synthetic fertilizers, mitigates soil degradation, and strengthens agricultural resilience, striking a balance between productivity and ecological preservation.

Studies have shown that combining organic manures with inorganic fertilizers significantly boosts the growth of crops such as *Zea mays* (maize). For example, a 50% blend of farmyard manure (FYM) and vermicompost, along with 50% chemical fertilizer, has proven to be highly effective in improving maize production, outperforming the use of either input alone (Garima and Pant, 2017). When nutrient levels were increased by 75%–125% of the recommended dose, crop yield showed a notable improvement (Singh et al., 2023), with organic-inorganic combinations enhancing key soil parameters like organic carbon, nitrogen, and phosphorus.

In black pepper cultivation, combining 75% of the recommended fertilizer dose with bio-fertilizers such as Azospirillum, PSB, and VAM has significantly improved yields. This integrated approach also preserved pepper quality, ensuring stable oleoresin and piperine content (Riyaz et al., 2023). Similarly, INM practices have led to yield increases ranging from 1.3% to 66.5% across various cropping systems, showing the potential of this strategy to boost both productivity and soil health (Paramesh et al., 2023). The integration of organic materials and nutrient retention practices enhances soil aggregation, microbial diversity, and water-holding capacity, offering long-term soil and crop benefits.

In groundnut cultivation, the application of full recommended doses of NPK combined with organic manures like FYM and vermicompost substantially boosted crop growth and

Table 2: Integrated nutrient management in different agroforestry systems

Agroforestry system	Tree	Crop	INM	State/Region / ACZ	Reference
Agri-silviculture	*Populus deltoides* (Poplar)	*Zea mays* (Maize)	50% (25% FYM+25% Vermicompost)+50% chemical fertilizer	Dr. YSPUHF, Nauni, Solan (HP)	Garima and Pant (2017)
	Grewia optiva (Beul)	*Triticum aestivum* (Wheat, HD-3086)	100% FYM (Farm yard manure)	Dr. YSPUHF, Nauni, Solan (HP)	Prakash et al. (2024)
	Melia dubia (Maha Neem)	*Pennisetum glaucum* (Pearl Millet)	75% RDN+Pongamia green leaf manure @10 t ha^{-1}	AICRP on Agroforestry, Rajendranagar, Hyderabad	Chandana et al. (2021)
	Populus deltoides (Poplar)	*Triticum aestivum* (Wheat); *Zea mays* (Maize) and *Vigna unguiculata* (cowpea)	125% of RDNP (50% N through inorganic+50% through FYM)	PAU, Ludhiana	Singh et al. (2023)
	Populus deltoides (Poplar)	*Triticum aestivum* (Wheat)	100% RDN through vermicompost	Pantnagar, Uttararakhand	Ghosh et al. (2020b)
	Azadirachta indica (Neem) and *Melia azedarach* (Bakain)	*Helianthus annuus* (Sunflower)	Subabul green leaf manure 5 t ha^{-1}+30 kg N ha^{-1}	College of Agriculture, Hyderabad	Panneerselvama and Arthanari (2011)
	Moringa oleifera (Drumstick)	*Solanum melongena* (Brinjal)	50% FYM+50% Neem cake	Prayagraj, Uttar Pradesh	SwethaSree et al. (2021)
	Melia dubia (Maha Neem)	*Zea mays* (Maize)	75% RDF (NPK kg ha^{-1})+25% N through FYM	Regional Sugarcane and Rice Research Station, Rudrur, Telangana	Swapna et al. (2020)
	Pongamia pinnata (Karanj)	*Ricinus communis* (Castor)	75% RDN through urea and 12.5% N through organic source (neem cake) and 12.5% through FYM	College of Agriculture, Rajendranagar, Hyderabad	Hemalatha et al. (2015)
	Pongamia pinnata (Karanj) and *Melia azedarach* (Bakain)	*Pennisetum glaucum* (Pearl millet)	80 N kg ha^{-1} +Pongamia Green Leaf Manure (PGLM) 10 t ha^{-1}	PJTSA University, Rajendranagar campus, Hyderabad	Khan and Krishna (2016)
	Melia azedarach (Bakain)	*Setaria italica* (Foxtail millet)	75% RDN+25% N Poultry manure	PJTSA University, Rajendranagar campus, Hyderabad	Khan and Krishna (2017)
Agri-horticulture	*Hardwickia binate* (Anjan)	*Arachis hypogaea* (Groundnut var. TMV-2)	RDF+Vermicompost (2 t ha^{-1})	College of Agriculture, Rajendranagar, Hyderabad	Rajanikanth et al. (2016)
	Morus alba (Mulberry)	*Abelmoschus esculentus* (Okra)	100% poultry manure @ 25.08 q ha^{-1} along with basal dose of FYM @10 t ha^{-1}	Dr. YSPUHF, Nauni, Solan (HP)	Bhuyan et al. (2021)

Agroforestry system	Tree	Crop	INM	State/Region / ACZ	Reference
	Emblica officinalis (Aonla)	*Cicer arietinum* (Chickpea), *Brassica juncea* (Mustard), *Vigna mungo* (Black gram) and *Sesamum indicum* (Sesame)	• 75% inorganic fertilizer+25% Vermicompost • 50% inorganic fertilizer+25% FYM+25% Vermicompost	Regional Horticulture Research and Training Station, Jachh, Kangra (HP) India	Singh (2024)
Silvi-pasture	*Melia dubia* (Maha Neem)	*Zea mays* (Maize) and *Sorghum bicolor* (Sorghum)	50% RDN+50% N FYM	PJTSA University, Rajendranagar campus, Hyderabad	Khan and Krishna (2017)
Plantation crop based agroforestry and other	*Grevillea robusta* (Silver oak)	*Coffea arabica* (Coffee), *Piper nigrum* (Black pepper var. Panniyur 2)	75% RDF+(50 g)+PSB (50 g)+VAM (100 g)	Uttar Kannada district, Karnataka	Riyaz et al. (2023)
	Cocos nucifera (Coconut)	*Piper nigrum* (Pepper var. Panniyur 1), *Musa acuminate* (Banana var. G9) and *Theobroma cacao* (Cocoa, F1 hybrid)	50% RD of NPK+50% N through vermicompost, vermiwash, biofertilizer and in situ green manuring	Veppankulam, Tamil Nadu	Rani et al. (2024)
	Terminalia bellirica (Baheda)	*Aloe vera* (Gwar Patha)	Neem cake treatment; FYM 5 t ha^{-1}+Vermicompost 2 t ha^{-1}	PJTSA University, Rajendranagar campus, Hyderabad	Khan and Krishna (2017)

productivity (Rajanikanth et al., 2016), a trend also observed in wheat grain and straw yields (Ghosh et al., 2020a). The combined use of organic and inorganic nutrients improves nutrient uptake, soil structure, and microbial enzymatic activity, contributing to a more fertile growing environment.

Research by Rani et al. (2024) evaluated four nutrient management approaches in intercrops like black pepper, banana, and cocoa. The results showed that combining 50% inorganic fertilizer with organic nitrogen resulted in the highest yields, improved soil health indicators, and a favorable economic outcome. Organic amendments enhanced soil moisture retention and supported fungal and bacterial populations, further boosting soil quality and crop performance.

In a turmeric agroforestry system, a study by Painkra et al. (2020) demonstrated the superior benefits of organic inputs, with 100% FYM outperforming other treatments in plant growth and soil quality. The combination of 25% inorganic fertilizer and 75% FYM was also effective, highlighting the importance of organic amendments for better crop and soil health outcomes. Similarly, research on medicinal plants like bhringraj in a *Grewia*-based agroforestry system (Kumar et al., 2023) confirmed that 50% RDF combined with 50% vermicompost achieved the highest yields and optimal soil nutrient levels, providing substantial economic returns. Other studies, such as those by Hemalatha et al. (2015), showed that combining organic sources like neem cake and farmyard manure with urea increased seed yield, stalk yield, and nutrient uptake while maintaining or surpassing the performance of 100% urea. This highlights the potential of INM to optimize nutrient availability and crop performance across various systems. In agroforestry systems like those integrating Cassava and Chillies with Dalbergia sissoo, tailored nutrient management based on soil testing has significantly increased crop yields while preserving soil fertility (Sivakumar et al., 2022). Likewise, Kumari and Kumar (2024) found that combining 50% recommended nitrogen with organic manure and Jeevamrit yielded superior results in crop yields and soil health, underscoring the effectiveness of INM in maintaining soil fertility while enhancing productivity.

The study also revealed that while the sorghum+pearl millet

-oat+sarson cropping systems offered higher productivity and profitability, they did not significantly improve soil nutrient levels compared to the sorghum+pearl millet-wheat system. The latter system, which incorporated both fodder and grain crops, proved to be more effective in integrating nutrient management for sustained soil fertility and crop production.

Sujatha and Manjappa (2015) explored the effects of various nutrient management strategies on seedling growth and biomass. Their research found that vermicompost (30 g per seedling) was more effective than farmyard manure (50 g per seedling) in promoting growth parameters such as seedling height, collar diameter, leaf area, root length, and root-shoot ratio. Among bio-fertilizers, a combination of *Azospirillum* and Phosphate Solubilizing Bacteria (PSB) produced the best results, outperforming individual applications of *Azospirillum*, PSB, and no bio-fertilizers. Inorganic fertilizers also contributed to enhanced seedling growth, with 1.0 g of NPK yielding better results than 0.5 g or no NPK at all. The optimal combination of vermicompost, PSB, and 1.0 g NPK led to the highest growth and biomass metrics, including seedling height (154.6 cm), collar diameter (8.53 mm), and leaf area (126.0 cm^2), underscoring the synergy between organic, inorganic, and bio-fertilizer inputs for maximum seedling development.

Singh and Khare (2024) evaluated different nutrient treatments and found that the treatment with 100% vermicompost (no FYM or NPK) achieved the highest growth and yield outcomes. This treatment resulted in impressive growth parameters such as plant heights of 19.80 cm at 30 days, 46.43 cm at 60 days, and 52.51 cm at 90 days after sowing. The highest number of branches (4.33 at 30 DAS, 8.67 at 60 DAS, and 12.33 at 90 DAS) and a test weight of 28.00 grams per 100 seeds were also recorded. This treatment produced the highest grain yield (14.51 q ha^{-1}) and maximum pod count (32.27 pods $plant^{-1}$), along with an excellent harvest index of 44.18%. The financial analysis highlighted the effectiveness of using 100% vermicompost, with a benefit-cost ratio of 2.91 and a net return of Rs. 115,255, indicating that this approach provided strong economic returns alongside improved crop performance.

Sarvade et al. (2014a) conducted a study on wheat cultivation under different tree species, showing that wheat yields were significantly higher when grown under Poplar trees (44.60 q ha-1) compared to *Melia* trees (42.60 q ha^{-1}). This increase was achieved at a fertilization level of 180-60-40 kg NPK per hectare, which was critical for enhancing crop growth and productivity. The wider spacing of 3×2.5 meters also proved to be more beneficial for wheat growth than closer spacings, with a positive correlation between soil fertility levels and wheat growth parameters.

For castor cultivation, integrated nutrient management (INM) combining farmyard manure (FYM), recommended fertilizer doses (RDF), and microbial inoculants like *Azospirillum* and PSB was found to be highly effective. This approach consistently resulted in higher yields compared to using RDF alone across different regions in India, including Tindivanam, Andhra Pradesh, Saurashtra, and North Gujarat (Reddy et al., 2013). The integration of organic and inorganic nutrients with microbial treatments enhanced both castor crop productivity and soil health, showcasing the benefits of this combined approach.

A recent study (2023, unpublished data) at Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, found that applying 125% of the recommended fertilizer dose (RDF) resulted in the highest seed yield of 633.73 kg ha^{-1}, outperforming 75% RDF by 11.39%. The study also revealed that pruning practices impacted net monetary returns (NMR), with 25% pruning yielding the highest return of Rs. 81,011 ha-1, while combining 50% pruning with 125% RDF resulted in the highest net return of Rs. 99,260 ha^{-1}. In contrast, open conditions with any level of fertility produced the lowest returns, underscoring the importance of integrated nutrient management for optimal crop performance and economic outcomes.

7. CHALLENGES AND CONSIDERATIONS

• The implementation of Integrated Nutrient Management (INM) in agroforestry faces several challenges that must be carefully managed to ensure its success. A primary challenge is meeting the diverse nutrient needs of the various plant species within an agroforestry system. Since agroforestry systems integrate crops, shrubs, and trees, each with distinct nutrient requirements, it becomes essential to understand the nutrient dynamics of the system. Proper management is needed to prevent competition among plant species and to promote the optimal growth of all components.

• Another critical issue is the risk of nutrient imbalances and soil degradation, especially in systems involving continuous cropping and tree planting. Without proper management, these practices can lead to nutrient depletion, undermining soil fertility over time. To mitigate this, agroforestry systems must incorporate strategies that restore soil nutrients, such as organic amendments, green manures, and leguminous cover crops. Long-term planning and effective integration of these practices are essential to maintain soil health and prevent degradation.

• The variability in soil types and environmental conditions across different agroforestry systems adds another layer of complexity to INM. Different soils have varying capacities to retain and supply nutrients, and environmental factors like rainfall, temperature, and climate influence nutrient availability. Tailoring INM strategies to these specific conditions requires careful soil testing and continuous monitoring to ensure that management practices are adapted to the unique needs of each agroforestry system.

• Economic constraints also present significant challenges in the widespread adoption of INM in agroforestry. The costs associated with nutrient management, including the use of organic fertilizers, soil amendments, and specialized equipment, can be prohibitively high, particularly for smallholder farmers. Developing cost-effective nutrient management strategies, as well as providing access to affordable inputs and technology, is critical for making INM practices more accessible and scalable.

• Moreover, there is a clear need for capacity building and knowledge dissemination among farmers and land managers. The complexity of INM, which involves understanding interactions between soil health, plant growth, and environmental variables, requires proper training and ongoing support. Ensuring that practitioners have the necessary expertise is crucial for the successful implementation of INM.

• Lastly, the integration of INM into agroforestry systems must be done with consideration for biodiversity and ecosystem services. While nutrient management aims to improve plant growth and productivity, it is equally important to avoid practices that may negatively affect the broader ecosystem. Balancing nutrient inputs with ecological conservation goals is essential to ensure the sustainability and resilience of agroforestry systems in the long run.

• Addressing these challenges requires a holistic approach, combining scientific research, practical experience, and socio-economic factors to design INM strategies that are both effective and sustainable for agroforestry systems.

8. CONCLUSION

Integrating organic and inorganic nutrient sources, such as Farm Yard Manure (FYM), vermicompost, and chemical fertilizers, enhances crop yield, growth, and soil health. This approach improves nutrient uptake, organic carbon levels, and microbial activity. Adding microbial inoculants like *Azospirillum* and Phosphorus Solubilizing Bacteria (PSB) further boosts results. Tailored practices, like using 125% of the recommended fertilizer dose, optimize economic returns and soil fertility. Generally, integrated nutrient management promotes sustainable agriculture and environmental well-being.

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