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Fruit Tree Based Agroforestry: A Scalable Solution for Climate Change and Food Security.

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Abstract:
"Fruit-based agroforestry systems, integrating fruit trees with crops and/or livestock, present a multifunctional strategy to address pressing global challenges, including climate change, biodiversity loss, soil degradation, and economic insecurity. This review examines their potential through a comprehensive analysis of ecological, agronomic, and socio-economic benefits, drawing upon global case studies such as India's traditional home gardens, Central America's shade-grown coffee systems, and Africa's Faidherbia albida parklands. Findings reveal that these systems enhance carbon sequestration, with tree biomass significantly increasing storage capacity over time. They support biodiversity through habitat creation and genetic diversity conservation. Soil health is bolstered via improved nutrient cycling and organic matter inputs, with studies demonstrating an average increase of 15-20% in soil nitrogen levels in fruit-tree intercropped systems. Economically, they diversify livelihoods and mitigate climate-induced agricultural risks. Despite land-use constraints, fruit-based agroforestry presents a scalable, resilient alternative to conventional farming, bridging environmental sustainability and human well-being. This review underscores the need for policy incentives and further empirical research to optimize their adoption, particularly in climate-vulnerable regions."

Keywords: *Agroforestry, Fruit Trees, Climate Change Mitigation, Biodiversity Conservation, Soil Health, Economic Security, Sustainable Agriculture.*

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I. Introduction:

"Climate change, characterized by shifts in long-term temperature and precipitation patterns driven primarily by greenhouse gas emissions, poses a significant threat to global ecosystems and human societies (IPCC 2021). The agricultural sector, a critical pillar of food security, is particularly vulnerable to these changes, experiencing increased frequency of extreme weather events, altered growing seasons, and reduced yields (FAO 2022). Conventional agricultural practices, often reliant on monocultures and intensive inputs, contribute to greenhouse gas emissions and soil degradation, exacerbating these challenges.

Fruit-based agroforestry systems, which integrate fruit trees with crops and/or livestock, offer a promising alternative by enhancing ecosystem services and diversifying farm income. These systems have been practiced for centuries in various regions, demonstrating resilience and adaptability. However, their potential for widespread adoption in mitigating climate change and enhancing sustainable agriculture remains underexplored. This review aims to synthesize existing research on the ecological, agronomic, and socio-economic benefits of fruit-based agroforestry, examining their role in carbon sequestration, biodiversity conservation, soil health improvement, and economic diversification. By highlighting successful case studies and identifying knowledge gaps, this review seeks to inform policy and research initiatives aimed at promoting the adoption of these systems globally."

II. Methodology:

"This review employed a systematic approach to synthesize relevant literature on fruit-based agroforestry systems. A comprehensive search was conducted using academic databases, including Web of Science, Scopus, and Google Scholar, with keywords such as 'fruit agroforestry,' 'agroforestry benefits,' 'carbon sequestration agroforestry,' 'biodiversity agroforestry,' 'soil health agroforestry,' and 'economic agroforestry.' The search was limited to peer-reviewed articles published in English between 2000 and 2023.

Case studies were selected based on their representation of diverse agroforestry systems, geographical distribution, and availability of data on ecological, agronomic, and socio-economic impacts. Data extraction focused on quantifying carbon sequestration, biodiversity metrics, soil nutrient levels, and economic benefits. Qualitative analysis was used to identify common themes and trends across the selected studies.

Limitations of this review include potential biases in the literature search and challenges in comparing diverse agroforestry systems with varying ecological and socio-economic contexts. However, the comprehensive approach and inclusion of diverse case studies aim to mitigate these limitations and provide a robust overview of the benefits of fruit-based agroforestry."

Climate Change Mitigation: Climate is a crucial environmental factor influencing region, country, and the planet (Kabir et al. 2023). Climate change is defined as a shift in climate patterns primarily caused by greenhouse gas emissions, leading to increased temperatures across various regions (Fawzy et al. 2020; Schuurmans 2021). It encompasses average of factors such as light, temperature, humidity, wind, gases, air, water, and soil, over 30 years of time. It is characterized by long-term trends in temperature and precipitation, along with other factors such as atmospheric pressure and humidity levels (Abbass et al. 2022). Climate change (CC) is a multifaceted global challenge that requires intergovernmental cooperation due to its widespread impact on ecology, environment, socio-political, and socio-economic systems (Feliciano et al. 2022; Leal et al. 2021). Climate change mitigation encompasses strategies and interventions aimed at reducing or preventing the emission of greenhouse gases (GHGs) responsible for climate change mainly due to anthropogenic activities (Kumar 2022). As emphasized in recent reports by the Intergovernmental Panel on Climate Change (IPCC), agroforestry stands out as a promising agroecological strategy for climate change adaptation. This is due to the numerous co-benefits it offers beyond adaptation alone, including synergies with climate change mitigation through carbon sequestration, improved food security and income generation, enhanced ecosystem services, and the conservation of biodiversity (Meybeck et al. 2020; Tschora and Cherubini 2020).

Causes:

Greenhouse gas emissions trap heat in the Earth's atmosphere, serving as the primary driver of global warming (Fawzy et al. 2020). Energy consumption has contributed to rising greenhouse gas (GHG) levels and increasing temperatures, as fossil fuels remain the primary source of energy production in many developing countries (Balsalobre-Lorente et al. 2022; Usman et al. 2022b; Abbass et al. 2021a; Ishikawa-Ishiwata and Furuya 2022). Total greenhouse gas (GHG) emissions increased almost from 746.5 million tonnes of CO equivalent (Mt CO) in 1970 to 3,375 Mt CO in 2018 (World bank 2022). These emissions originate from both natural systems and human activities, with key contributors including urbanization, industrialization, and transportation, all of which lead to rising atmospheric temperatures (Huang et al. 2016; Kabir et al. 2023).

The impacts of climate change have been noticed to increase in recent times as compared to past years, influencing biodiversity, economy and all sectors related to them (Moon 2024). Over the past 150 years, atmospheric CO levels have rised significantly from 280 to 416 parts per million primarily due to industrial activities (Krishnapriya et al. 2020). Furthermore, during the twentieth century, the global average surface air temperature increased by 0.5°C approximately which is expected to increase up to 1.4–5.8 °C by the end of twenty-first century, which can increase the magnitude and frequency of extreme events such as heat waves, droughts, increased precipitation and wildfires (Solomon and Manning, 2007; Beniston et al. 2007). Other than the irregular weather patterns, continuous melting of global ice sheets have led to increase in the sea levels which is among the most prominent impact of climate change globally (Michel et al. 2021; Murshed and Dao 2020). Climate change mitigation is crucial to reduce its impacts because of the fact that it cannot be halted with respect to the global developments (Mikulcic et al. 2022).

Agroforestry mitigation:

Agroforestry involves intentional integration of trees, crops, and/or livestock in interactive systems to enhance crop yields, mitigate food insecurity, improve environmental services, and strengthen ecosystem resilience. Promoting the growth of trees and shrubs through agroforestry practices holds significant potential for carbon storage and the removal of atmospheric carbon dioxide. Forest are large carbon sinks but increase in the forest area is limited by the limited availability of land which can be replaced by increase carbon storage methods through planting trees in agroforestry fields. India has been practicing traditional agroforestry from a long period of time and the practice of growing scattered trees on farmlands has been prevalent for centuries most of which remained unchanged over time (Kumar et al. 2019). Trees in agroforestry systems improve carbon sequestration with time as with increase in tree age, 'tree's biomass increases (Khan et al. 2020). Recent studies estimate the carbon sequestration potential of tropical agroforestry systems between 12 and 228 megagrams per hectare (Mg ha ^{1}), with a median value of 95 Mg ha ^{1} (Kumar et al. 2024). Furthermore, it has been reported that at five years of age, *Gmelina* in an agrisilviculture system had a total stand biomass of 14.1 Mg ha ^{1} (Swamy S and Puri S 2005).

Economic security:

The rising population and the depletion of agricultural land pose significant challenges to the sustainable food production and supply systems (Karabulut et al. 2018). The impacts of climate change on agriculture have emerged as a critical concern for the global scientific community, governments, and policymakers (O'Neill et al. 2020 and Wang et al. 2023). Agroforestry systems contribute to farm diversification by integrating a greater variety of plant species, tree varieties, or animal breeds within a single farm or farming community enhancing the overall economic resilience and productivity (Raj et al. 2019). Agroforestry plays a significant role in employment generation due to its labour- intensive nature, by creating diverse job opportunities across various stages of the value chain including nursery management, tree planting, on-farm labor, harvesting, processing, and marketing of agroforestry products. Cash trees and agroforestry practices among smallholder farmers contribute to the restoration and improvement of rural farmland management systems while optimizing agricultural productivity and household income (Tega and Bajoga 2023; Staton 2022). Furthermore, agroforestry is anticipated to reduce the poverty gap within communities (Kadigi 2021).

Biodiversity Conservation:

High biodiversity is essential for the resilience of ecosystems to disturbances and stresses, supports vital ecosystem services, including food production, water purification, disease regulation, and climate regulation. and provides genetic resources necessary for developing new crop varieties and medicines Biodiversity which is critical for maintaining ecosystem health and stability is threatened by climate change and this is exacerbated by human activities like high fossil fuel consumption and deforestation, which contribute to the loss of biodiversity (Shivanna 2022). Agroforestry is an integrated land-use management system where agricultural and forestry technologies merges to form more diverse, productive, profitable, and sustainable land-use systems (Lambin et al. 2010). It significantly contributes to biodiversity conservation by creating habitats, enhancing genetic diversity, and supporting various species (Jose et al. 2012).

Creation of Habitat:

Agroforestry plays a critical role in creating habitats that support a wide variety of flora and fauna. By integrating trees and shrubs with agricultural crops and livestock, agroforestry systems mimic natural ecosystems and offer nesting sites, food sources, and shelter for birds, insects, mammals, and other wildlife (Kumar et al. 2024). Moreover, agroforestry practices such as hedgerows and riparian buffer strips create corridors that connect fragmented habitats, facilitating wildlife movement and gene flow across landscapes. This connectivity is crucial for maintaining viable populations of species that require large territories or specific habitat conditions (Fig 1). Agroforestry systems also contribute to the conservation of endangered species by providing alternative habitats in agricultural landscapes, thus reducing pressure on natural forests (Jose et al. 2012). One prominent example is the shade-grown coffee systems in Central and South America. These systems integrate coffee plants with shade trees, which not only provide a suitable microclimate for coffee production but also support high levels of biodiversity. Studies have shown that shade grown coffee plantations harbor a rich variety of bird species, insects, and other wildlife, contributing to biodiversity conservation and ecosystem health (Buechley et al. 2015).

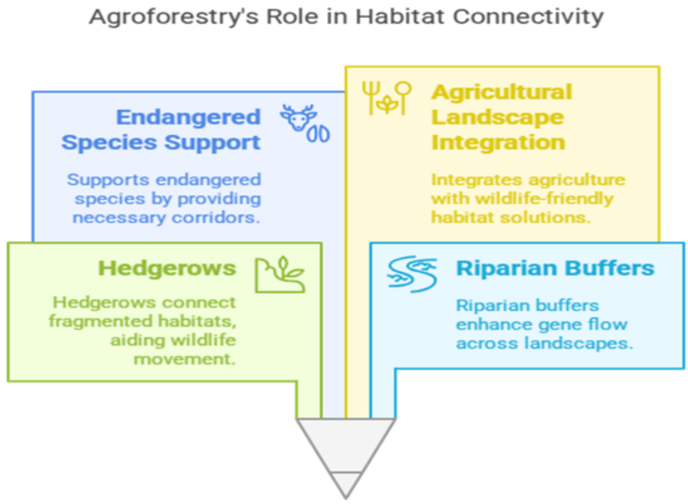

Fig 1: Depicting how agroforestry contributes in habitat diversity

Genetic diversity:

Agroforestry systems significantly enhance genetic diversity by integrating a variety of tree species into agricultural landscapes, thereby promoting both interspecific and intraspecific variation. This integration not only conserves biodiversity but also bolsters ecosystem services and the resilience of farming systems. By maintaining and diversifying specific trees on farms, agroforestry systems can support species richness that exceeds 60% of that found in natural forests (Bhagwat et al. 2008). The presence of diverse tree species within agricultural lands provides habitat and resources for numerous species, including birds, insects, mammals, and microorganisms, thereby enhancing overall biodiversity (Jose 2009). Moreover, agroforestry practices contribute to the conservation of genetic resources by preserving traditional and indigenous plant varieties, which are often at risk from monoculture practices. This conservation of genetic diversity is crucial for the resilience and adaptability of crops to changing environmental conditions (Dawson et al. 2009). Furthermore, the increased environmental heterogeneity in agroforestry systems favors species coexistence and diversification, thereby promoting genetic variation (Torralba et al. 2016). Additionally, the presence of trees and varied vegetation within agricultural systems provides habitat and resources for numerous species, including birds, insects, mammals, and microorganisms, which enhances overall biodiversity and supports ecosystem services such as pollination, pest control, and nutrient cycling (Jose 2009). Therefore, agroforestry serves as a vital strategy for enhancing genetic diversity, promoting sustainable agriculture, and conserving biodiversity within agricultural landscapes.

For example, the traditional home gardens of Kerala, India. These multi-layered agroforestry systems include a diverse mix of trees, shrubs, herbs, and crops, providing food, fuel, fodder, and other resources year-round. Home gardens in Kerala are known for their high species richness and play a crucial role in conserving plant genetic resources, including many traditional and indigenous species. Forest farming, another temperate agroforestry practice, involves cultivating high-value crops such as mushrooms, medicinal plants, and herbs under the canopy of an existing forest. This practice enhances biodiversity by maintaining forest structure and composition while providing economic benefits to farmers. For instance, ginseng and goldenseal are commonly grown in forest farming systems in the Appalachian region of the United States, contributing to both biodiversity conservation and rural livelihoods (Small 2023).

Soil Enhancement:

Agriculture is directly linked to human life, providing food for survival and health. It is threatened by a number of challenges, such as climate change, resource depletion, and abiotic stresses, including heavy metals (HMs), salinity, drought, etc (Salam et al. 2022). Agroforestry which integrates woody perennials with arable crops, livestock, or fodder in the same piece of land, provides various soil-related ecological services such as fertility enhancements and improvements in soil physical, biological, and chemical properties, along with food, wood, and fodder (Fahad et al. 2022).

For example, in the United States, black walnut trees are commonly grown in alley cropping systems with crops like corn or soybeans. These systems enhance soil health and provide valuable wood and nut products (Sharma et al. 2016). A similar trend of results was reported by Siriri et al. (2013) when they intercropped tree fallows on the degraded upper section of bench terraces for examination of soil water content and evaporation with *Sesbania sesban, Caliandra calothyrsus, Alnus acuminata, Phaseolus vulgaris,* maize. Similarly, Lin, 2010 evaluated the role of agroforestry in reducing water loss and found that with 60-80 per cent shade cover soil evaporation rates significantly decreased by 41 per cent which led to a higher moisture content in the soil as compared to low shade sites. Similarly, Devi et al. (2020) found that when wheat intercropped under Kinnow and *Eucalyptus* enhanced soil organic matter content, available nutrients and improved soil properties were found. Also, Tufa et al. (2019) found the lowest electrical conductivity in agroforestry systems which may be attributed to the uptake of bases by tree biomass and the acidic nature of litter after its decomposition. The results of Kar et al. (2019) also reported a significant increase in nitrogen, phosphorus, potassium, organic carbon, electrical conductivity under *Grewia optiva* + garden pea agroforestry system as compared to sole cropping of garden pea. Likewise, Dhara et al. (2015) when intercropping black gram with mango and *Eucalyptus tereticornis* significant improvements in soil properties *viz*., nitrogen, phosphorus, potassium, organic carbon was observed. Similar findings were observed by Soa and Prajapati (2018) when they intercropped wheat under *Ceiba pentandra* and found maximum organic carbon, nutrients under tree-crop combination as compared to sole cropping. Likewise, Gebrewahid et al. (2019) reported a significant increase in available phosphorus, nitrogen and other chemical properties when intercropping black oats and maize with *Leucaena diversifolia* as compared to pure crops.

Nutrient cycling

A dynamic and living resource, the soil is crucial for maintaining global biogeochemical cycling, ecosystem health, and sustainable food production. However, a lot of farmland soils are severely degraded (Du et al. 2022). Soil organic carbon has been depleted as a result of heavy tillage, intensive cropping, and insufficient Carbon inputs (Salceda et al. 2022). Therefore, one of the main objectives in the development of sustainable farming techniques is to improve soil health (Eddy et al. 2022)Agroforestry is considered practical agro-ecology due to its ecological approaches and principles on which its design and management are based; it is subject to various interactions between trees and crops and has been identified as a potential intensification pathway to make agriculture more sustainable (Pretty et al. 2018).These perennial systems performs better than annual croplands in terms of soil health because of their potential for sustaining agricultural by serving as a significant supply of soil organic matter, it can positively affect the physical, chemical, and biological soil qualities and promote plant development (Du et al. 2022) and due to higher belowground C inputs and less soil disturbance (Pretty et al. 2018).

Agroforestry promotes more effective resource usage than monocropping due to the structural and functional diversity of the components acquired in a mixed cropping canopy (Hailu et al. 2015). Trees play an important role in the cycling of nutrients by recapturing and pumping back leached nutrients via deep roots, which work as a ‘safety net’ against nutrient losses from the nutrient cycle (Fig 2). Trees in tree-based systems also capture nutrients present in the atmosphere and help in dry deposition (Schroth et al. 2003). Agroforestry provides a promising opportunity to store and capture carbon in the soil that is lost due to the intensification of agriculture and the use of heavy tillage and fertilizers (Chatterjee et al. 2018).

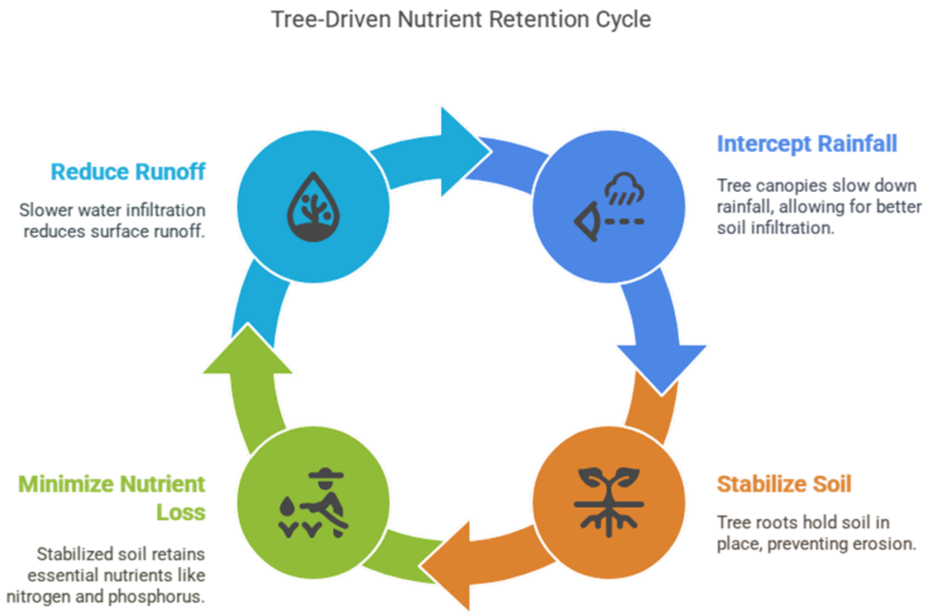

Fig 2: Role of agroforestry in nutrient retention

Nutrient dynamics and enhancement in soil properties

Agroforestry leads to higher soil C-sequestration rates; moisture contents; and levels of available soil K, N, and P, the residues of which are available for subsequent crops, allowing more sustainable farming in the upcoming seasons and reducing the use of chemical fertilizers (Surki et al. 2020). Along with this the integration of trees on farmlands may improve physicochemical soil properties (Nair 1984). The better cycling of basic cations in the agroforestry system might assist in the amelioration of soil acidity (Riyadh et al. 2018). In croplands, the presence of a few scattered trees greatly increases the nutrient status of the soil and decreases the requirement for an additional input of fertilizer. Many agroforestry systems include nitrogen-fixing tree species, such as legumes, which form symbiotic associations with nitrogen-fixing bacteria in their root nodules (Mekuria et al. 2018). These trees convert atmospheric nitrogen into plant-available forms, enriching the soil with nitrogen. This continuous addition of organic matter enhances soil structure, water-holding capacity, and nutrient retention, thus promoting sustainable crop growth (Montagnini et al. 2004).

Agroforestry systems consistently improve soil fertility indicators relative to conventional monocrops. For example, meta-analyses and field studies indicate that tree–crop systems promote greater soil C sequestration and moisture retention alongside elevated available N, P, and K. Farooq et al. (2022) note that incorporating trees "leads to higher rates of soil carbon sequestration, improved moisture retention, and increased availability of nutrients such as K, N, and P". Similarly, Kuyah et al. (2019) report that agroforestry significantly increased total soil nitrogen, organic carbon, and available phosphorus compared to control plots without trees. In other words, on average across diverse agroecosystems, soils under tree-based systems hold more organic C and nutrients, which benefits subsequent crops and reduces the need for chemical fertilizers.

This enhancement of **soil organic carbon (SOC)** is well documented. In a ginger–*Neolamarckia cadamba* alley-cropping experiment, Shekhawat et al. (2025) found that closer tree spacing raised SOC from 0.39% in sole ginger plots to 0.51% under a 5×3 m tree spacing. Likewise, Bisht et al. (2017) observed increased SOC (up to ~1.07%) in wheat plots intercropped with poplar, relative to open-field wheat. These individual results align with broader findings: meta-analyses confirm that agroforestry systems accumulate significantly more soil carbon than annual cropping (Kuyah et al., 2019). The extra carbon comes from continuous leaf litter and deeper root inputs provided by trees, which not only build SOC but also improve soil structure and moisture retention.

Similarly, available **soil nitrogen, phosphorus, and potassium** generally increase under tree–crop combinations. Shekhawat et al. (2025) reported that reducing tree spacing in the ginger–*N. cadamba* system produced the highest levels of available N, P, and K at the closest spacing. In a tropical cereal–tree system, Sao and Prajapati (2018) found that soil under a wheat–*Ceiba pentandra* alley contained significantly more organic

C and higher available N, P, and K than soil under sole wheat cultivation. In a poplar–wheat agroforest, Bisht et al. (2017) measured available N of ~253.5 kg/ha and K of ~219.6 kg/ha within the tree plots – values well above those typical of sole wheat (also see Bisht et al., 2017). Across studies, these nutrient gains are attributed to enhanced litter decomposition, root turnover, and, in some systems, biological N fixation. Consistent with the field data, the meta-analysis by Kuyah et al. (2019) showed that agroforestry significantly increases soil N and available P relative to tree-free controls. Thus, integrating trees tends to enrich the soil N, P, and K pools, offsetting losses from annual cropping.

Beyond chemical fertility, tree crops also affect **soil moisture and physical properties**. Field trials often report lower bulk density and higher porosity under trees, which together improve water holding capacity. For example, Chaudhary and Ghaley (2025) observed that an alley-cropped system had markedly lower soil bulk density (1.48 g/cm^3) than an adjacent conventional wheat field (1.74 g/cm^3), with correspondingly higher soil organic matter and available K. This enhanced structure translates into better moisture retention: Chaudhary and Ghaley also found significantly higher soil moisture under the agroforest plots than under the monoculture. More broadly, Kuyah et al. (2019) report that agroforestry improves infiltration and maintains greater soil moisture content on average. In short, shading and root channels provided by trees, combined with higher organic matter, tend to keep soils cooler and wetter compared to open fields (Chaudhary & Ghaley, 2025; Farooq et al., 2022).

These nutrient and water benefits have important **implications for sustainable agriculture**. By recycling carbon and nutrients in situ, tree–crop systems build soil reserves that can buffer crops against seasonal stresses. For example, Shekhawat et al. (2025) conclude that ginger intercropped with kadam "demonstrates significant improvements in soil nutrient status" with only minimal competition between components. In practice, the greater soil N, P, K and organic carbon in agroforestry systems means that farmers can often maintain yields with lower synthetic fertilizer inputs (Farooq et al., 2022). As an example, Farooq et al. (2022) note that higher nutrient residues under trees allow "more sustainable farming in the upcoming seasons, reducing the use of chemical fertilizers". Taken together, the comparative findings imply that well-designed agroforestry (choice of tree species, spacing, and crops) can enhance N, P, K, SOC and moisture while sustaining productivity. In summary, diverse tree–crop systems offer a viable path to improve soil health and long-term farm resilience under sustainable intensification (Sao & Prajapati, 2018; Bisht et al., 2017; Farooq et al., 2022

III. Conclusion

Fruit-based agroforestry systems represent a promising and multifaceted approach to tackling the intertwined challenges of climate change, biodiversity loss, soil degradation, and economic insecurity. By integrating fruit trees with crops and livestock, these systems enhance carbon sequestration capacities significantly, with tropical agroforestry systems capable of storing between 12 and 228 Mg of carbon per hectare, depending on species and management (Kumar et al., 2024; Khan et al., 2020). Beyond carbon storage, they contribute substantially to biodiversity conservation by creating diverse habitats and supporting genetic diversity, often maintaining over 60% of species richness compared to natural forests (Bhagwat et al., 2008; Jose, 2009). Soil health improvements through enhanced nutrient cycling and organic matter inputs have been documented, including increases of 15-20% in soil nitrogen levels in intercropped systems (Kumar et al., 2024).

Economically, fruit-based agroforestry diversifies farm income and reduces vulnerability to climate-related shocks by providing multiple products and employment opportunities across the value chain (Raj et al., 2019; Tega and Bajoga, 2023). These systems support rural livelihoods by integrating high-value fruit trees that contribute to food security and poverty alleviation (Kadigi, 2021). However, despite these benefits, widespread adoption is hindered by regulatory, infrastructural, and knowledge barriers, such as restrictive tree-felling laws and limited access to quality planting materials (Kumar et al., 2019). Policy support, including streamlined regulations, financial incentives, and capacity-building initiatives, is essential to scale up these systems effectively.

Future research should focus on long-term, site-specific studies to better quantify agroforestry's role in climate resilience, optimize species combinations for resource use efficiency, and leverage technological advances for monitoring and market integration. Ultimately, fruit-based agroforestry offers a resilient, scalable pathway that aligns agricultural productivity with ecological sustainability and socio-economic well-being, making it a critical strategy in global efforts to mitigate climate change and enhance food security.

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