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Agroforestry for pollinator support and food security: a review

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Agroforestry is a land use system encompassing techniques that incorporate woody perennial plants alongside crops/animals. It is a multifunctional land-use approach, highlighting its potential contribution to pollinators and food security. Agroforestry farming practices are resource-efficient methods that support sustainable food production even in diverse situations. The global population is projected to reach approximately 9 billion by 2050, presenting a significant challenge in adequately feeding this expanding populace on limited land. There remains a pressing need to adopt more sustainable measures to boost food production for the expanding global population. This review synthesizes findings from over 75 peer-reviewed articles across more than 25 countries to understand the role of agroforestry in supporting pollinators and subsequently food security through increased pollination services and other benefits. The findings indicate that agroforestry can increase crop yields by 25–80%, boost dietary diversity by 22–25%, and improve soil organic carbon by 20%. The enhanced pollination services driven by floral diversity, habitat connectivity, and improved microclimates resulted in 2.4 times more bumblebees, twice as many solitary bees and hoverflies, and achieved 4.5 times higher seed set than monocultures. The income diversification and improved economic returns with 30–50% higher household income, 15–30% agroforestry income share, and benefit–cost ratios (BCR) above 2 underscore its strong economic potential. However, challenges such as high upfront costs, delayed returns, pest pressures, and adoption barriers exist, especially for smallholders. These outcomes are also context-dependent, influenced by scale, design, and landscape integration. The review highlights that agroforestry can simultaneously advance pollinator conservation and food system resilience. For the wider adoption of agroforestry, policy interventions, farmer training, and financial incentives are needed, alongside research that integrates long-term ecological and socioeconomic outcomes across diverse regions.

KEYWORDS

ecosystem services, resilience, biodiversity conservation, sustainability, food security

1 Introduction

The complex dynamics between agroforestry systems, pollinators, and food security represent multidimensional ecological, agricultural, and socioeconomic interactions (Garibaldi et al., 2013; Jose, 2009; Kremen and Miles, 2012). In this review, ecosystem services refer to ecological processes such as pollination that directly or indirectly support agricultural productivity and human well-being. The modern agricultural practices, such as monocropping, intensive fertilizer and pesticide use, and mechanized cultivation, have increased food production but often at the cost of biodiversity, soil fertility, and long-term ecological stability (Akanmu et al., 2023). These losses are further worsened by the growing impacts of climate change, which threaten both ecological integrity and global food security (Cheng, 2024; Richardson et al., 2023). Rising temperatures, altered rainfall patterns, and increasing frequency of extreme weather events like storms, floods, and droughts disrupt crop phenology, reduce yields, and shift the timing and availability of floral resources for pollinators (Forrest, 2017; Lee et al., 2024). These climatic stresses hinder food production and decline key pollinator populations, which sustain more than 75% of the world's food crops (IPBES, 2016; Klein et al., 2007). Furthermore, the recent estimates from the Food and Agriculture Organization of the United Nations (FAO) indicate that between 638 and 720 million people—about 7.8–8.8 percent of the global population—faced hunger in 2024. This was down from 8.5 percent in 2023 and 8.7 percent in 2022, reflecting a slight global improvement but persistent increases in parts of Africa and Western Asia (FAO and IUWW, 2025). The FAO predicts that a 70% increase in food production will be needed to feed an estimated nine billion people by 2050 (FAO, 2009; Godfray et al., 2010) and achieving this goal is increasingly difficult. These interlinked challenges emphasize the need to understand how ecological processes (pollination), land-use practices (agroforestry), and food-system outcomes interact to shape sustainable agricultural solutions.

Agroforestry encompasses land use systems and techniques that deliberately incorporate woody perennials such as trees, shrubs, bamboos, etc., alongside crops, and/or animals within the same integrated land management unit, whether through spatial arrangement or temporal sequence (Lundgren et al., 1983). It is a multifunctional land use practice that can enhance biodiversity, improve soil fertility, and provide economic diversification for farmers to strengthen environmental and social sustainability (Nair et al., 2021; U.S. EPA, 2024). Across the United States and Canada, six principal agroforestry practices are recognized: riparian and upland forest buffers, wind breaks, alley cropping, silvopasture, forest farming, and urban food forests (Jose et al., 2021). These different agroforestry systems improve soil fertility, crop yield stability, income diversification, and resilience to climatic fluctuations through microclimatic benefits (Barbeau et al., 2018; Jose, 2009; Mosquera-Losada et al., 2009; Schoeneberger, 2009). Moreover, the Intergovernmental Panel on Climate Change report identifies agroforestry as a crucial strategy for mitigating greenhouse gas emissions, restoring degraded land, and promoting sustainable food production under climate stress (IPCC, 2019). Thus, agroforestry represents a promising land-use pathway to integrate biodiversity conservation and food system resilience. Understanding the role of these diversified systems in influencing pollinator ecology and, in turn, food production is central to linking agroforestry's ecological and socio-economic dimensions.

Pollinators, including bees, butterflies, moths, flies, beetles, birds, and bats, are indispensable contributors to global food production. Approximately 75% of the food crops in the world depend, at least partly, on animal pollination, which contributes an estimated US$235–577 billion annually to the global economy (IPBES, 2016; Klein et al., 2007; Siopa et al., 2024). In the tropical regions, the percentage may reach up to 94% of crop species (Ollerton et al., 2011). Yet, the IPBES Global Assessment (2016) estimated that nearly 40% of invertebrate pollinator species, particularly bees and butterflies, face extinction risk due to habitat loss, pesticide exposure, invasive species, pathogens, and climate change (IPBES, 2016; Potts et al., 2010). The decline of these pollinators poses a serious threat to biodiversity and crop productivity worldwide. These declines in pollinator populations have already been linked to measurable reductions in crop yields (Reilly et al., 2020). The recent study suggests that pollination deficits—a shortfall in crop production due to a lack of sufficient pollination- limit yields in 28–61% of crop systems, with the greatest vulnerability occurring in tropical regions (Millard et al., 2023; Rahimi and Jung, 2024; Turo et al., 2024). Agroforestry systems can mitigate these pressures by providing diverse and continuous floral resources, nesting habitats, and microclimatic stability that support pollinator diversity and activity (Dainese et al., 2019). The structural complexity and temporal diversity of agroforestry landscapes also reduce pesticide exposure and enhance pollination services (Jose, 2009). However, the magnitude of these benefits varies among regions and management systems. This highlights the need for context-specific, pollinator-friendly agroforestry designs that integrate ecological and socio-economic considerations.

Despite extensive research on the influence of agroforestry on pollinators and enhancing food security, the existing studies remain scattered and uneven. Many have approached from traditional indigenous practices (Gonçalves et al., 2021) and focused on specific applications such as fertilizer trees in Malawi (Coulibaly et al., 2017). Various attempts to review agroforestry and pollinators have been carried out, but food security was not included (Centeno-Alvarado et al., 2023). Moreover, quantitative syntheses comparing different agroecological contexts remain limited, and the mechanisms linking pollination services in agroforestry to the four pillars of food security—availability, access, utilization, and stability—are still poorly understood.

This review, therefore, seeks to address three interrelated questions: 1. How does agroforestry practice support pollinators or pollinator activity? 2. How does agroforestry practice influence food security? 3. How does pollinator activity in agroforestry systems contribute to food security? To answer these questions, we reviewed the literature on agroforestry systems, pollinators, and food security to explore the role of various agroforestry practices in supporting pollinators and enhancing food security. The goal is to synthesize existing knowledge on the role of agroforestry practices in supporting pollinators, improving food security, understanding pollinators' contribution to food security, and identifying potential areas for future research. Beyond yield improvements, this review considers how agroforestry contributes to broader aspects of food and nutritional security through diversified production, livelihood stability, and climate resilience. Thus, it highlights agroforestry as a nature-positive, climate-resilient farming approach that can enhance biodiversity, support pollinator communities, and improve agricultural productivity. The IPBES report emphasizes the transition to nature-positive practices, including agroecological and diversified farming, to restore biodiversity (such as pollinator habitats), enhance ecosystem resilience, and improve agricultural productivity and nutrition outcomes (IPBES, 2024). The study's significance lies in the comprehensive synthesis of the role of agroforestry in enhancing pollinators and supporting resilient food systems, and addressing the four pillars of food security.

2 Methodology

A systematic literature search was conducted following PRISMA 2020 guidelines, using Scopus and Google Scholar to identify peer-reviewed, English-language articles published between 1980 and 2025. The Scopus search used the following Boolean string:

TITLE-ABS-KEY (agroforestry OR "alleycropping" OR "silvopasture" OR "windbreak" OR "forest farming" OR "hedge grow" OR "shelter belt" AND "pollinat*" OR "bee*" AND food*) AND PUBYEAR > 1980 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")).

This search returned 558 documents, and an additional 148 relevant articles were identified through Google Scholar searches and by screening reference lists of key articles and review papers to capture studies not indexed under the main search terms. The overall process is summarized in the PRISMA flow diagram (Figure 1).

All eligible studies were imported into Microsoft Excel for de-duplication, screening, and data extraction. Two reviewers independently screened the abstracts and full texts, excluding non-peer-reviewed or methodologically weak studies and those that did not address pollinators or food-related outcomes in agroforestry systems. Extracted data included publication year, study region/country, agroforestry practice adopted, pollinator group, response variables (e.g., abundance, richness, visitation rate, yield, or nutritional outcomes), socio-economic indicators, and main findings.

Study quality was evaluated using five criteria: clarity of objectives, methodological rigor, data transparency, relevance to agroforestry-pollinator-food security linkages, and peer-review status. Each criterion was scored (1 = met, 0 = not met), and studies scoring below 50% were excluded ($n = 16$). While the checklist reduced bias, subjective judgment is acknowledged as a minor limitation.

3 Results

3.1 Benefits of agroforestry to support pollinators

3.1.1 Diverse floral resources for pollinators

Agroforestry systems provide diverse floral resources over a longer period to help pollinators for food throughout the season. In contrast, monocultures bloom all at once and provide little to no resources afterward. The combination of trees, shrubs, and crops in

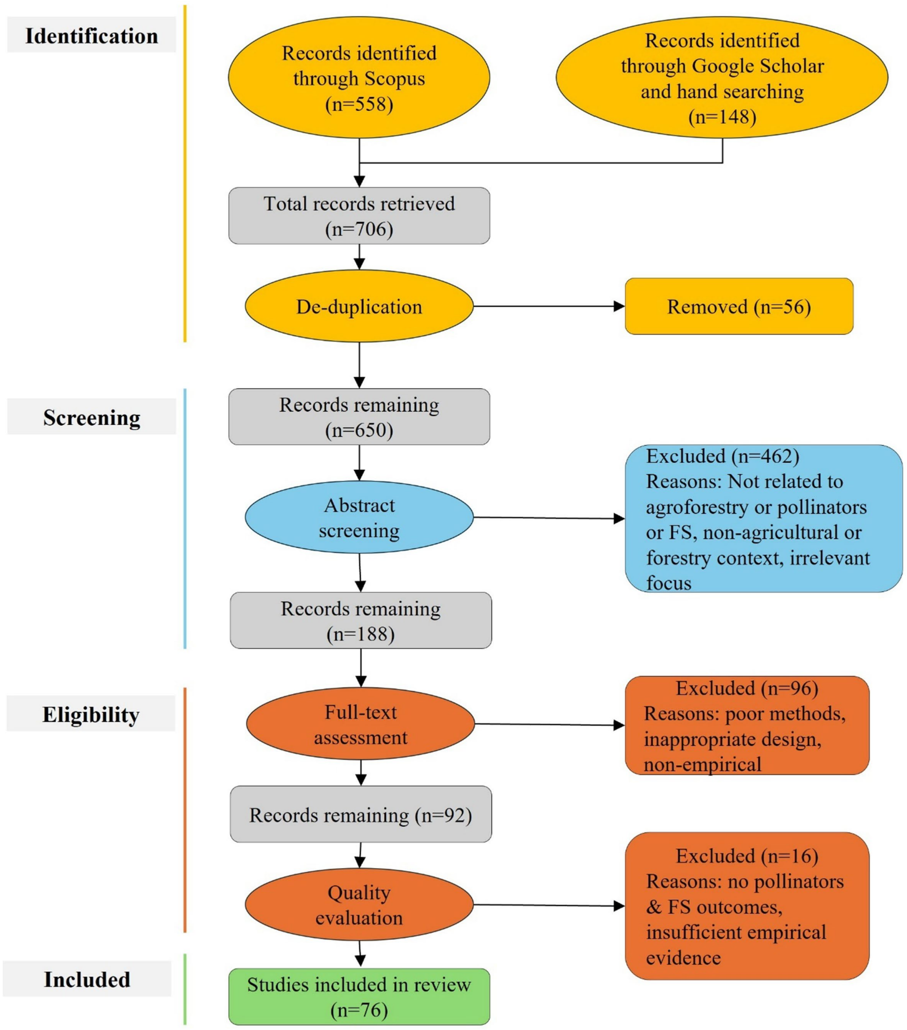

FIGURE 1
PRISMA flow diagram showing the stepwise process of identification, screening, eligibility, and inclusion.

agroforestry creates a continuous flow of nectar and pollen to be used by different pollinators (Garibaldi et al., 2011; IPBES, 2016). By incorporating species that flower at different times of the year, agroforestry systems buffer seasonal fluctuations in floral availability, helping to sustain pollinators during periods when crops are not in bloom (Bentrup et al., 2019). For example, in traditional grassland–cherry agroforestry systems in Switzerland, a single old cherry tree produces a maximum of 520,000 flowers, expanding the foraging area to 2.7 times its canopy size and supporting solitary bee populations (Kay et al., 2020). In tropical cocoa agroforestry, flower abundance strongly correlates with dipteran pollinators such as midges, whose density peaks during intensive cocoa flowering(Arnold et al., 2018; Toledo-Hernández et al., 2021). A mix of woody species, such as maple, basswood, horse chestnut, willow, plum, and brambles, supports continuous nectar sources and nesting substrates (Bentrup et al., 2019). Altogether, the diversity and flowering at different times in agroforestry systems help maintain consistent foraging options, support better nutrition and reproductive success, ultimately strengthening pollinator communities and the essential ecosystem services they provide (Figure 2).

3.1.2 Increased pollination services for crops

Agroforestry systems boost pollination services by supporting more abundant and diverse pollinator communities than monocultures, which in turn improves crop yield and quality. Global studies show that farms with greater crop and habitat diversity support pollinator populations and improve crop yield (Garibaldi et al., 2011; Klein et al., 2007). The presence of native flowering plants within agroforestry has higher visitation by wild bees and butterflies compared with conventional farmlands (Taki et al., 2013), and bee abundance increases when surrounding landscapes include flowering legume crops that provide additional forage (Vogel et al., 2021). In the United Kingdom, temperate agroforestry has twice as many solitary bees and hoverflies, and 2.4 times more bumblebees than monocultures, leading to seed set increases of up to 4.5 times (Varah et al., 2020). In strawberries, proximity to forest-connected hedgerows increased fruit weight by about 30% and boosted marketable yield by as much as 90%, underscoring the benefits of connected habitats for pollinator movement (Castle et al., 2019). Similar patterns are seen in tropical systems, where higher tree diversity and canopy cover in coffee and cocoa agroforestry improve bee richness and visitation, resulting in more reliable fruit set and yield stability (Jha and Vandermeer, 2010; Toledo-Hernández et al., 2021). Altogether, these findings highlight the role of plant diversity and habitat structure found in agroforestry in creating better conditions for pollinators, ultimately strengthening both pollination efficiency and the productivity of pollinator-dependent crops (Tables 1, 2).

3.1.3 Enhancement of habitat and nesting sites

Agroforestry systems strengthen pollinator habitats by providing a wider range of nesting sites, microhabitats, and a safe place to rest and hide than simplified croplands. Trees, shrubs, and perennial vegetation provide suitable conditions for both ground- and cavity-nesting species, expanding the availability of places for pollinators to reproduce and shelter (Klein et al., 2007; Morandin and Kremen, 2013; Potts et al., 2005). In North America, around 30% of native bees nest in cavities, and they benefit from features such as hedgerows, windbreaks, and deadwood that are common components of agroforestry systems (Bentrup et al., 2019). Bumble bees also commonly nest along field edges where woody vegetation meets open fields, showing how habitat connectivity supports social bee colonies (Kells and Goulson, 2003; Svensson et al., 2000). Research from Mexico and Switzerland demonstrates that greater tree-canopy cover and species diversity can boost solitary bee nesting and overall pollinator abundance (Jha and Vandermeer, 2010; Kay et al., 2020). On a global scale, pollinator visitation drops by about 50% when fields are more than 0.6 km from natural habitats, emphasizing the benefits of connected woody elements to help pollinator movement across farmland (Ricketts et al., 2008). Collectively, these studies show that the structural diversity and well-connected field edges in agroforestry systems provide essential nesting resources, supporting more stable pollinator populations and enhancing ecosystem resilience.

3.1.4 Microclimate regulation

Microclimate regulation is one of the most immediate ecological benefits of agroforestry. The presence of trees adds

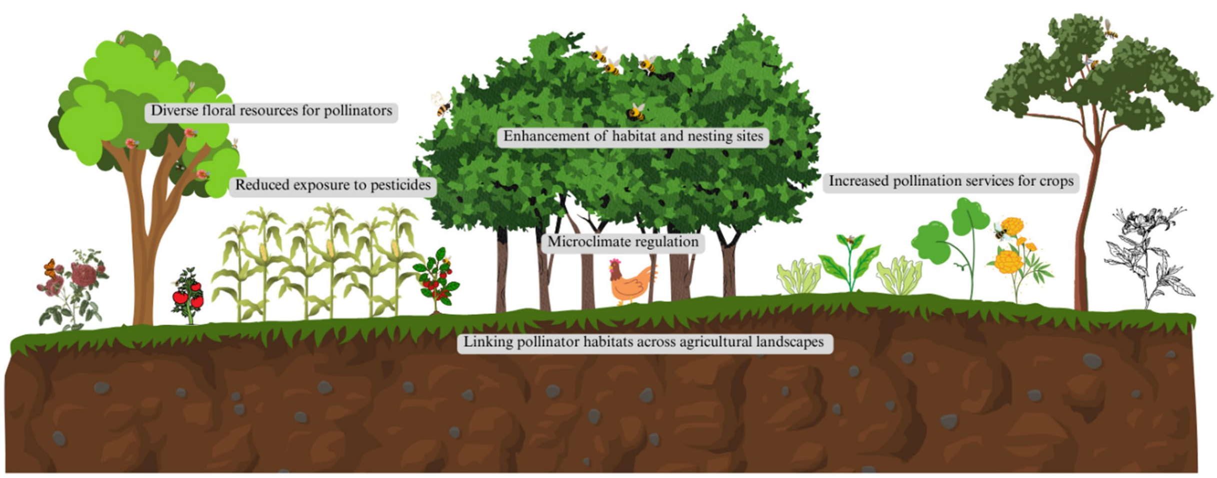

FIGURE 2
Benefits of agroforestry to support pollinators.

TABLE 1 Pollinator responses and ecological benefits across agroforestry systems.

Region/country	Agroforestry system	Key findings	Pollinator response/ ecological effect	References
Switzerland	Grassland-cherry system	Each old cherry tree produced a maximum of 520,000 flowers, expanding the foraging area by 2.7 canopy size	Solitary bee abundance and visitation rates increased proportionally with floral area	Kay et al. (2020)
Tropical regions	Cocoa-based agroforestry	Cocoa flower density positively correlated ($r > 0.7$) with dipteran pollinator abundance; midge numbers peaked during flowering	Enhanced fruit set and pod quality through synchronized pollination activity	Arnold et al. (2018) and Toledo-Hernández et al. (2021)
North America	Hedgerows, windbreaks, riparian buffers	Mixed tree/shrub assemblages (maple, basswood, willow, plum, brambles) maintained continuous bloom 6–8 months $yr.^{-1}$	Supported both early- and late-season bees, butterflies, and hoverflies; improved functional diversity	Bentrup et al. (2019)
Global synthesis	Various pollinator-dependent cropping systems	Greater pollinator dependence led to reduced mean yield (up to 50% higher yield variability) and slower yield growth	Yield instability linked to inadequate pollination	Garibaldi et al. (2011)

TABLE 2 Quantitative evidence of enhanced pollination services and crop yield in agroforestry.

Region	System/crop	Comparison baseline	Key findings	Outcome	References
Temperate	Mixed temperate agroforestry (arable + pasture)	Adjacent monoculture fields	2 × solitary bees and hoverflies, 2.4 × bumblebees, and up to 4.5 × higher seed set in agroforestry treatments	Greater pollination service magnitude and stability	Varah et al. (2020)
Temperate	Strawberry phytometers at hedgerows	Isolated hedgerows and grassy margins	29–32% higher fruit weight, 90% marketable yield at forest-connected hedgerows vs. 48% on grass margins	Enhanced crop quality and economic return	Castle et al. (2019)
Tropical	Coffee agroforestry	Open coffee monoculture	Bee richness ↑ with canopy cover and tree diversity; higher fruit set in shaded systems	Stronger pollination efficiency and yield stability	Jha and Vandermeer (2010)
Tropical	Cocoa agroforestry	Unshaded cocoa plantations	Flower density $r > 0.7$ with midge abundance; pollination peaks with shade-tree bloom overlap	Increased pod set and yield stability	Toledo-Hernández et al. (2021)

vertical structure and shade, helping soften the harsh conditions typical of open farmland, cooling the soil, balancing humidity, and reducing wind exposure for both crops and insects. These conditions are more important for pollinators with foraging activity strongly influenced by temperature and wind. Research in European landscapes has found that semi-natural habitat patches can buffer daily temperature swings by several degrees, helping prevent heat-related declines in bee diversity and abundance (Papanikolaou et al., 2017). When these habitats are removed and replaced with uniform cropland, pollinator diversity and foraging time both drop noticeably (Kormann et al., 2015). Trees also function as windbreaks: shelterbelts and hedgerows can reduce wind speeds by 30–50% within 10–20 m of tree rows (Norton, 1988), allowing insects like honeybees, normally grounded above roughly 11 m s^{-1} (25 mph), to continue flying (USDA, 2016). Similar benefits have been documented in subtropical mango orchards, where partial canopy cover improved fruit set by reducing heat and wind stress during flowering (Amin et al., 2015). Through these combined effects, agroforestry helps keep field conditions stable, supporting pollinator activity and crop reproductive success even under increasingly unpredictable weather.

3.1.5 Reduced exposure to pesticides

Pesticides are one of the biggest ongoing threats to pollinators, affecting their ability to grow, navigate, forage, and reproduce, and causing direct deaths too (Stanley and Preetha, 2016). Agroforestry systems help reduce these risks through both ecological processes and smart landscape design. They include a mix of trees, shrubs, and ground vegetation to support natural predators that help control pests, lowering reliance on chemical sprays (Sollen-Norrlin et al., 2020). The structural elements, like hedgerows and windbreaks, also serve as barriers that block drifting pesticides from reaching flowers and nesting areas (Ratnadass et al., 2012). Pollinators are more likely to find untreated food sources and protected nesting places to reduce their chances of encountering contaminated pollen or nectar. The healthier soils in agroforestry systems with more organic matter and diverse microbes further improve natural pest suppression. Together, these factors create a protective buffer that limits pollinator exposure to harmful chemicals while supporting productive and more environmentally balanced farming systems.

3.1.6 Linking pollinator habitats across agricultural landscapes

Habitat fragmentation is a major threat to biodiversity (Fahrig, 2003). It strongly contributes to pollinator decline as extensive monocultures separate food sources from nesting areas and limit insect movement. Agroforestry helps counter this by creating ecological corridors, such as hedgerows, riparian buffers, and shelterbelts, that reconnect habitats and support pollinator travel across farmland. These woody features offer flowers and nesting sites throughout the season, effectively linking patches of semi-natural vegetation. Studies show that such habitat connections increase pollinator abundance, visitation, and species diversity (Hannon and Sisk, 2009; Morandin and Kremen, 2013). In tropical agroforestry, stingless bee populations grow with greater nearby forest cover that supports long-term pollinator persistence (Brosi et al., 2008). The landscapes with more edges also tend to host more pollinators and stronger ecosystem services (Martin et al., 2019). This is especially critical for solitary bees and other species with short foraging ranges that rely on close access to nesting substrates (Kay et al., 2020). Shade-grown coffee and cocoa systems demonstrate this clearly, supporting richer and more stable bee communities than surrounding open plantations (Centeno-Alvarado et al., 2024; Jha and Vandermeer, 2010). Overall, agroforestry turns simplified agricultural land into a connected network of pollinator-friendly habitats, strengthening biodiversity, improving pollination reliability, and supporting food production (Figure 3).

3.2 Benefits of agroforestry practice in achieving food security

3.2.1 Crop yield and stability

Agroforestry systems are widely shown to boost crop productivity and make yields more reliable over time, thanks to improvements in soil fertility, microclimate moderation, and stronger pollination services (Castle et al., 2021; Rahman et al., 2012; Sunderland and O'Connor, 2020). Across many crops and regions, yields in agroforestry are often 25–80% higher than in monocultures, averaging about a one-third increase (Table 3). The benefits are especially strong in nitrogen-fixing tree systems and semi-arid regions where soil and climate are more limiting. Agroforestry also contributes to household food security. Studies in Indonesia and the Philippines found that diversified crop production from agroforestry supports moderate but important improvements in food availability for smallholders (Wulandari et al., 2019), while home-garden produce, such as fruits and vegetables, provides essential nutrition and supplementary income (Suwardi et al., 2023). These outcomes are particularly valuable for farmers with limited land resources; those managing less than 2 acres often gain the most from diversified production (Coulibaly et al., 2017). Best results generally occur at moderate tree densities, around 30–35% woody cover, since too much shade can reduce crop growth (Leroux et al., 2020). Agroforestry also improves food security by offering multiple harvests across the year and creating diverse income sources that help farmers bridge seasonal shortages

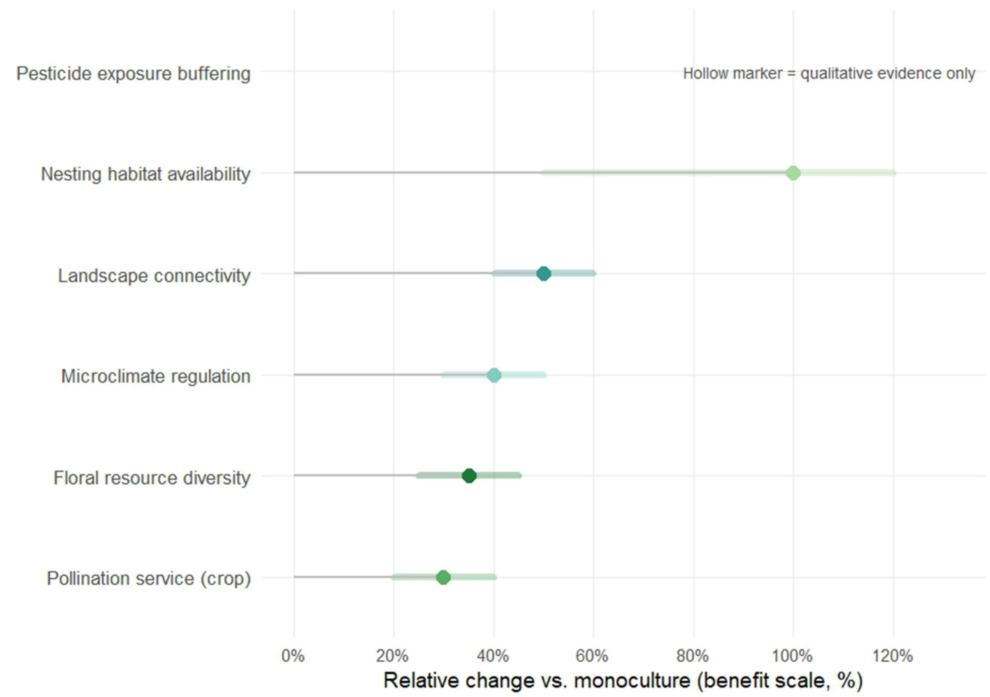

FIGURE 3
Relative improvements in key pollinator-supporting functions in agroforestry compared with monoculture systems. Points represent estimated percentage benefits based on quantitative evidence from global studies; extended bars indicate variability across contexts. Hollow markers denote factors supported primarily by qualitative evidence. Together, these results highlight agroforestry's role in enhancing floral resources, nesting habitats, microclimate regulation, habitat connectivity, and crop pollination services.

(Pandit et al., 2019; Quinion et al., 2010). Yield outcomes can still vary, and some systems prioritize conservation or premium markets even if yields are slightly lower(Castle et al., 2021). Overall, when trees are well managed, agroforestry supports higher and more consistent crop production, making it a strong and resilient farming approach under changing conditions (Figure 4).

3.2.2 Nutrition and medicinal properties

Agroforestry can improve both nutrition and health by incorporating nutrient-rich and culturally valued tree species into smallholder farms. A review of 55 case studies from low- and middle-income countries found that systems integrating trees, crops, and livestock increased dietary diversity and overall food availability (Kerr et al., 2021). In Arunachal Pradesh, India, for example, communities rely on around 50 wild edible fruit species for essential nutrients and traditional medicines, with leaves being the most used plant part, followed by fruits and bark, highlighting the importance of conserving these species through agroforestry (Hazarika et al., 2022). Similar benefits are seen in Ethiopia, where home-garden agroforestry supports 20–30 edible and medicinal species per household, improving diets and household income (Kebebew et al., 2011), and where climate-smart adopters report higher dietary-diversity scores and more stable food supplies (Teklu et al., 2024). Domestication of native species such as *Allanblackia* has unlocked new nutritional and market opportunities for farming families (Ofori et al., 2014). In Malawi, agroforestry shortened seasonal hunger gaps by roughly 2 months (Quinion et al., 2010), and broader evidence shows neutral to positive impacts on diet quality and food security (Castle et al., 2021). Forest-derived foods, ranging from fruits and nuts to leafy vegetables and bushmeat, also act as nutritional safety nets and complementary income sources for rural and Indigenous communities (Chamberlain et al., 2020). Altogether, these findings show that integrating edible and medicinal trees into farms can improve diet quality, strengthen health and cultural practices, and build more resilient livelihoods.

3.2.3 Improving soil health and sustainable food production

Agroforestry improves soil fertility, structure, and long-term productivity by harnessing the ecological functions of perennial trees, which add organic matter, recycle nutrients, and help prevent erosion. Evidence from Africa and Asia shows that tree–crop systems strengthen soil health while making farms more resilient to land degradation. For example, the Conservation Agriculture with Trees program in the southern Philippines helped stabilize hillsides, prevent landslides, and improve farmer incomes (Trivino et al., 2016), while traditional Enset-based home gardens in Ethiopia enhance soil fertility, water storage, and erosion control (Sahle et al., 2021). In northern Ecuador, cocoa agroforestry stored nearly 111 Mg ha^{-1} of above-ground biomass, almost three times more than unshaded plantations, illustrating its combined benefits for carbon sequestration and soil enhancement (Middendorp et al., 2018). A global meta-analysis found that agroforestry increases soil organic carbon and

TABLE 3 Summary of yield responses of crops under agroforestry compared to monoculture systems.

Region	Crops	Yield in AF (ton per ha or %)	Yield in monoculture (ton per ha or %)	Δ Yield (%)	Log response ratio [LRR = ln (T/C)]	Context	References
Sub-saharan Africa	Maize+N-fixing shrubs	8 t ha^{-1}	5 t ha^{-1}	+60%	0.47	Improved soil N and microclimate; regional average from multiple trials	Akanmu et al. (2023)
Malawi	Maize	+25% vs. non-adopters	Baseline = 100%	+25%	0.22	Fertilizer tree adoption among smallholders	Quinion et al. (2010)
Kenya	Maize	+35% vs. controls	Baseline = 100%	+35%	0.30	Tree integration program; household panel data	Thorlakson and Neufeldt (2012)
Sudan	Sorghum	1.2 t ha^{-1}	0.8 t ha^{-1}	+50%	0.41	Ten-year average; semi-arid parkland system	Fahmi et al. (2018)
Sudan	Millet	0.9 t ha^{-1}	0.5 ha^{-1}	+80%	0.59	Ten-year average; semi-arid parkland system	Fahmi et al. (2018)
Senegal	Millet	Peak benefit ≤35% woody cover	–	–	–	Yield rises below 35% woody cover; declines above threshold	Leroux et al. (2020)
Indonesia	Canna+Teak	LER > 1	LER = 1	+ > 0%	–	Shade-tolerant crops are more productive under a teak intercrop	Maharani et al. (2022)
Sub-saharan Africa	Mixed food crops	≈ 2 times higher mean yield	Reference = 1 time	+100% (approx)	0.69	Aggregated from >90 cases	Kuyah et al. (2019)
Nepal	Mixed subsistence crops	Food sufficiency 52 → 69%	–	+17% points	–	Improved food sufficiency and poverty decline	Pandit et al. (2019)

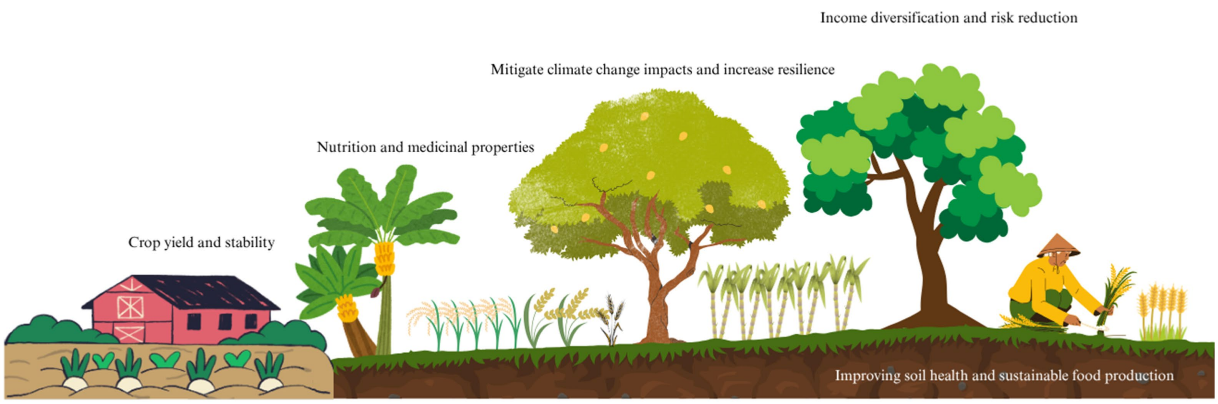

FIGURE 4
Benefits of agroforestry practice in achieving food security.

total nitrogen by 15–25% and can reduce soil loss by up to nine times compared to treeless croplands (Kuyah et al., 2019). Across tropical regions, integrating nitrogen-fixing or deep-rooted trees boosts soil biodiversity and nutrient cycling (Barrios et al., 2018). These improvements are crucial for sustainable food production, as healthier soils maintain yields, reduce drought impacts, and lower dependence on synthetic fertilizers. When combined with strategies such as indigenous tree domestication and stronger value chains, soil-focused agroforestry can reinforce both food security and rural livelihoods (Leakey, 2018). Overall, maintaining soil health through agroforestry is central to building climate-smart farming systems that support productivity while protecting ecological integrity.

3.2.4 Mitigate climate change impacts and increase resilience

Agroforestry enhances the resilience of farming systems by buffering climate extremes, improving resource-use efficiency, and providing diversified income and food sources. In Nepal's mid-hill regions, households facing land fragmentation and climate shocks increasingly adopted improved agroforestry practices, particularly where awareness of climate risks was higher (Paudel et al., 2022). Across East Africa, agroforestry reduced the need for negative coping strategies during droughts and floods, as trees supplied food and income even under stress (Thorlakson and Neufeldt, 2012). A global review confirmed that agroforestry interventions in low- and middle-income countries enhance biodiversity, soil and water conservation, and carbon sequestration (Castle et al., 2021). In semi-arid Africa, Australian acacias showed strong drought tolerance and provided nutritious, storable seeds serving as famine reserves (Rinaudo and Cunningham, 2008), while parkland systems in Ethiopia stored the highest biomass carbon stocks, followed by home gardens and woodlots (Semere et al., 2022). Macadamia-based systems sequester about 3 t CO_2 ha^{-1} $yr.^{-1}$ and generate additional carbon-market income (Araya et al., 2023). Likewise, improved fallows with leguminous trees increased soil carbon and fertility while stabilizing crop yields and water retention (Partey et al., 2017). Collectively, these results show that agroforestry simultaneously mitigates greenhouse gas emissions and strengthens adaptive capacity, providing a climate-smart pathway that sustains food availability, household income, and ecological stability in both tropical and semi-arid environments.

3.2.5 Income diversification and risk reduction

Agroforestry provides multiple income streams that help households better cope with market volatility and climate-related risks, leading to more stable and resilient livelihoods. Across Asia, Africa, and Latin America, farmers who integrate trees with crops or livestock benefit financially from products such as fruits, timber, medicinal plants, and other non-timber forest goods (Cardozo et al., 2015; Hazarika et al., 2022; Race et al., 2022). This diversification allows smallholders to weather seasonal price drops or crop losses far more effectively than those relying on a single commodity. Studies from Africa and South Asia show that agroforestry enterprises often deliver higher net present values and benefit–cost ratios compared with conventional monoculture systems, underscoring their long-term economic attractiveness (Fahmi et al., 2018; Jahan et al., 2022) Evidence from Malawi, Nepal, and Indonesia also demonstrates that tree–crop systems make a significant contribution to household income, especially when farmers engage in value-added processing or local marketing (Pandit et al., 2019; Quinion et al., 2010; Race et al., 2022). Although initial establishment can require greater investment, steady returns from multiple products act as a financial buffer for rural families. Overall, agroforestry enhances the "access" and "stability" dimensions of food security by improving income reliability, reducing production risks, and strengthening livelihood resilience across diverse farming environments (Tables 4, 5).

3.2.6 Overall synthesis: agroforestry and the four pillars of food security

Taken together, the evidence shows that agroforestry supports all four pillars of food security. It improves availability by increasing and stabilizing crop yields, strengthens access through more diverse and reliable income streams, enhances utilization by providing nutritious foods and improving diet quality, and boosts stability by restoring soils, moderating microclimates, and reducing risks from droughts and market fluctuations (Castle et al., 2021; Kuyah et al., 2019; Ntawuruhunga et al., 2023). Across many regions, tree–crop systems not only raise farm productivity but also build ecological and economic resilience for farming families. These wide-ranging benefits position agroforestry as a climate-smart, nature-based approach that supports livelihoods while protecting the environment. By bringing together ecological processes and socioeconomic gains, agroforestry creates a practical pathway toward more resilient, inclusive, and food-secure farming landscapes (Figure 5).

3.3 Policy support and implementation: overcoming barriers

Agroforestry adoption is motivated by livelihoods, food security, and resilience, yet uptake remains uneven due to structural, economic, and institutional constraints that demand targeted policy and extension responses. Evidence from Nepal, Uganda, Ethiopia, and Malawi shows that adoption is often hindered by land scarcity, tenure insecurity, limited finance, weak extension capacity, and low awareness (Araya et al., 2023; Kamugisha et al., 2022; Kebebew et al., 2011; Paudel et al., 2022). In Nepal, farmers adopt mainly for income and food production but lack consistent technical support, while in Uganda and Ethiopia, fewer than half of respondents have adequate land or training to sustain tree–crop systems. Tenure insecurity, as in South Sudan, further discourages long-term investment (Gonçalves et al., 2021). Climate-smart agroforestry (CSAF) also faces high upfront costs and slow returns that deter smallholders (Ntawuruhunga et al., 2023). Two key policy pathways can help bridge these gaps: (i) capacity and input support (nursery materials, training, and technical assistance) and (ii) incentive mechanisms such as certification or payments for ecosystem services that reward environmental performance (Castle et al., 2021). Strengthening tenure security, access to credit, extension networks, and market linkages, alongside public–private partnerships and farmer education, will be essential to scale agroforestry as a climate-smart, livelihood-enhancing solution for sustainable rural development (Smith et al., 2012).

3.4 Agroforestry, pollinators, and food security

Animal pollination supports roughly 75% of major food crops worldwide (Klein et al., 2007), making the stability of this ecosystem service essential for both yields and diet quality. Agroforestry helps sustain pollinators by incorporating trees and shrubs into farmland, which provides season-long floral resources, a wider range of nesting habitats, and protective microclimates (Bentrup et al., 2019; Garibaldi et al., 2011). A growing body of research shows that agroforestry systems host greater pollinator abundance, species richness, and foraging activity than monocultures, particularly in landscapes with diverse and flower-rich vegetation (Kay et al., 2020; Varah et al., 2020). Crucially, these ecological gains translate into real benefits for food production. For example, bean plots grown in agroforestry settings recorded nearly double the insect visitation and higher total yields (Kingazi et al., 2024), while in traditional shea parklands, fruit set increased significantly in more tree-diverse sites due to stronger pollination by wild bees, an important food and income buffer during the dry season (Stout et al., 2018). A global meta-analysis further confirms that proximity to natural or semi-natural habitats boosts pollinator richness and visitation, particularly in pollinator-dependent crops (Ricketts et al., 2008).

Rather than a simple linear chain from agroforestry to pollinators to yields, studies highlight a dynamic feedback system: diverse tree cover stabilizes pollination services over time and across landscapes, strengthening food-production resilience under variable conditions (Bartomeus et al., 2014). Seasonal overlap in flowering between trees and crops also maintains pollinator populations during off-crop periods (Bentrup et al., 2019). In return, consistent pollination enhances not just yield quantity but also quality, for example, higher oil content in oilseed rape, fewer empty seeds in buckwheat, and better commercial grades in strawberries (Bartomeus et al., 2014). Taken together, these findings show how agroforestry supports not only food availability but also nutrition and overall food-system resilience through its strong and reciprocal links with pollinators.

The strength of the agroforestry–pollinator–food security relationship depends on multiple contextual factors. Benefits vary with crop type, baseline pollinator populations, farm management, and landscape design, for example, whether flowering trees are included or pesticide exposure is minimized. Vezzani et al. (2025) found a strong link between pollinator abundance and crop yield, but also noted that outcomes differed across sites depending on floral availability and chemical use. Poorly planned systems, such as those using tree species that offer few floral resources or that strongly compete with crops, can limit expected gains (Leroux et al., 2020). In contrast, when agroforestry is intentionally designed to support pollinators, a positive cycle emerges: healthy pollinator communities boost food production, and the resulting benefits motivate farmers to maintain biodiversity-enhancing practices.

Overall, the evidence shows that agroforestry enhances pollination services and, when matched to the right crops and environments, can deliver meaningful food security benefits across availability, access, utilization, and stability. These improvements extend beyond yield, contributing to better nutrition, steadier incomes, and stronger climate resilience. This highlights the importance of embedding pollinator needs into agroforestry design and applying a landscape perspective that maintains habitat connectivity. As illustrated in Figure 6, the relationships between agroforestry, pollinators, and food security form an interconnected system of ecological functions and feedback. Many of these pathways are already well supported,

TABLE 4 Summary of dietary diversity outcomes associated with agroforestry interventions.

Source	Location	Reported outcome	Approx involvement	Confidence
Kerr et al. (2021)	Global (LMICs)	+ 1–3 food groups in the diet	+15–35%	High
Teklu et al. (2024)	Ethiopia	+2 food groups	+20–25%	High
Kebebew et al. (2011)	Ethiopia	Higher DDS	+	Moderate
Chamberlain et al. (2020)	Global review	Greater dietary variety	+	Moderate

TABLE 5 Economic outcomes of agroforestry systems.

Study (year)	Country/ region	System/crop type	Income metric	Outcome
Race et al. (2022)	Indonesia	Mixed smallholder agroforestry	Share of total household income	29% from agroforestry; timber ≈ 55% of that share
Hazarika et al. (2022)	India	Wild-fruit agroforestry	Fruit market price	USD 0.125–0.25 $lb.^{-1}$; potential for value-addition income
Cardozo et al. (2015)	Eastern Amazonia	Home gardens	Profitability vs. alternatives	Highest net income and profitability vs. plantations/shifting cultivation
Quinion et al. (2010)	Malawi	Fertilizer-tree systems	Household income contributions	Tree-seed/fuelwood ≈ 15% of income; 30% higher for >1 ha farms
Fahmi et al. (2018)	Sudan parklands	Sorghum-tree systems	NPV and BCR	NPV ≈ USD 1200 ha^{-1}; BCR ≈ 2.5 vs. monoculture USD 800; 1.8
Pandit et al. (2019)	Nepal	Banana-based systems	Income gain	Household income +37–48%; profit margin ≈ 56%
Jahan et al. (2022)	Bangladesh	Mango-based agroforestry	Economic return	Highest NPV and IRR among compared systems; financially viable

while others call for continued empirical testing across diverse farming contexts.

4 Contextual dynamics, trade-offs, and limitations

Although this review shows that agroforestry can deliver consistent ecological and socioeconomic benefits, these outcomes are not universal and depend heavily on local conditions. Many of the strongest gains, like higher pollinator abundance and increased yields, are most evident at the field or farm scale, yet their long-term success often relies on landscape-level connectivity, including nearby hedgerows, woodlots, and semi-natural habitats. This highlights the importance of planning agroforestry not just within individual farms but as part of a coordinated landscape strategy that supports biodiversity and ecosystem services.

There are also important trade-offs to consider. If tree density is too high, shading and below-ground competition can reduce crop performance in the short term, even if those trees contribute long-term benefits for soil, climate regulation, and habitat quality (Leroux et al., 2020). Economic viability can vary as well: establishment costs, labor needs, limited market access, and delayed financial returns may challenge adoption, especially for smallholders with tight budgets or limited risk tolerance. In some systems, the most significant benefits only emerge after several years, which can deter farmers who require quicker payoffs.

As summarized in Table 6, these trade-offs represent common ecological and economic constraints in agroforestry. However, they can be managed with thoughtful system design, careful species selection, supportive policies, and market development to maximize benefits and minimize risks for farmers and the environment.

5 Knowledge gaps and future research needs

Despite strong evidence of ecological and food security benefits, several critical knowledge gaps constrain the full integration and scalability of pollinator-friendly agroforestry. These gaps span ecological, socioeconomic, and implementation domains:

5.1 Lack of long-term monitoring of pollinator diversity and performance

Most studies included in this review offer short-term or seasonal data, providing limited insights into how pollinator populations persist over time. Longitudinal monitoring remains rare (Ollerton et al., 2011; Ricketts et al., 2008), which restricts understanding of temporal dynamics, community turnover, and resilience of pollination services in agroforestry landscapes.

5.2 Poor integration of ecological and socioeconomic outcomes

Many agroforestry studies emphasize biophysical metrics such as pollinator abundance or crop yield but fall short of linking these outcomes to livelihoods, dietary diversity, or household resilience (Castle et al., 2021; Sunderland and O'Connor, 2020). This disconnect weakens our ability to understand how ecological gains translate into meaningful food security outcomes. Interdisciplinary frameworks that bridge ecology, economics, and nutrition are needed to fill this gap (Miller and Nair, 2006).

5.3 Limited understanding of native vs. exotic tree species

There is a paucity of studies comparing the value of native versus exotic species for pollinator habitat and services in agroforestry systems (Leakey, 2018; Morandin and Kremen, 2013). Some exotic species may support floral resources, but native plants are more likely to align with local pollinator preferences and phenology. More targeted research is required to guide species selection that balances ecological and production goals.

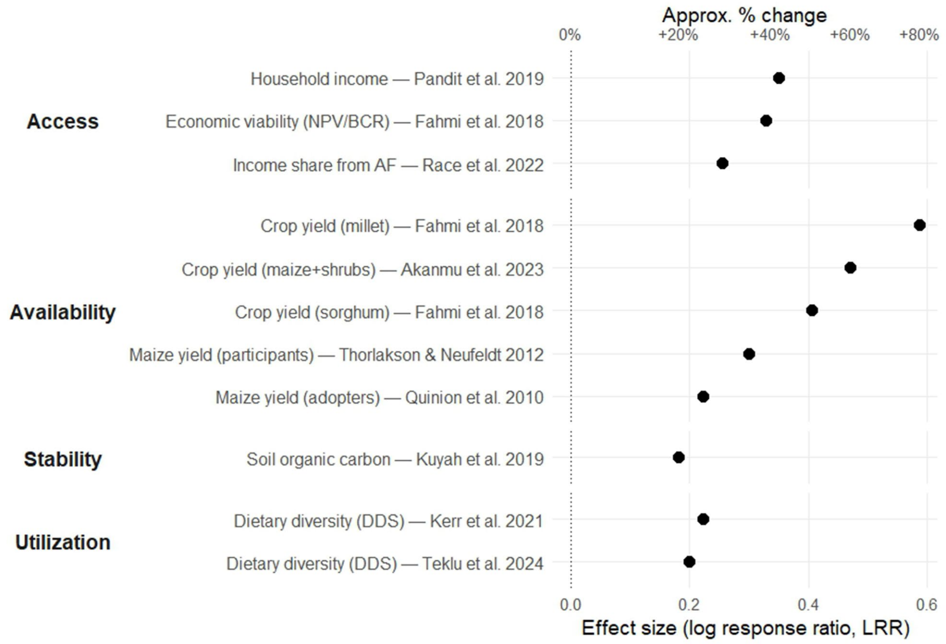

FIGURE 5
Estimated effects of agroforestry on key dimensions of food security across multiple studies, expressed as log response ratios (LRR) and approximate percent change relative to non-agroforestry systems.

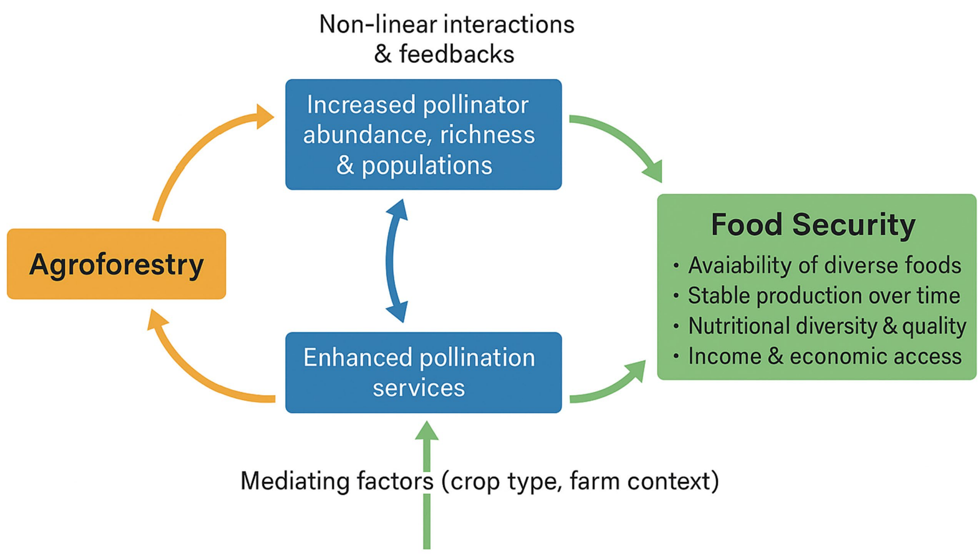

FIGURE 6
Conceptual framework illustrating the reciprocal linkages between agroforestry, pollinators, and food security.

5.4 Temporal gaps in floral provisioning and pollinator support

Agroforestry systems are not always designed to provide continuous nectar and pollen resources across seasons. This results in potential forage dearth during critical periods (Bentrup et al., 2019; Kay et al., 2020). Studies that map flowering phenology across diverse agroforestry trees and crop assemblages can help identify combinations that sustain pollinators year-round.

5.5 Barriers to adoption and evidence at the landscape level

Many studies focus on field-level benefits but overlook the social and institutional barriers that hinder widespread adoption. These include insecure land tenure, lack of capital or extension support, and limited policy incentives (Kamugisha et al., 2022; Ntawuruhunga et al., 2023). Moreover, evidence on the impacts of agroforestry at landscape or national scales remains sparse, limiting

TABLE 6 Potential disservices of agroforestry systems and mitigation strategies.

Potential disservice	Ecological/economic mechanism	Impact on the system	Mitigation strategy
Resource competition	Tree/crop competition for light, water, and nutrients (Leroux et al., 2020)	Reduced short-term crop yields	Optimized spatial arrangement, strategic pruning, deep-rooted species, fertilizer trees (e.g., *Faidherbia albida*) (Garrity et al., 2010)
Delayed economic return	High initial investment and long time to maturity for perennials (Nigussie et al., 2020)	Financial strain; low adoption among resource-poor farmers	Subsidies, grants, low-interest loans, and short-term cash crops for early returns (Mbow et al., 2014)
Pest/disease harboring	Trees act as pest hosts; humid microclimates may increase disease incidence (Schroth et al., 2000)	Localized pest outbreaks (e.g., *Leucaena* psyllid)	Selection of compatible plant species, spatial arrangement, shade density optimization, and integrated biological control (Pumariño et al., 2015; Schroth et al., 2000)
Pollinators sink effect	Pesticide drift from adjacent farms contaminates AF habitats (Holzschuh et al., 2008)	Increased pollinator exposure risk	Design of vegetative buffer zones, chemical-use regulation near AF zones, and residue monitoring programs

our understanding of its broader scalability and resilience contributions.

Addressing these gaps will require interdisciplinary and regionally diverse research agendas, with stronger linkages between ecological design, farmer realities, and food system goals. Closing these evidence gaps will help optimize agroforestry practices for both pollinator conservation and food security under dynamic environmental and socioeconomic conditions.

6 Geographic bias and implications for global applicability

The studies synthesized in this review show an uneven geographic distribution which are shaped by regional research priorities and agroecological contexts. Approximately 50% of the reviewed studies were conducted in Africa, primarily addressing agroforestry's role in improving food security, soil fertility, and smallholder livelihoods. Around 28% originated from Asia, emphasizing home-garden systems, climate-smart agroforestry, and livelihood diversification. About 13% of studies came from Europe, focusing largely on pollinator ecology, landscape connectivity, and ecosystem service quantification, while around 8% represented North America.

The regional concentration indicates that Africa and Asia have been the main testing grounds for agroforestry-pollinator-food security interactions. The underlying mechanisms, such as diverse floral resources, enhanced pollination services, and improved yield stability, are globally relevant. The synthesis provides broadly generalizable insights, but these should be applied with contextual awareness of regional differences in climate, species composition, and socioeconomic conditions. Agroforestry practices in temperate regions, for example, may differ structurally yet operate through similar ecological processes that enhance pollination and resilience.

The current evidence base provides a strong foundation for understanding agroforestry's multifunctional benefits. However, studies from underrepresented regions are still limited. The greater inclusion of research from these regions would further improve global transferability and inform context-appropriate scaling strategies. Expanding the regional diversity of studies will allow more precise cross-continental comparisons and strengthen the evidence for agroforestry's role as a universal, adaptable model for sustainable food systems.

7 Conclusion and recommendations

Agroforestry emerges from this review as a multifunctional, nature-based farming approach with integrated ecological, agronomic, and socioeconomic benefits. It supports diverse pollinator communities by enriching floral resources, habitat complexity, and landscape connectivity, which in turn enhances pollination services and crop productivity, particularly for pollinator-dependent species. The reviewed evidence reveals agroforestry's capacity to strengthen all four pillars of food security: increasing crop yields and income (availability and access), improving diet quality through diversified outputs (utilization), and buffering farming systems against climate shocks (stability).

However, several methodological and contextual limitations should be acknowledged. A formal quality assessment was applied to improve consistency and reliability, although some subjectivity in evaluating diverse studies remains. As discussed in section 6, most research originated from Africa and Asia, with fewer studies from Europe and America. This uneven representation reflects regional research priorities but also highlights the need for broader global evidence. Even so, the core ecological and socioeconomic mechanisms identified are broadly applicable across contexts. Agroforestry adoption remains constrained by high initial investment costs, labor demands, and land tenure insecurity, particularly for smallholders. These barriers limit large-scale uptake without substantial policy and institutional support.

To overcome these constraints and advance agroforestry's impact, we recommend the following:

- Farmer Training and Extension: Provide targeted technical guidance on agroforestry design, species selection, and pollinator-friendly practices to enhance farmer capacity.
- Financial Incentives and Risk Sharing: Offer subsidies, low-interest loans, and payments for ecosystem services (PES) to offset establishment costs and bridge the period before returns.
- Landscape-Level Coordination: Promote coordinated planning of agroforestry and pollinator corridors (e.g., hedgerows, buffers) across farms to maximize ecosystem service continuity.
- Research Expansion and Integration: Prioritize long-term, multi-scale studies that link ecological outcomes with socioeconomic indicators. This includes rigorous assessment of pollinator dynamics, yield, nutrition, and economic returns.

- Inclusive and Context-Specific Approaches: Design agroforestry models suited to local climates, market conditions, and cultural practices. Ensure inclusive adoption pathways through land tenure security, seedling access, and participatory planning.

Agroforestry is increasingly recognized as a climate-resilient strategy to promote biodiversity and address pressing global food and livelihood challenges. For its wider adoption, national and global policy frameworks must actively integrate agroforestry into agricultural development, biodiversity conservation, and climate adaptation agendas. Continued innovation, inclusive engagement, and solutions that fit local conditions are essential to scale agroforestry as a transformative solution linking pollinator health, ecosystem resilience, and sustainable food systems.

Author contributions

SP: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. SB: Writing – review & editing. SU: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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