Discovery

The role of agroforestry systems on pollinator diversity and the provision of pollinator services

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To Cite:
Abrahão M, Santos-Ferreira BHD, Garcia LC, Torezan-Silingardi HM. The role of agroforestry systems on pollinator diversity and the provision of pollinator services. *Discovery* 2025; 61: e1d1493
doi: https://doi.org/10.54905/disssi.v61i337.e1d1493

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Peer-Review History
Received: 29 August 2024
Reviewed & Revised: 02/September/2024 to 02/December/2024
Accepted: 06 December 2024
Published: 03 January 2025

Peer-Review Model
External peer-review was done through double-blind method.

Discovery
pISSN 2278–5469; eISSN 2278–5450

DISCOVERY SCIENTIFIC SOCIETY

ABSTRACT

Pollination is one of the most relevant aspects of the complex interactions that guarantee ecosystem functionality, since it is directly related to crop productivity. We reviewed the literature on how agroforestry systems (AFS) may enhance pollination services, increasing crop yield and supporting local and regional pollinator diversity and abundance within adjacent agricultural landscapes. We also overviewed the potential of AFS as an ecological restoration approach. Out of 396 studies, we included 129 scientific papers from 23 countries between January 2004 and August 2024. However, there is an imbalance in research distribution regarding countries, scope, and study types. We found that the United States, Brazil, and Germany have the highest number of publications in the area, accounting for nearly 50% of the publications included in this review. There has been a growing investment of studies on this topic over the past two decades, but just recently, the field has gained attention, particularly in the last five years. The most discussed areas were the provision of pollination services and its economic impacts, and the effect of agroforestry management on pollinator diversity. Moreover, we identified a data gap regarding mammalian pollinators, economic costs, and financial return among currently published data. The potential of AFS in restoring landscape remains underexplored (18% of the analyzed studies) despite its importance in ecosystem sustainability through the restoration of ecological networks, particularly mutualistic interactions like pollination, which holds great significance pursuing long-term ecosystem health.

Keywords: Bees; conservation; crop yield; ecosystem services; restoration.

1. INTRODUCTION

Ecosystem services (ES) can be understood as the significant benefits provided to society through the maintenance, recovery, or improvement of environmental conditions by the functioning of ecosystems (Freitas et al., 2009). The land conversion of natural areas, especially for agriculture, threatens the provision of ES and the conservation of biodiversity (Freitas et al., 2009). Hence, considering that forest cover located on the foraging ranges of the pollinators can substantially increase yields in adjacent habitats, there is an urgent requirement for the development of landscape management plans. These plans should not only strive to maintain ES while meeting essential economic demands but also focus on the conservation and restoration of biodiversity and the services it provides.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) states that the degradation of more than three-quarters of the Earth's land surface through human activities compromises the well-being of at least 3.2 billion people. Furthermore, deforestation has reduced productivity in 23% of the arable land, and between $235 billion and $577 billion in global crop productivity per year is at risk due to pollinator loss (IPBES, 2019). Agroforestry practices play a vital role in generating a wide range of ES, such as biodiversity conservation, carbon sequestration, biomass production, nutrient cycling, improvement of air and water quality, provision of raw materials and food, and crop pollination (Bergamo et al., 2023).

Recognizing the significance of these factors, agroforestry systems (AFS) has emerged as a topic of recent discussion for ecological restoration, as well as friendly practices complementing restoration efforts contributing to a mosaic restoration approach (Bergamo et al., 2023). Among the aspects related to ecosystem functionality, the pollinator diversity and pollination services are of paramount importance. In arable areas, bees play an essential role, being responsible for up to 90% of pollination in commercial crops and native species (Barbosa et al., 2017). From an economic perspective, pollination services contribute to approximately 10% of agricultural gross domestic product (GDP), equivalent to a value of U$200 billion annually.

Furthermore, naturally pollinated crops tend to have a higher rate of fruiting and larger fruits (Barbosa et al., 2017). Despite well-documented pollinator value for crop yield, there is still a knowledge gap about the influence of AFS on the diversity and abundance of pollinators and their financial benefits or costs. In this scenario, through a systematic review, we aimed to: (1) evaluate how pollination services differ in AFS versus conventional agroecosystems, (2) identify AFS role in supporting local and regional pollinator diversity and abundance within adjacent agricultural landscapes, and (3) discuss the potential of AFS as an ecological restoration approach.

2. MATERIAL AND METHODS

Overall, the procedure consisted of four steps: (1) literature search using relevant keywords, (2) screening all literature found in the initial search, (3) retrieval of data from sources deemed to be in line with chosen criteria and (4) analysis of data extracted from these sources. We used the following search arguments that appeared in the title, keywords, and, or abstract: (1) agroforest AND pollinat*; (2) agroforestry AND pollinat*; (3) pollination service* AND agroforest*; (4) restoration AND agroforest*; (5) agroecosystems AND pollinat*. We selected all searched references based on the following inclusion criteria: (a) the investigated organisms involved pollinators; (b) the data survey was carried out in agroforestry systems; (c) the publication date fell within the last two decades (from Jan/2004 to Aug/2024).

We organized the data by the number of publications per year and country, study type, adopted agroforestry model, and pollinator groups. In addition, whenever the data were available, we assessed different ecological restoration methods and their respective economic costs and financial returns. We converted the values in the reference year of the study concerning the exchange rate of the dollar to real (USD BRL). For each study, we classified the primary crop (the most used plant) associated with each AFS. We considered an AFS as biodiverse when multiple plant species were intercropped.

3. RESULTS

Initially, our bibliographic search yielded 396 scientific publications. After removing duplicate documents, conference proceedings, technical reports, dissertations ant theses, we found 129 articles that met the inclusion criteria for this study. This systematic review revealed a significant increase in scientific publications in the past two decades ($P < 0.05$, R2 = 0.33; Appendix 1). Altogether, studies within the approached subject were conducted in 23 countries. The United States had the highest number of publications, followed by Brazil and Germany (Appendix 2). Original research papers predominated in terms of publication type, with review articles and book chapters being in the minority (Appendix 3). The most adopted system was *Coffea* spp. as the primary crop (33%), followed by biodiverse AFS (28%) and *Theobroma cacao* (Cocoa, 12%). Most of the AFS was located in the USA (20%) and Indonesia (20%, Figure 1). The review unveiled a substantial increase in scientific publications on this matter over the past two decades.

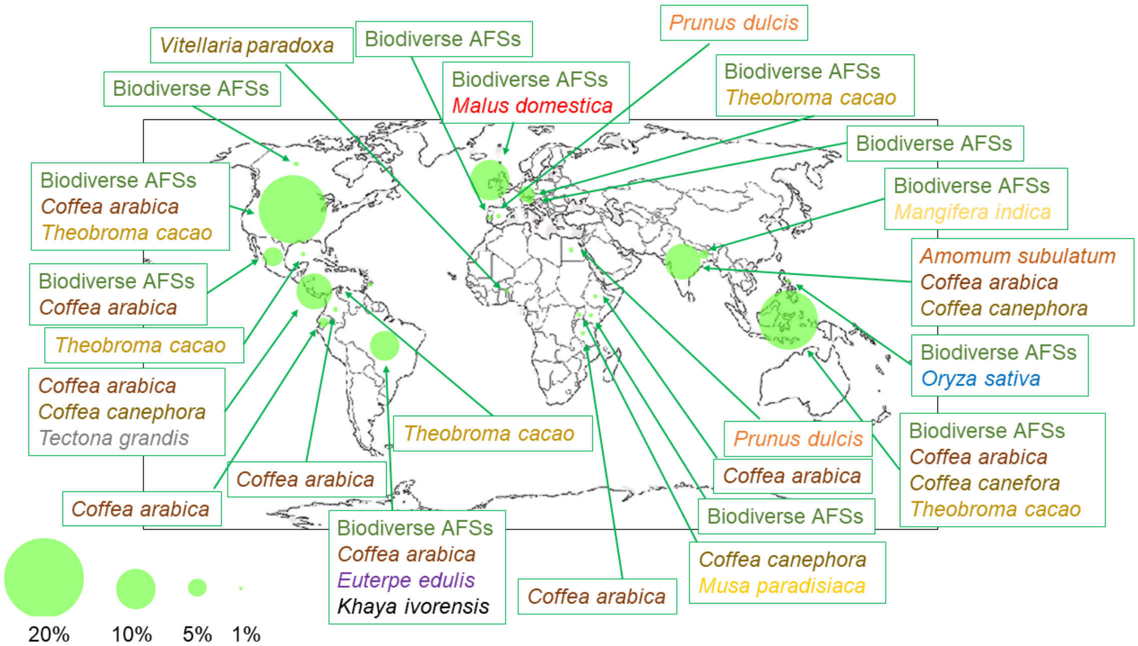


Figure 1 Representation of the agroforestry systems (AFS) regions where data collection was carried out, along with the percentages of 129 assessed studies developed in these areas over the last two decades. In the boxes we have the primary crop categories associated with each AFS. *Coffea arabica* (Coffee); *Euterpe edulis* (Palm's heart); *Khaya ivorensis* (African mahogany); *Manguifera indica* (Hose tree); *Tectona grandis* (Teak); *Coffea canephora* (Coffee); *Theobroma cacao* (Cocoa); *Amomum subulatum* (Cardamom); *Prunus dulcis* (Almond); *Musa paradisiaca* (Banana); *Oryza sativa* (Rice); *Malus domestica* (Apple); and *Vitellaria paradoxa* (Shea).

However, we identified a significant bias in the distribution of studies concerning topics and study types. The provision of pollination services was the most commonly studied aspect, discussing the effect of pollinator diversity and abundance in AFS on agricultural crop yields, including monocultures and agroforestry settings. Another widely investigated topic was the influence of agroforestry management intensity on pollinator diversity, especially comparing shaded (low management intensity) and less shaded (high management intensity) sites (Appendix 4). Studies also frequently examined the landscape effects at local and regional scales, particularly assessing how environmental heterogeneity affected pollinator communities (Graham and Nassauer, 2019). There were a few published papers focusing on the potential of AFS as a restoration method, with only 18% of the total publications included in our scope (Appendix 4).

Brazil played a central role in this matter, with most of publications (39%; Appendix 5). This overlooked approach merits further attention, although there has been a growing investment in this subject in the last five years. Furthermore, very few studies raised the economic costs and financial return of the implementation of these systems (5%), which represents a knowledge gap (Appendix 4), generating a scientific and economic burden (Miccolis et al., 2017). When we compared these few available AFS data costs and benefits with different restoration strategies costs, we found that despite higher cost of AFS it may generates considerable income (Table 1). Moreover, considering landscape context, only two papers assessed the effect of the distance from the nearest forest patch over the abundance and richness of pollinators in agroecosystems and AFS (Appendix 4).

Table 1 Published data on different ecological restoration methods and their respective economic costs and financial return.

Restoration method	**Cost/ha (US$)**	**Financial return (R$/ha)**	**Biome**	**Source**
Assisted regeneration (seed and seedling planting)	802.69 *	Not assessed	Amazon	Cury and Carvalho, (2011)
Assisted regeneration (seed planting)	4,298.85 **	Not assessed	Amazon	Campos-filho et al., (2013)
Assisted regeneration (seedling planting)	6,920.00 ***	Not assessed	Atlantic Forest	Rodrigues et al., (2009)
Assisted regeneration (seedling planting and wood utilization)	17,092.25 *****	29,177.65 *****	Atlantic Forest	IIS, (2014)
AFS	18,254.90 ******	45,865.26 ******	Atlantic Forest	-
AFS	29,790.00 ***	121,601.00 ******	Atlantic Forest	Hoffmann, (2013)
	8,934.00 ***	88,323.00 ******	Atlantic Forest	Hoffmann, (2013)

*Costs refer only to initial implementation.
** Costs refer to implementation and management up to the 3rd year.
***Costs include planting and management up to the 2nd year.
****Costs include implementation and management in the 1st year.
*****Costs and financial return projected over 40 years.
******Costs and profit include implementation, management and harvesting services up to the 10th year.
Financial return refers to the NPV (Net Present Value) of the same period.

Finally, only one paper measured pesticide effects in agriculture matrices over pollinators (Appendix 4). Considered pioneers of studying pollinators in AFS, India and Germany conducted the first studies in 2004. However, from 2005 to 2015, no further studies were recorded in India (Figure 2). Germany, on the other hand, stood up as one of the countries with the highest number and constancy of publications. In contrast, research on this topic in Brazil is relatively recent, particularly in the last five years. The United States demonstrated a more homogeneous publication trend over the years. Among the groups of pollinators investigated, bees were the most frequently studied, followed by flies, butterflies, and wasps. Bats were the only vertebrate pollinators evaluated, albeit infrequently (Figure 3).

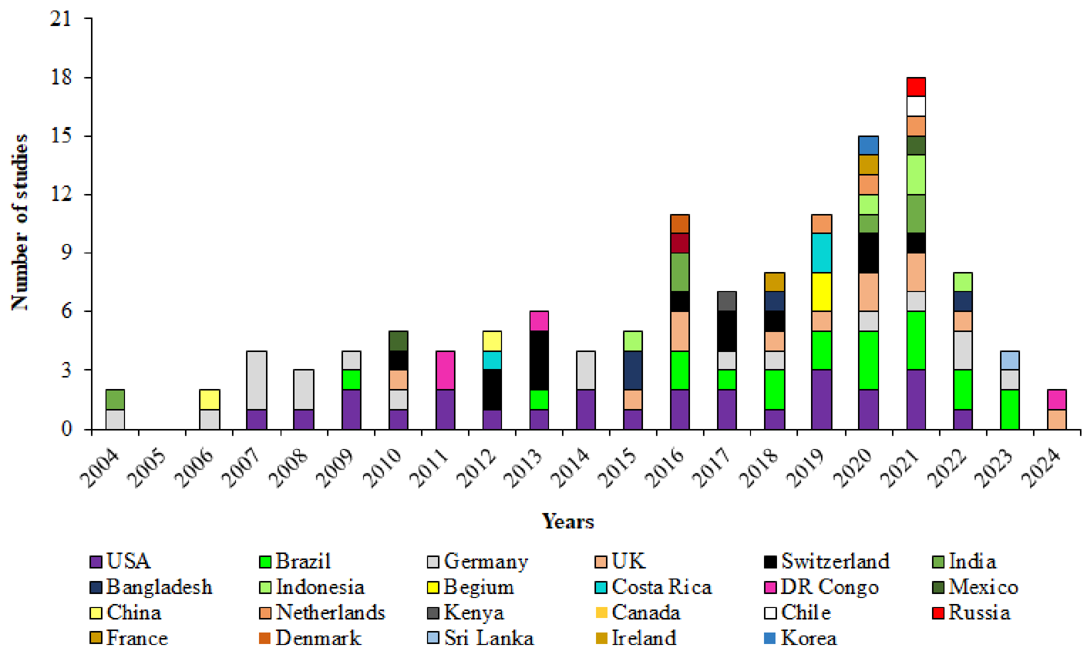


Figure 2 Time progression of studies addressing the role of agroforestry systems with pollinator's abundance, diversity and conservation, provision of pollination services and/or landscape restoration over the last two decades (2004 - 2024). Each bar represents the year of publication, and the colors represent different countries. Larger bars mean higher number of publications in that year.

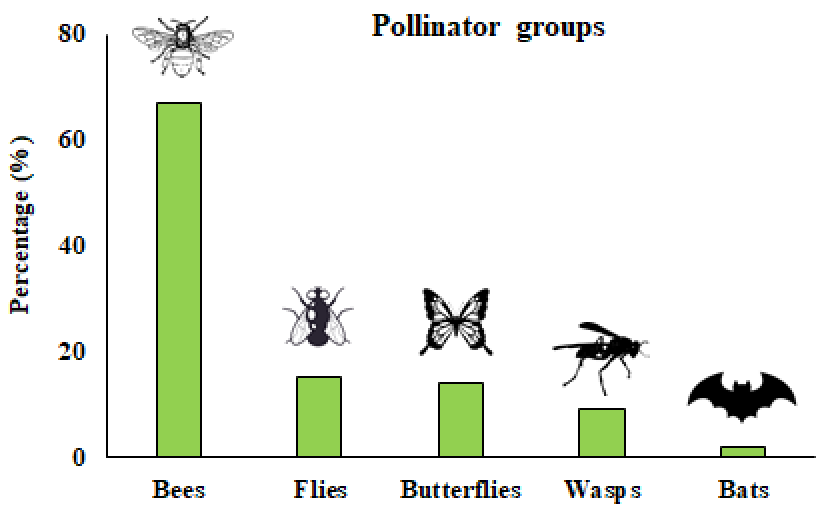


Figure 3 Percentage of pollinator groups investigated across all studies included in this review about agroforestry systems over the past two decades (2004-2024).

4. DISCUSSION

The most discussed topic in the surveyed studies was the potential of agroforestry systems to provide pollination services. However, while these studies have demonstrated the optimization of crop productivity, only a tiny number have evaluated the economic gains resulting from the pollination services offered by AFS or the potential of AFS as an ecological restoration approach. In addition, very few brought a survey of the implementation costs and financial return of ecological restoration through AFS (e.g., Cury and Carvalho, 2001; Campos-Filho et al., 2013). For the AFS implementation, it is essential to stablish clear rules regarding which species can be planted and how they should be managed. This ensures that AFS will generate additional income for farmers without compromising ecosystem functioning, besides promoting the restoration of ecosystem services, and contributing to biodiversity conservation.

A good surprise was that our data showed most papers are based on biodiverse agroforestry systems, which is key for ecological restoration since restoration success depends on biodiverse systems compared to low-diversity mixtures (Andres et al., 2023). Many of the studies (28%) were developed in biodiverse AFS. However, some of them was developed in less complex systems, which showed that the type of agroforestry system also has an impact on biodiversity (Varah et al., 2020). Silvoarable systems (crops intercropped with trees) tend to exhibit more extraordinary richness and diversity compared to silvopastoral systems (crops intercropped with pastures). This difference is likely because silvoarable systems allow the development of understory vegetation, providing nesting habitats and foraging resources for pollinators (Andres et al., 2023).

Therefore, silvoarable systems can be a more sustainable approach to agriculture than silvopastoral systems. To ensure high biodiversity in AFS, it is necessary to maintain environmental heterogeneity (Bentrup et al., 2019). For example, disturbances in the canopy often occur in primary forests due to clearings resulting from falling trees. These disturbances foster the development of denser herbaceous vegetation and higher insect richness compared to the interior of the thick forest (Wunderle et al., 2005). The medium intensity disturbances in AFS create remarkable and temporal heterogeneity, leading to increasing floral abundance. This dynamic resembles the processes seen in forest canopy gaps, resulting in high beta diversity within these areas (Hoehn et al., 2010). The literature raised in this study showed that agroforestry fragments interspersed within the agricultural landscape play a crucial role in preserving pollinator biodiversity in crop agroecosystems (Boscolo et al., 2016).

Moreover, it contributes significantly to crop yield (around 75% globally) (Boscolo et al., 2016). Hence, given that higher richness, abundance, and diversity of pollinators enhance the quality of pollination, conserving this diversity is crucial for our own food security (Potts et al., 2016). Therefore, sustainable agricultural practices that reduce input usage, promote rational land use, and ensure pollinator preservation, such as agroforestry systems, should be actively encouraged. Many studies have shown that agroforestry systems can provide suitable habitats for numerous plant and animal species, with consideration for the composition of plant species and their management (Jha and Vandermeer, 2010). The primary goal in designing and managing agroforestry systems is to maximize positive interactions between trees and crops (e.g.; nutrient cycling, nitrogen fixation, reduced soil erosion) while minimizing negative ones (competition for resources).

Ideally, trees utilize resources that herbaceous and shrubby crops do not, primarily due to differences in root depth (Jose et al., 2004). Therefore, the success of AFS implementation and management projects is crucial for manipulating these interactions and, consequently, determining its productivity. Bees were the most studied pollinator group in AFS. To keep their diversity, stratification is an essential strategy and can be managed in AFS, since its maintenance is usually a key aspect for its yielding. Reduced understory flower availability can negatively impact the diversity of bee functional groups Klein et al., (2007) and other pollinators. Predictive factors for bee diversity include plant richness, flowering species number, and canopy cover of the local agroforestry landscape (Jha and Vandermeer, 2010).

Solitary bees thrive in habitats with high canopy cover, while social bees are more abundant in habitats with greater flowering species diversity (Jha and Vandermeer, 2010). This underscores the vital role of agroforestry managers in biodiversity conservation through diversified plant species management within the AFS. However, we can see that the impact of management intensity on pollinator communities varies (Klein et al., 2007). Wasps and solitary bees, for example, appear to benefit from intensive management within AFS, while the opposite is observed for social bees (Klein et al., 2007). Solitary bees typically establish nests in open areas outside dense forests, preferring conditions with reduced humidity, lower shade, and abundant floral resources, which are commonly found in agroforestry systems (Klein et al., 2007).

Moreover, solitary bees are recognized as highly effective coffee pollinators, often surpassing the efficiency of social bees (Andres et al., 2023). AFS management must take into account practices that provides nesting spots for pollinators. For instance, open soil areas on slopes are suitable for solitary bees. Additionally, increasing the availability of alternative flower resources is essential. This can be achieved through the cultivation of herbaceous plants and the establishment of hedgerows, which can serve as additional resources, especially after the mass flowering period of crops (Petit and Landis, 2023). This approach ensures the year-round maintenance of nests, even beyond the flowering season of cultivated species. The combination of inputs gathered during this study showed that agroforestry systems can sustain high levels of biodiversity, often resembling preserved natural forests (Amin et al., 2018).

The diversification of agricultural systems, exemplified by agroforestry, play a crucial role in enhancing biodiversity, including predatory insects, which can help in the biological control of crop pests (Petit and Landis, 2023). Tomazella et al., (2018) carried out a survey of wasps (Hymenoptera: Vespidae) visiting coffee (*Coffea arabica*) intercropped with different tree species. The results showed wasps benefited from this diversification, exhibiting greater richness, diversity, and abundance in intercropped systems than monocultures. Trees provided several advantages for wasps, including access to alternative food sources for adults (e.g., nectar, pollen and carbohydrates), favorable microclimate, nesting substrate and nesting sites (Cruz et al., 2006). Furthermore, the presence of prey and alternative hosts contributed to more effective pest control and increased stability of coffee plantations.

Regarding the only group of vertebrate pollinators that we found in our study, Williams-Guillén and Perfecto, (2011) investigated how bat diversity patterns in coffee agroforestry change with increasing management intensity. The bats maintained similar richness across management regimes but showed significant declines in abundance across the gradient, from forest fragments through low-management shade polyculture and commercial polyculture to high-management coffee monocultures. The proportions of large frugivores increased with management intensity. Conversely, those of nectarivorous and gleaning bats decreased, the latter being absent from intensively managed coffee monocultures. Both forest fragments and the diverse and structurally complex shade polyculture systems may provide adequate roosting and food resources to sustain high levels of bat diversity.

This contrasts strongly with the situation in low-shade monocultures, which offer reduced feeding and roosting opportunities and, thus, may serve more as commuting than foraging habitat (Williams-Guillén and Perfecto, 2011). Regarding the potential of AFS in restoring landscape and ecological processes, our review showed a knowledge gap. Responses to changes in land use typically exhibit negative impacts but vary considerably among different taxa (Prado et al., 2021). Some anthropic matrices, such as monocultures, can reduce connectivity, while others may offer resources or even become secondary habitats for some bees. For instance, Rosa et al., (2015) evaluated the permeability of *piassava* palm crops cultivated in AFS to the forest dwellers Euglossine bees.

They found that even though the *piassava* is submitted to extensive selective cutting and clearing of large native trees, this agroforest still provided key flower resources and moderate shading conditions, which offered overall good conditions of occupation by the orchid bees (Prado et al., 2021). Several studies indicated that moderate land use levels can optimize the richness and abundance of pollinators, including butterflies, bees, flies, and birds. Low-intensity disturbances can potentially enhance habitat and resource diversity, consequently promoting niche diversity (Burger et al., 2010). For instance, pollinators may stablish nests in forested habitats while foraging in agricultural habitats (Prado et al., 2021). In line with this concept, habitat borders generally show greater butterfly and bee diversity (Hodgson et al., 2010).

However, this pattern may be driven by common species, thus masking effects in rare species and leading to large-scale homogenization. Therefore, further studies on landscape-scale pollinator community composition are needed to better understand the distribution pattern and foraging behavior of less frequent species. Floral resources play a critical role in attracting pollinators, and the diversity of flowering species found in AFS plays an important role to maintain their populations (Burger et al., 2010). Bee species exhibit varying preferences for nectar sugar concentrations. *Apis* species prefer concentrations of 30 to 50%, while larger *Bombus* bees prefer concentrations below 40% (Nicolson et al., 2007). Prado et al., (2021) investigated the effect of microclimatic conditions on nectar characteristics in coffee AFS (*Coffea canephora* and *C. arabica*) with low and high shade. In low-shade systems, the higher temperature and wind speed led to increased sugar concentration in the nectar of *C. arabica* due to higher evaporation rates.

However, they didn't observe wind or temperature-related effects in the low-shaded system on *C. canephora* nectar. It might be due to differences in size and floral morphology between species. The larger flowers and longer corolla tubes in *C. canephora* can reduce the effects of wind and heat, which leads to less nectar evaporation, preventing sugar concentration to increase (Prado et al., 2021). Hence, both floral attributes and specific microclimatic conditions can indirectly influence pollinator visitation (Prado et al., 2021). Another interesting topic discussed in the studies was the connection between the abundance and richness of pollinators in agroecosystems and AFS and their proximity to neighboring forest fragments. However, a less discussed issue is the landscape connectivity between these areas (Miccolis et al., 2017). For instance, research on bird distribution in Khao Luang Mountain in southern Thailand revealed that 38 to 48% of bird species inhabiting neighboring forests are also found in AFS.

Therefore, effective landscape management should prioritize functional connectivity to facilitate pollinator movement, ensuring enhanced gene flow and fruit and seed production (Miccolis et al., 2017). When it comes to ecological restoration using AFS, we noticed that this method can yield significantly higher financial return compared to traditional restoration models, especially in a relatively short period (Hoffmann, 2013). Besides playing an essential role in pollination diversity, the multiple ecosystem services provided by

AFS indicate their suitability for restoration purposes, and these socioeconomic benefits for traditional communities should be regarded as a viable restoration strategy (Miccolis et al., 2017). However, this approach should avoid the use of invasive species and must be based on biodiverse systems (Miccolis et al., 2017).

5. CONCLUSION

While this bibliographic survey highlights the potential of agroforestry systems to enhance pollinator abundance and diversity while at the same time optimizing agricultural productivity, our understanding of these systems in their ecological, social, and economic aspects is still limited. The long-term sustainability of the flora and fauna within AFS has received little investigation, with most studies focusing on a restricted range of taxa and narrow spatial and temporal scales, often without considering cost-benefit analysis. We suggest future studies focus on the economic and ecological aspects of these systems, particularly their role in mutualistic interaction networks like pollination, which are crucial for gene flow and ecosystem functionality restoration.

Acknowledgments

We thank the participants who were all contributed samples to the study. We also thank the Federal University of Uberlândia – Behavior Ecology and Interactions Lab, and the Federal University of Mato Grosso do Sul – Intervention Ecology Lab, for their support. We are grateful to the Brazilian National Council for Scientific and Technological Development (CNPq) - and Coordination for higher Education Staff Development – Brazil (CAPES) for their financial support.

Author contributions

Abrahão M: Conceptualization, Investigation, Writing (Original Draft); Ferreira BHS: Data Analyses. Garcia LC: Conceptualization, Project Administration, Writing (Reviewing and Editing), Torezan-Silingardi HM: Writing (Reviewing and Editing), Supervision, and Acquisition of Funding.

Informed consent

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

Ethical approval

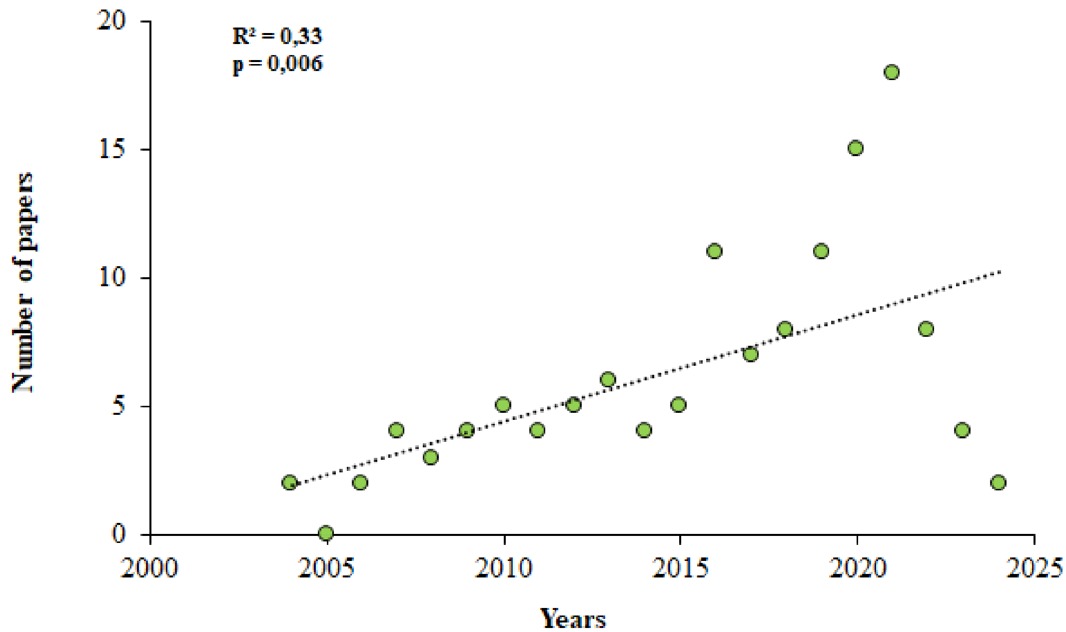
Not applicable.

Funding

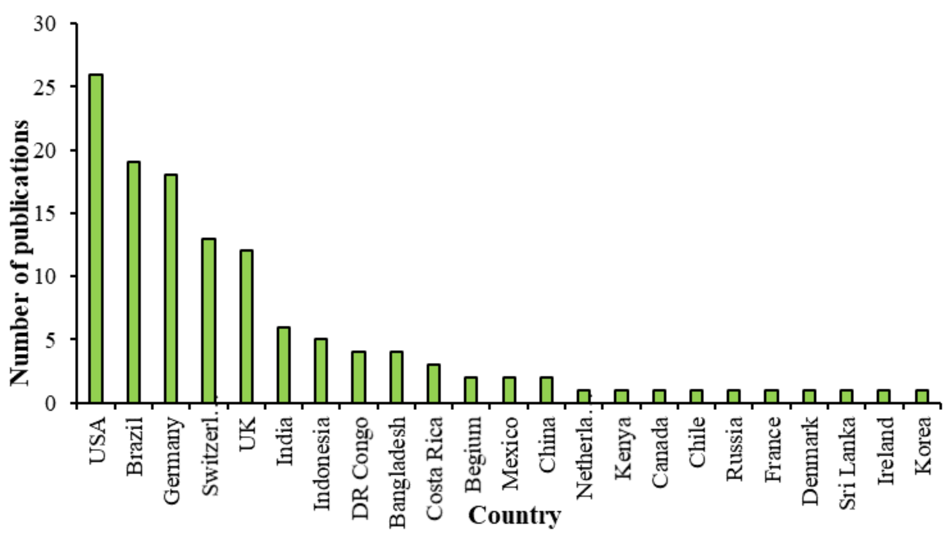
This study was supported by the Brazilian National Council for Scientific and Technological Development (CNPq) - Finance code 403647/2021-5 (research grant to Torezan-Silingardi HM) and Finance code 310963/2023-0 (research grant to Garcia LC), and Coordination for higher Education Staff Development (CAPES) – Finance code 88887.644525/2021-00 (doctoral scholarship to Abrahão, M).

Data and materials availability

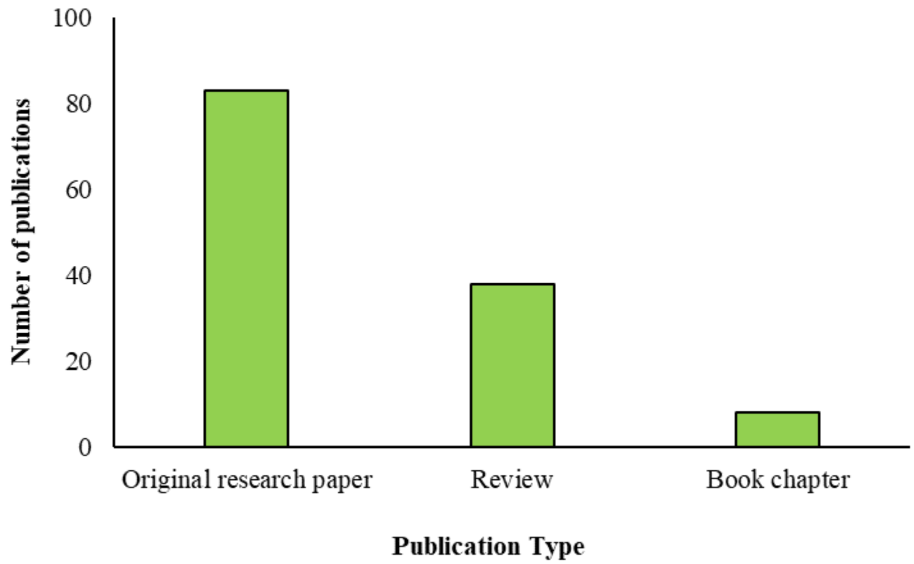
All data associated with this study are present in the paper.



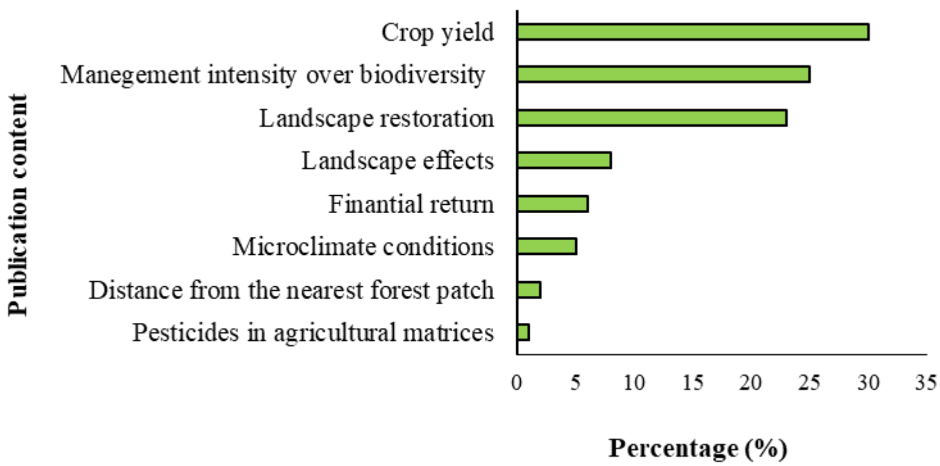
Appendix 1 Number of publications related to the potential of agroforestry systems in providing pollinator diversity, pollination services, or landscape restoration over the last two decades (2004-2024).



Appendix 2 Number of studies were conducted in 23 countries



Appendix 3 Frequency of different published paper types on the potential provision of pollination services and pollinator preservation in AFS over the last two decades (2004 to 2024).



Appendix 4 The scientific publications (provision of pollination services) over the past two decades.

Appendix 5 Studies that discussed the potential of agroforestry systems as a restoration method with their respective year and the country of origin.

Authors	Year	Country
Vieira et al.,	2009	Brazil
Schroth et al.,	2016	Brazil
Miccolis et al.,	2017	Brazil
Tubenchlak et al.,	2019	Brazil
Tubenchlak et al.,	2021	Brazil
Badari et al.,	2020	Brazil
Padovan et al.,	2021	Brazil
Agostinho et al.,	2022	Brazil

Bergamo et al.,	2023	Brazil
Pradana et al.,	2015	Indonesia
Noordwijk et al.,	2020	Indonesia
Murniati et al.,	2022	Indonesia
Lu et al.,	2006	China
Xu et al.,	2012	China
Dosskey et al.,	2011	United States
Young	2017	United States
Chowdhury et al.,	2022	Bangladesh
Sahoo et al.,	2020	India
Reith et al.,	2020	Germany
Moreno-Calles & Casas	2010	Mexico
Saputra et al.,	2020	Netherlands
Korneeva	2021	Russia
Shennan-Farpón et al.,	2021	United Kindom

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