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Research paper

Agroforestry as a tool to promote sustainability in Colombia: A bibliometric analysis

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ABSTRACT Current food systems are important contributors to the transformation and degradation of natural ecosystems. These conditions have contributed drastically to climate change and global warming. Agroforestry is a form of integrated land use, relevant for the linking of sustainable production models. However, in Colombia, there is no comprehensive analysis of agroforestry knowledge that allows for an understanding of its scientific dynamics over time. The objective of this study was to carry out a bibliometric analysis on agroforestry as a tool to promote sustainability in Colombia to quantify the scientific production, actions and impact of this area of knowledge on the sustainability of the national territory. A literature search was conducted in the Scopus database for original and review articles published between 2011 and 2024. The results were obtained using R-Studio's Bibliometrix package, analyzing scientific production on a yearly basis, relationships between Countries, key actors and sources of relevant information. A multiple correspondence analysis (MCA) was run to identify thematic clusters. 59 documents were found, including scientific (93%) and review (7%) articles. There has been an increase in scientific production since 2019, highlighting the contribution of ten countries on topics such as biodiversity, ecosystem services and silvopastoral systems. Three conceptual groups were identified: 1) Agroforestry and sustainability, 2) technology drivers: ecosystem services, and 3) traditional production practices. Agroforestry has shown sustained growth in scientific production in Colombia, standing out as a key strategy for sustainability and food security. It is recommended to strengthen funding, technical support, and the integration of traditional knowledge to ensure its effective adoption in rural territories.

KEYWORDS: Climate change, environment, food security, livestock.

Introduction

Conventional food systems have generated global concern due to their environmental impact. These production models are significant contributors to the transformation of natural ecosystems, the deforestation of 10% of the world's forests, biodiversity loss, and nearly 30% of anthropogenic greenhouse gas emissions (Pacheco et al. 2021). Given this situation, work has been done to develop initiatives to facilitate the transition to sustainable systems (Bacca et al. 2024). In this context, agroforestry emerges as a promising alternative for achieving this transformation. It is an integrated soil management approach that combines trees, shrubs and crops, with or without animals, in the same production system.

In Colombia, research on agroforestry has focused on the transformation of land use for cattle ranching (Jara-Rojas et al. 2020) and its functionality in capturing atmospheric carbon (Silva-Parra et al. 2021), increasing biodiversity (Rodríguez et al. 2022), conserving ecosystems (Guzmán et al. 2016), and ancestral and sustainable agricultural production (Hernández Marentes et al. 2022). This demonstrates the existence of information reflecting the comprehensive benefits of agroforestry practices in Colombia. However, there is no comprehensive analysis of agroforestry knowledge that would allow us to understand the scientific dynamics over time in a national context. Furthermore, there is a lack of clarity regarding the most frequently addressed thematic areas, relevant actors, and scientific collaboration networks. This disarticulation hinders the development of evidence-based public policies, limits technology transfer, and hinders the development of agroforestry models adapted to the realities of the Colombian territory. Furthermore, it restricts coordination between academic, government, and community actors.

In the aforementioned context, bibliometric analysis represents a strategic tool for understanding and harnessing the potential of agroforestry for the country's sustainable transformation. It allows to quantify and visualize the evolution of scientific production, identify the main collaboration networks, emerging topics and contributions of the academic community, in relation to agroforestry sustainability (Aria and Cuccurullo 2017). Furthermore, it provides concrete evidence to guide the allocation of resources in science, technology and innovation, improve public policy formulation and strengthen rural education and extension processes (Cadena-Zamudio et al. 2023). Therefore, this study aims to carry out a bibliometric analysis on agroforestry as a tool to promote sustainability in Colombia.

Materials and methods

The analysis of scientific dynamics began with the collection of information in the Scopus database. The search criteria included publications from 2011 to the first half of 2024, original and review articles both in English and Spanish, a search field that included title, abstract and keywords. The search engine was the following: "agroforestry" OR "silvopastoral" OR "agroforestry" OR "successional" AND "sustainable" AND "Colombia". Subsequently, the loading and conversion of data to a Bib-

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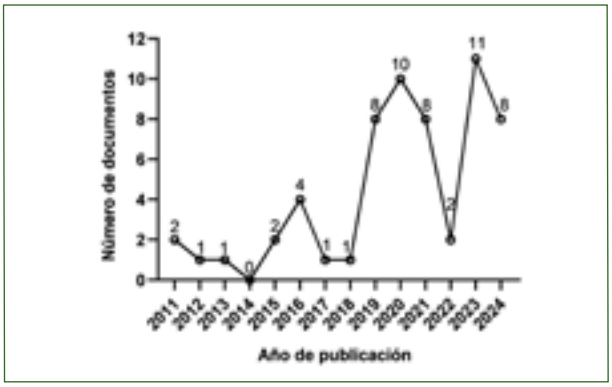
tex format was worked on. Finally, data exploration and cleaning were performed to strengthen the quality of the analysis.

The results found in the exploration analysis were processed in the statistical software R-Studio, making use of the Bibliometrix tool. The interpretation of the data considered descriptive analysis and network extraction. In the structuring of the networks, the most important keywords of the documents were linked, which demarcate the conceptual area of the study. In addition, it integrated the analysis of co-authors which examines the authors and their affiliations, delimiting the social structure and the network of collaborations. Likewise, the co-citation of journals, authors and scientific journals was related. Once the networks were built, a multiple correspondence analysis was carried out to identify thematic clusters. (Aria and Cuccurullo 2017).

Results

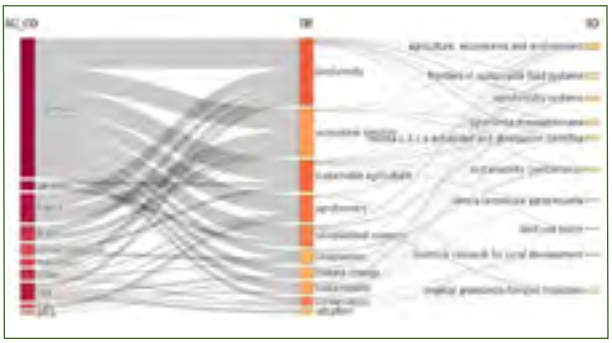
A total of 59 documents were collected in this study; 55 original articles and 4 were bibliographic reviews. 20% of the articles were published between 2011 and 2018. Between 2019 and the first half of 2024, 80% of the publications were reached (Fig. 1). However, in 2022, atypical behavior was observed with only two studies reported. The results reflect a substantial increase in the number of publications by the end of 2024 (72% of the publications reported in 2023).

Figure 1 - History of publications (2011-2024) in Scopus.



In the scientific dynamics, collaboration was found between 10 countries, with Colombia being the most influential (Fig. 2). The concepts of biodiversity, ecosystem services, sustainable agriculture, agroforestry, silvopastoral systems, climate change, sustainability and conservation were primarily addressed. In another sense, 20 % (2) and 80% (8) of the most prominent journals in the publications found were Colombian and international, respectively. In this context, the publication of articles was more oriented towards international journals.

Figure 2 - Sankey diagram relating to authors, keywords, and journals.



The conceptual analysis shows that agroforestry and ecosystem services have been maintained from 2016 to 2024. However, conservation, biodiversity and sustainability were maintained between 2019 and 2023. Currently, sustainable agriculture and silvopastoral systems are concepts that are gaining in 2024.

Multiple correspondence analysis identified three distinct Clusters: a) Cluster 1, directed research towards sustainable production, linking keywords such as conservation, rehabilitation, agroecology, carbon sequestration, sustainable agriculture, among others. Additionally, it accounts for 72% of the articles and shows continuity in publications throughout the entire period analyzed, b) Cluster 2, with 15% of the studies published between 2019 and 2024, linked the analysis of ecosystem services and their impact on the adoption of green technologies, and c) Cluster 3, which represents 13% of the documents which exposes ancestral agriculture, with publications mainly concentrated between 2021 and 2024. Table 1 shows the 3 clusters identified.

Table 1 - Cluster Identification.

Cluster Name	Keywords
Cluster 1 Agroforestry and Sustainability	diversity climate.change animal.welfare sustainable.intensification carbon.sequestration sustainable.cattle.ranching sustainability silvopastoral.systems.sps ecological.rehabilitation agroecosystems agroecology soil.structure
Cluster 2 Technology drivers: Ecosystem services	ecosystem.services social.metabolism ecosystem.services biocultural.landscapes agroforestry.systems
Cluster 3 Traditional production practices	amazon traditional.knowledge chagra

Table 2 - Relevant agroforestry systems and description of their contributions to sustainability in Colombia.

System	Geographic location	Benefits	Reference
			Andean Pacific
SSPi (*Leucaena leucephala*, >10,000 trees/ha)	Andean Pacific Caribbean	Survival of 50-80% of wildlife, increases animal load by up to 42.8%, increases forage biomass by 47%, increase between 24 and 36 t/ha/year in DM production, improved milk production/ha/year by 66%, increases by 12.3% IRR, 56% increase in revenue and 72% increase in profitability, 12.3% reduction in GHG emissions (0.29 kg CO2-eq, 37% decrease in non-renewable energy use.	(Cadavid et al. 2019, Jara-Rojas et al. 2020[a], Murgueitio et al. 2019)
SSPi with *Eucalyptus tereticornis* (>500 trees/ha)	Andean	Carbon sequestration–26.6 t CO2 eq ha $^{-1}$ year $^{-1}$	(Silva-parra and Brevik 2021)
SSP with grazing pigs (*Sus scrofa domestica)*	Caribbean Orinoquia Andean	Nitrogen fixation, thermal comfort and microclimates, forage biomass production, productive diversification, climate resilience and adaptability, improves soil health and nutritional quality	(Alfonso-Pardo et al. 2023)
Growing coffee under shade	Andean	Ecosystem conservation, increasing biodiversity, improves soil quality, income generation for families	(Guzmán et al. 2016, Roach et al. 2021, Rodríguez et al. 2022)
Agroforestry Systems with Cocoa	Caribbean Amazon		
Palma (*Elaeis guineensis)* in combination with natural ecosystems	Orinoquia	Carbon sequestration (402.76 Mg ha $^{-1}$), territorial development	(Calderón-Balcázar et al. 2023)

Cluster 1: Agroforestry and sustainability

This group of studies focuses on the identification of agroforestry alternatives with the potential to strengthen sustainability in Colombia. In the departments of Cesar, Tolima, Valle del Cauca, and Quindío, intensive silvopastoral systems (SSPi) which combine *Leucaena leucocephala* (Lam.) de Wit with improved pastures stand out. This form of land management promotes carbon sequestration, reduces energy expenditure, and improves meat and milk production. Consequently, it supports increased income for rural families. However, its adoption faces limitations such as high costs, lack of technical knowledge, and sociocultural variations, suggesting the need for more research and funding.

In the departments of Santander, Magdalena, Caquetá, Cesar, and Meta, agroforestry systems with *Coffea arabica* L., *Theobroma cacao* L., and *Elaeis guineensis* Jacq. out in a differentiated mannerstand (Tab.2). These are alternatives that simultaneously promote productive diversification and ecosystem conservation. In their review analysis, Alfonso-Pardo et al. (2023) also highlight the relevance and potential of combining agrosilvopastoral systems with *Smallanthus sonchifolius* (Poepp. & Endl.) H. Robinson, *Moringa oleifera* L., *Manihot esculenta* Crantz, and native Colombian creole pigs. These combinations show potential to improve household economies and the country's food security. These models would have potential primarily in departments such as Santander, Boyacá, Meta, Nariño, Antioquia, Quindío, Risaralda, and Córdoba, where this species is distributed.

Cluster 2: Technology drivers: ecosystem services

This group presents ecosystem services as an important axis for decision-making, adoption and development of agroforestry strategies with a sustainability approach. Agroforestry contributes to the increase of biodiversity, recovery and conservation of ecosystems, production of non-timber forest products, carbon sequestration, improvement in productive indicators, and strengthening of people's quality of life (Bravo-Monroy et al. 2015). These ecological changes directly (products with monetary value) and indirectly (products with no monetary value) favour the economy of production systems. These impacts are measured through the linking of environmental economics tools, which allows estimating the economic benefit offered by agroforestry through ecosystem services (Banerje et al. 2024).

This cluster also includes research that highlights the potential for ecological recovery in degraded landscapes of the Amazon and Chocó regions. It is based on agroecological practices, agroforestry systems, plantations, and successional forests (Eguiguren et al. 2020). The reviewed evidence shows that it is possible to restore severely degraded areas through planned agricultural use. In this way, ecosystem services and their multi-functionality are recovered. As a result, the gap between conservation and the economic activities of rural communities is reduced. This condition encourages the adoption of sustainable production practices.

Overall, this group of studies demonstrates that the study of the multi-functionality of ecosystem goods and services is key to promoting the development and adoption of agroforestry systems that respond to the eco-

logical, social, and economic conditions of the national territory. Integrating approaches such as payments for ecosystem services, habitat banks, productive restoration, and technical support allows for biodiversity conservation, strengthening rural livelihoods, optimizing the use of degraded landscapes, and bridging the gap between conservation and food production.

Cluster 3. Traditional Production Practices

This group gathers traditional production practices developed by indigenous and Afro-Colombian Communities. In the department of Amazonas, the use of Chagra stands out. This is an Indigenous polyculture with a transitory vegetative cycle (2 to 4 years), which then undergoes a natural regeneration process. It is considered a relevant area in the transmission of traditional knowledge regarding the sustainable use of plants for food, magical-religious and medicinal purposes. This involves linking processes of domestication, multiplication and selection of species of cultural importance (Hernandez Marentes et al. 2022). In this sense, the Chagra becomes a key tool for territorial planning and conservation of the Amazon (Garavito et al. 2021). However, it faces challenges such as agricultural expansion, deforestation, and climate change, which reduce its visibility and recognition compared to large-scale agricultural models.

In the Indigenous and Afro-descendant communities of the Chocó department, mixed home gardens or 'azoteas' are used. These are gardens built on elevated wooden structures or canoes that protect plants from animals and flooding (Perez-Abadia and Medina-Arroyo 2024). Another relevant practice is the use of 'parcelas,' which function as traditional productive units within the forest for the utilization of aromatic, medicinal, and seasoning plants. This type of production helps maintain agrobiodiversity, utilize forest resources without destroying them, and preserve traditional knowledge (Marmolejo-Liloy et al. 2018).

Discussion

The answer in the trend of increasing papers published from 2019 onwards can be attributed to current global challenges. This includes increased demand for food, climate change, overexploitation of natural resources, loss of biodiversity and food waste (Garavito et al. 2021). In this sense, agroforestry is reflected as an alternative that promotes sustainability by integration sociocultural, economic and environmental elements (Guzmán et al. 2016, Calderón-Balcázar et al. 2023, Bravo-Monroy et al. 2015). It is possible that Colombia, as the second country with the greatest renewable natural resources, is seen as a key point for the development, implementation, and adoption of socio-ecological conservation and restoration practices to address global challenges (Rodriguez et al. 2022).

International cooperation was a relevant point in this work, visualizing the participation of 10 countries, with Colombia having the highest contribution (25%), followed by Brazil (15%) and Mexico (10%). This response suggests that Colombian researchers are working on the development of sustainable technological capable of comprehensively addressing the country's sociocultural and environmental challenges. However, it has been indispensable to establish strong alliances with researchers and institutions from other countries. This has enabled better knowledge and experience exchange to develop technologies, production practices, and public policies that promote both national and global sustainability (Salvador and Sancho 2021).

The analysis of the number of studies grouped in each of the three identified clusters allows for interpreting the orientations of agroforestry research. The identification and development of agroforestry technological tools aimed at improving productive and environmental indicators has been a sustained priority over time, as evidenced by the concentration of publications in Cluster 1. In contrast, Clusters 2 and 3—focused respectively on strategies for adopting agroforestry alternatives and on ancestral practices—represent emerging research lines, reflected by the relatively small number of studies in these groups compared to Cluster 1. Moreover, most studies in Clusters 2 and 3 have been published within the last four years.

The three clusters are distinct, but they face common challenges in agroforestry transformation. These include high costs, limited technical knowledge, and lack of funding and research. In addition, sociocultural diversity makes it difficult to connect social aspects with agricultural production (Hernández-Nuñez et al. 2024). In this context, co-construction and participatory diagnostic approaches are relevant. These processes engage local actors in identifying needs and solutions. They also strengthen community development, territorial planning, and sustainability (Anyaegbunam 2008).

The bibliometric findings of this study align with Colombian public policies aimed at sustainability. The implementation of intensive silvopastoral and agroforestry systems in departments such as Cesar, Tolima, Meta, and Caquetá (Clusters 1 and 2) incorporates principles from the 2022–2023 National Green Business Plan (MADS 2022). These systems promote sustainable production models that mitigate environmental impacts and generate social and economic benefits for rural communities. At the same time, these practices contribute to the objectives of the Sustainable Beef Cattle Policy – GBS 2022–2050 (MADR and MADS 2021) by improving productivity, reducing greenhouse gas emissions, and facilitating ecosystem restoration through efficient landscape management.

Agroecological and traditional experiences (Cluster 3), such as the indigenous Chagra and the Chocó "azoteas," are in line with the emerging National Agroecology Policy (MADR 2024), which intends to recover and strengthen ancestral knowledge, promote diversified production, and protect agrobiodiversity. Together, these policies aim to bridge the gap between conservation and production, but the studies warn that their success de-

pends on strengthening technical support, economic incentives, and territorial governance to ensure active community participation.

Although the strategies of agroforestry to promote sustainability in Colombia are clear, it requires a determined commitment and availability of labor and monetary resources on the part of producers and financing institutions, which tends to generate a negative response in the adoption of these technologies. However, there is a positive response to incentives (Calderon-Balcázar et al. 2023), which ends up being one of the most influential factors given by policies and government support, both national and local, as well as public-private partnerships (Jara-Rojas et al. 2020). On the other hand, technological adoption faces technical and scientific, socioeconomic and sociocultural challenges that must be addressed to maximize its effectiveness and sustainability.

Conclusion

Agroforestry in Colombia has gained greater scientific relevance since 2019, with an emphasis on sustainability, ecosystem services, and traditional knowledge. This trend reflects the growing interest in integrating productive and ecological approaches in response to the challenges of climate change and food security. It is recommended to strengthen funding, technical support, and community participation in the adoption of agroforestry practices, as well as to promote inter-institutional partnerships and evidence-based public policies that integrate ancestral knowledge with innovation for sustainable territorial transformation.

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