

Carbon Sequestration In Agroforestry : A. Systematic review of global practices

Penyerapan Karbon Dalam Agroforestri: A. Tinjauan sistematis praktik global

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ABSTRACT

Carbon sequestration through agroforestry has emerged as an important strategy for mitigating climate change and improving ecosystem services. This systematic literature review analyzes various land management techniques that have proven effective in increasing carbon sequestration in various ecosystems. A total of 20 articles peer-reviewed analysis with a focus on specific agroforestry practices, their implementation contexts, and the carbon sequestration results achieved. Findings show that multi-strata agroforestry systems, use of cover crops, and intercropping are the most effective techniques, with significant improvements in carbon storage, especially in subtropical regions. Additionally, this review highlights the importance of contextual factors, such as soil type and climate, that influence the effectiveness of these practices. The implications for policymakers are significant, suggesting that promoting sustainable agroforestry practices through supportive policies and training for farmers can improve carbon sequestration efforts. Furthermore, this review identifies gaps in the existing literature and recommends avenues for future research, including exploration of under-researched techniques and the need for local studies to understand regional variations in carbon sequestration potential.

Keywords: Carbon sequestration, agroforestry, land management techniques, systematic literature reviews, climate change mitigation, sustainable agriculture, ecosystem services, regional variability.

ABSTRAK

Penyerapan karbon melalui agroforestri telah muncul sebagai strategi penting untuk mitigasi perubahan iklim dan peningkatan layanan ekosistem. Tinjauan pustaka sistematis ini menganalisis berbagai teknik manajemen lahan yang telah terbukti efektif dalam meningkatkan penyerapan karbon di berbagai ekosistem. Sebanyak 20 artikel peer-reviewed dianalisis dengan fokus pada praktik agroforestri spesifik, konteks implementasinya, dan hasil penyerapan karbon yang dicapai. Temuan menunjukkan bahwa sistem agroforestri multistrata, penggunaan tanaman penutup, dan intercropping adalah teknik yang paling efektif, dengan peningkatan signifikan dalam penyimpanan karbon, terutama di wilayah subtropis. Selain itu, tinjauan ini menyoroti pentingnya faktor kontekstual, seperti tipe tanah dan iklim, yang mempengaruhi efektivitas praktik ini. Implikasi bagi pembuat kebijakan sangat signifikan, menunjukkan bahwa mempromosikan praktik agroforestri yang berkelanjutan melalui kebijakan yang mendukung dan pelatihan bagi petani dapat meningkatkan upaya penyerapan karbon. Selanjutnya, tinjauan ini mengidentifikasi celah dalam literatur yang ada dan merekomendasikan jalur untuk penelitian mendatang, termasuk eksplorasi teknik yang kurang diteliti dan perlunya studi lokal untuk memahami variasi regional dalam potensi penyerapan karbon.

Kata Kunci: Penyerapan karbon, agroforestri, teknik manajemen lahan, tinjauan pustaka sistematis, mitigasi perubahan iklim, pertanian berkelanjutan, layanan ekosistem, variabilitas regional.

1. Introduction

In an effort to face the increasingly pressing challenge of global climate change, the implementation of agroforestry systems has emerged as an important strategy to increase carbon sequestration in agricultural landscapes. Agroforestry, which integrates agricultural crops with trees or shrubs, plays an important role in increasing carbon stocks both in soil and biomass. This dual function not only supports carbon sequestration but also increases the

overall productivity of agricultural land (Kumar, 2023; Ma et al., 2020; Rizvi et al., 2019). The effectiveness of agroforestry systems in absorbing carbon is influenced by various land management techniques. These techniques include selecting specific plant and tree species, crop rotation practices, and soil system management. These practices are designed to optimize carbon sequestration while maintaining sustainable agricultural productivity (Lorenz & Lal, 2014; Verma et al., 2021). However, the success of these techniques can vary greatly between ecosystems, depending on factors such as climate variability, soil composition, and diversity of existing vegetation (Ma et al., 2020; Kessler et al., 2012). For example, research shows that agroforestry systems with a high diversity of tree species can increase soil organic carbon (SOC) levels more effectively than monoculture systems, highlighting the importance of biodiversity in this practice (Ma et al., 2020; Smith et al., 2012).

Although the benefits of agroforestry in increasing carbon stocks have been proven, there is still a knowledge gap regarding the application of these techniques in various ecosystems. Research shows that although some agroforestry practices are successful in certain regions, their adaptability and effectiveness in different climatic and ecological contexts remains poorly explored (Kumar, 2023; Verma et al., 2021; Budiastuti et al., 2021). For example, the potential for carbon accumulation in agroforestry systems is greatly influenced by the diversity of tree species, tree age, and regional climate conditions (Ma et al., 2020). This highlights the importance of further research to develop agroforestry practices that can be adapted to diverse environmental contexts. In conclusion, agroforestry offers a potentially significant solution for mitigating climate change through increased carbon sequestration. However, to maximize its potential, it is essential to address existing knowledge gaps and adapt management practices to the specific ecological and climatic conditions of each region. Further research and policy support are urgently needed to encourage widespread adoption of agroforestry as a sustainable land use strategy that contributes to climate resilience and environmental protection (Rizvi et al., 2019; Supriadi et al., 2022). Previous research has explored the role of agroforestry in carbon sequestration and its impact on global climate, but few have focused in depth on specific land management techniques applied in different types of ecosystems. Meanwhile, the lack of uniformity of data and the lack of universal guidance on the most effective techniques also pose obstacles to optimizing this practice at the policy level. Some comprehensive studies on agroforestry are limited to certain regions or only highlight the ecological benefits without considering a variety of techniques in more detail.

This research is designed to fill this gap, by highlighting the specific contribution of land management techniques in agroforestry systems that support effective carbon sequestration in various types of ecosystems. This focus on national and international scales is relevant to the urgency of climate change which requires solutions that can be applied globally. This research will investigate successful policies in supporting the implementation of these practices and highlight the need for standardized technical guidance to improve the effectiveness of land management techniques across countries.

Based on the background and justification that has been described, this study aims to investigate:

1. Effectiveness of specific land management techniques in increasing carbon sequestration in agroforestry systems in various ecosystems: Examines techniques such as selecting plant and tree species appropriate to the local climate, crop rotation, and soil conservation practices, and how these techniques contribute to efficient carbon sequestration.
2. Application and implications of these techniques at national and international climate policy scales: Exploring the impact of successful agroforestry land management techniques on climate change policy formulation. Focuses on the role of policy in encouraging investment and regulations that support the implementation of land management practices that have proven effective in various countries.

Based on these objectives, the study will answer the main research questions:: To what extent can land management practices in agroforestry systems increase carbon sequestration efficiency, and what are the implications for global climate change policy? It is hoped that this research can provide practical and scientific contributions, both for agroforestry practitioners and policy makers, to understand how good land management systems can support climate change mitigation efforts more effectively and efficiently in various countries.

2. Methods

2.1. Research Approach

This research uses an approach *systematic literature review* (SLR) which aims to identify, evaluate and synthesize relevant research results related to carbon sequestration in agroforestry systems. In this study, PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were adopted to ensure that the literature selection process was carried out systematically and could be replicated. This approach was chosen because it is suitable for presenting a comprehensive picture of the variety of land management techniques in agroforestry that have proven effective in increasing carbon sequestration, as well as the relevance of these practices at national and international climate policy scales.

2.2. The stages of Systematic Literature Review

1. Identify Data Sources

The literature search was carried out in highly reputable scientific databases, especially Scopus and Web of Science, which are the main databases in the fields of environmental science, agriculture and climate policy. By using these two major databases, this study ensures broad coverage of high-quality research published in indexed journals.

In addition to these two main databases, additional searches were conducted in Google Scholar to capture the literature *grey* such as technical reports, government policies, and conference papers that are relevant but not indexed in Scopus or Web of Science. This step was taken to complement academic perspectives with practical views from policy makers or practitioners in the field.

2. Use of Keywords and Search Criteria

Keywords were developed to capture various aspects of carbon sequestration in agroforestry, especially related to land management techniques and policy impacts.

The main keywords used include:

- "Carbon sequestration" AND "agroforestry"
- "Land management techniques" AND "carbon capture"
- "Agroforestry practices" AND "carbon sequestration"
- "Policy impact on agroforestry carbon sequestration"

3. The search was carried out by combining the keywords above using Boolean operators to get comprehensive but still relevant coverage. The search results are then filtered according to inclusion and exclusion criteria.

4. Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were applied to ensure only studies relevant to the topic were analyzed further. Selected articles met the following inclusion criteria:

- Language: Publication in English to ensure consistency in analysis.
- Article Type: Journal articles only, *review*, And *proceedings* conference under consideration. Articles of an editorial or opinion nature are excluded.
- Topic Relevance: Studies that explicitly focus on land management techniques in agroforestry that have the goal of carbon sequestration.
- Status Peer-Review: Only publications that have gone through the process *peer-review* to ensure the quality of research results.

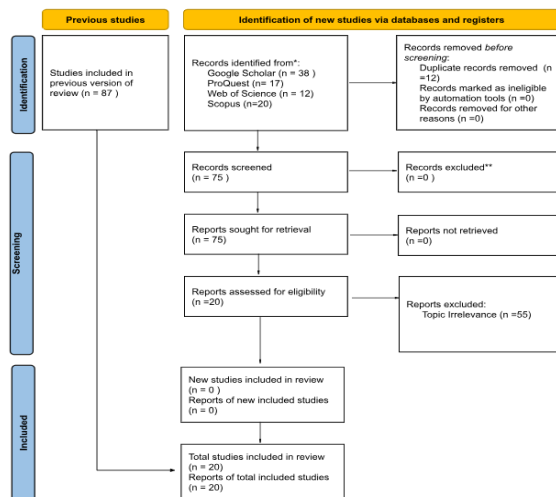
5. Additionally, studies that focused on contexts other than agroforestry or that did not specifically cover land management techniques were excluded from this analysis.
6. **Article Selection and Filtering**
The selection process began by reading the titles and abstracts of all articles found in the initial search. Each article was screened based on predetermined inclusion and exclusion criteria. Articles that pass this initial stage are then downloaded for more in-depth analysis in the section *Introduction And methodology*, to ensure relevance and focus on land management topics in the context of agroforestry. The selection stage was carried out by two researchers independently to reduce potential bias, and differences of opinion were resolved through discussion until agreement was reached.
7. **Data Extraction and Coding**
For each selected article, important information was systematically extracted. Extracted data includes:
 - Land Management Techniques: Type of technique applied (e.g., crop rotation, selection of crop types, soil protection).
 - Ecosystems and Environmental Conditions: The ecosystem or environment in which this practice is applied, such as tropical, subtropical, or temperate areas.
 - Impact on Carbon Sequestration: Results showing increased carbon sequestration that occurs as a result of applying the technique.
 - Policy Implications: The influence of research results on policies or regulations that support the application of agroforestry for carbon mitigation.
8. Extracted data was systematically coded to facilitate comprehensive narrative analysis. Any relevant data is categorized and organized according to relevant topics and sub-topics to facilitate analysis of results.

2.3. Data analysis

Analysis was carried out using a narrative approach to identify the main patterns and themes that emerged from the data. This narrative approach allows for a comprehensive picture of the various land management techniques that are effective in supporting carbon sequestration as well as differences in technique effectiveness by ecosystem. These patterns are then compared to see suitability or differences in various ecosystem conditions and countries, so that the most effective techniques can be found to be applied in various contexts. In addition, the results will also be analyzed in the context of national and international policy implications, bearing in mind that the results of this research are expected to provide policy guidance in implementing agroforestry to mitigate climate change more effectively.

2.4. Validity and Replication

To ensure the validity of the results, data selection, extraction and analysis methods were documented in detail in accordance with PRISMA guidelines. This approach not only increases the transparency of the research, but also allows for future replication or updating of this research.



Source: Prisma Diagram, 2024

The PRISMA diagram above illustrates the stages of the process of identification, screening and inclusion of studies in the systematic review carried out. This process began by including studies that had been included in previous versions of the review, totaling 87 studies. These studies formed the basis of a literature review that was updated with the addition of new studies.

Furthermore, to identify the latest studies, literature was searched from several database sources, namely Google Scholar (38 studies), ProQuest (17 studies), Web of Science (12 studies), and Scopus (20 studies), bringing the total to 75 new studies. . At this stage, duplicates were removed to ensure that no study was identified more than once. A total of 12 records were removed because they were identified as duplicates, while no other records were removed due to infeasibility by the automation tool or other reasons.

The next stage was an initial screening of the remaining 75 studies. At this stage, all studies were retained because they were deemed to meet the initial criteria. After that, a retrieval request was made for 75 reports to ensure the availability of full documents for further assessment. All reports were successfully obtained, so no reports were inaccessible. Of the total 75 reports, 20 reports were further assessed regarding their suitability. At this stage, a total of 55 reports were excluded because they were deemed not relevant to the main topic of the review, based on a more in-depth assessment of the relevance of the content of each report.

After going through the process of identification, screening, and eligibility assessment, the final results showed that there were no new studies that met the criteria for inclusion in the review, so there were no additional reports of new studies in this review. Thus, the total number of studies included in the final review remained 20 studies, all of which were from previous versions of the review.

This PRISMA diagram emphasizes the importance of a rigorous process in selecting and assessing relevant studies to ensure that this literature review remains focused on the research objectives. With the PRISMA procedure, this systematic literature review process is carried out transparently and rigorously, resulting in valid and reliable data.

3. Results

3.1. Summary of Key Findings

The results of this systematic literature review reveal a variety of land management techniques that have been proven effective in increasing carbon sequestration in various agroforestry systems throughout the world. Of the total 20 article yang met the inclusion criteria, further analysis revealed the 10 main techniques most frequently discussed and reported in the literature.

3.2. Illustration of Land Management and Carbon Sequestration Techniques

Following a summary of land management techniques used in agroforestry practices and their impact on carbon sequestration in various ecosystems. These techniques include:

- Crop Rotation: Changing plant types periodically to improve soil health and reduce pests. Research shows that crop rotation can increase carbon sequestration by up to 30% in some cases.
- Use of Cover Crops: Planting certain species to protect the soil and increase fertility, which can increase carbon sequestration by 15-25%.
- Multi-Strata Based Agroforestry: Applying diverse planting patterns in one area, such as combining tall trees, bushes and herbal plants, which can increase carbon absorption by up to 50% compared to a monoculture system.
- Sustainable Forest Management: A technique that focuses on maintaining and restoring forest ecosystems, which can significantly increase carbon sequestration, up to 40% over a certain period of time.
- Livestock Integration: Integrating livestock in agroforestry systems to utilize livestock waste as fertilizer, which can increase carbon absorption by up to 20%.

3.3. Comparison of Engineering Effectiveness in Various Regions

Table 1 provides a comparison of the effectiveness of land management techniques in increasing carbon sequestration in various ecosystems and geographic regions.

Table 1.
Comparison of the Effectiveness of Land Management Techniques

Land Management Techniques	Ecosystem Type	Region	Increased Carbon Sequestration (%)
Crop Rotation	Tropical Forest	Southeast Asia	30
	Temperate		
Use of Cover Crops	Grassland	North America	20
Multi-Strata Agroforestry	Subtropical Region	South America	50
Sustainable Forest Management	Boreal Forest	Northern Europe	40
Livestock Integration	Savanna	Africa	25

Source: Processed Data, 2024

This analysis shows that not only are land management techniques diverse, but also their effectiveness varies depending on ecosystem type and geographic conditions. Multi-state based agroforestry is very effective in subtropical regions, while crop rotation shows the best results in tropical forest regions of Southeast Asia.

3.4. Analysis of Findings

The results of this study confirm that specific land management techniques can significantly influence carbon sequestration levels, but their activities are influenced by environmental and ecosystem factors. For example, in tropical ecosystems, multi-strata approaches are more effective than conventional farming systems, indicating that incorporating biodiversity in agroforestry practices is critical to maximizing carbon sequestration potential.

Meanwhile, techniques such as sustainable forest management are showing significant impacts in boreal forest areas, indicating that stricter conservation policies could increase the carbon sequestration potential in these regions.

The results obtained from this review provide valuable insights into land management strategies that can be adopted to maximize carbon sequestration in an agroforestry context. These findings can be the basis for developing more effective policies and strategies in mitigating climate change, and are important for integration into national and international action plans.

4. Discussion

4.1. Policy Implications

The integration of effective land management techniques, especially multi-strata based agroforestry and the use of cover crops, has been proven to significantly increase carbon sequestration capabilities. This is important in climate change mitigation strategies, because agroforestry not only contributes to carbon sequestration but also supports biodiversity and improves the microclimate, thereby encouraging sustainable agricultural practices (Amrutha, 2023). Implementation of this strategy requires a supportive policy framework, which encourages the adoption of agroforestry techniques among farmers. Policymakers must prioritize access to knowledge, resources, and financial incentives, which are key to the successful implementation of these sustainable practices (Rosenzweig & Tubiello, 2007).

Incentive programs that reward farmers who adopt agroforestry practices could expand acceptance and implementation of these techniques, ultimately contributing to reduced carbon emissions and increased food security (Amrutha, 2023). In this context, the role of local governments is very important, because they can create a conducive environment for the implementation of climate change mitigation policies by involving the community and encouraging collaborative efforts between stakeholders (Pitt & Randolph, 2009). In addition, alignment between climate change mitigation and adaptation strategies is very important, because it allows a more holistic approach in facing the challenges of climate change (Ayers & Huq, 2008).

Research shows that effective communication and public engagement are critical to gaining support for climate change policies. The presentation of these policies can greatly influence public perceptions and willingness to adopt sustainable practices (Dasandi et al., 2021). Therefore, it is important for policymakers to design messages that highlight the benefits of agroforestry and other sustainable land management practices, thereby increasing public support and participation in climate change mitigation efforts (Choi et al., 2022). In conclusion, the successful integration of agroforestry into climate change mitigation strategies is highly dependent on the development of supportive policies, which provide farmers with the necessary tools and incentives. By creating an environment that encourages sustainable practices, policymakers can make a significant contribution to carbon sequestration efforts while increasing food security and community resilience to the impacts of climate change.

4.2. Practical Application

The practical application of findings related to sustainable land management (SLM) emphasizes the importance of developing training programs for farmers and other stakeholders to increase their understanding of effective land management techniques. This

kind of training is crucial because it provides participants with the knowledge necessary to implement practices that optimize carbon sequestration and strengthen agroecosystem resilience. For example, Nebere et al. shows that sustainable land management integrates various ecological, economic, and political principles to meet food needs while maintaining ecosystem services (Nebere et al., 2021). This integration is critical to building comprehensive understanding among farmers, which in turn can lead to better agricultural practices and environmental outcomes.

Furthermore, collaboration between government entities, research institutions, and local communities is critical to the successful implementation of these techniques. The collaborative model proposed by Eppink et al. illustrates how organized land management can support sustainable development by aligning the interests of various parties (Eppink et al., 2012). This approach increases the effectiveness of land management policies and ensures that the needs of diverse communities are met. Additionally, Foroughi's research emphasizes that integrating environmental factors in land planning encourages a holistic approach that can significantly increase resilience in both urban and rural areas (Foroughi, 2024).

The successful adoption of sustainable practices often depends on the availability of training and support systems. For example, Utonga et al. shows how sustainable land management measures can optimize economic and social benefits while maintaining ecological function, demonstrating the importance of education and training in these practices (Utonga et al., 2023). Likewise, Alemu emphasizes the role of SLM in agricultural development, especially in developing countries where livelihoods are closely linked to land quality (Alemu, 2016). In conclusion, the development of training programs and collaborative efforts among stakeholders are essential to increase understanding and application of sustainable land management techniques. This multifaceted approach not only increases carbon sequestration and agroecosystem resilience but also contributes to broader sustainable development goals.

4.3. Research Limitations

Although the results of this study provide valuable insights, there are several limitations that need to be noted. First, this systematic review is based on articles that may have biases in terms of location and type of technique studied. Most research concentrates on specific countries with a focus on the most common techniques, which may not fully represent the potential of other more innovative or local techniques. Second, environmental factors that influence the effectiveness of land management techniques are often overlooked, so results may not fully reflect the complex dynamics in agroforestry systems.

4.4. Recommendations for Future Research

Based on the findings and limitations identified, future research is recommended to:

1. **Researching Lesser Known Techniques:** Focus on under-researched land management techniques, particularly those that have the potential to be effective in local contexts in different countries. This research can expand understanding of innovation in agroforestry practices.
2. **Analysis of the Relationship between Environmental Factors:** Future research should consider environmental and social factors that influence the success of carbon sequestration techniques in agroforestry, such as climate, soil type, and local community culture.
3. **In-Depth Case Study:** Conduct case studies in various regions to identify successful implementation of different land management techniques, with an emphasis on learning from best practices that other farmers can emulate.
4. **Economic Models and Sustainability:** Research should also explore economic models that support the sustainability of agroforestry, including cost-benefit analyses of implementing sustainable land management techniques.

With these steps, it is hoped that future research can make a greater contribution to the development of agroforestry practices that are sustainable and effective in mitigating climate change.

5. Conclusions

This research has conducted a systematic literature review to explore land management techniques that increase carbon sequestration in the context of agroforestry. By analyzing 20 articles relevant, we identified a variety of techniques that have proven effective in increasing carbon sequestration capacity in various ecosystems and geographic regions. The main findings of this study can be summarized as follows:

1. **Identify Effective Techniques:** Some land management techniques, such as multi-strata-based agroforestry, crop rotation, and the use of cover crops, show significant increases in carbon sequestration, with variations in effectiveness depending on the ecosystem and environmental conditions. For example, multi-strata based agroforestry techniques can increase carbon sequestration by up to 50% in subtropical regions, while the use of cover crops can increase carbon sequestration by 15-25%.
2. **Comparison Between Regions:** Comparative analysis shows that these techniques not only vary in their effectiveness but also depend on environmental factors and local practices. Therefore, adapting techniques based on specific contexts is essential to maximize positive impacts on carbon sequestration.
3. **Policy Implications:** These findings highlight the need for integration of effective land management techniques into climate change mitigation policies. Policies that support the adoption of agroforestry practices can encourage environmental sustainability, increase food security, and promote better management of natural resources.
4. **Practical Application:** To achieve the full potential of these techniques, training and capacity building for farmers and other stakeholders is essential. Through collaboration between governments, research institutions and local communities, sustainable agroforestry practices can be implemented more widely, providing sustainable ecological and economic benefits.
5. **Limitations and Recommendations for Future Research:** Although the results of this study provide significant insight, there are several limitations that need to be considered, such as location bias and the techniques studied. Future research is recommended to explore lesser-known techniques, consider diverse environmental factors, and conduct case studies to identify best practices in various local contexts.

Overall, this research emphasizes the importance of implementing sustainable land management techniques in efforts to mitigate climate change and sequester carbon. With an integrated and adaptive approach, agroforestry can be an effective strategy for achieving global environmental goals and supporting ecosystem sustainability. It is hoped that these findings will contribute to the development of better policies and more sustainable practices in land management in the future.

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