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Eucalyptus replanting a comprehensive bibliometric review of research trends

Nurhayati Sembiring[1*], Humala Lodewijk Napitupulu[1]

[1] Department of Industrial Engineering, Faculty Engineering, Universitas Sumatera Utara, Medan, Indonesia
* Corresponding author's e-mail: nurhayatipandia68@usu.ac.id

ABSTRACT

This study presents a comprehensive bibliometric analysis of research developments in Eucalyptus replanting, focusing on key trends, influential contributors, and prominent research clusters. Utilizing data from the CrossRef database and network visualization via VOSviewer software, the analysis distilled 245 research papers down to 87 relevant manuscripts. Four primary research clusters were identified: plantation growth, productivity studies, influence and case studies, and impact analyses. The study highlights the pivotal role of optimized replanting strategies, particularly the timing of replanting and balanced fertilization, in enhancing plantation productivity and sustainability. Comparative analysis with existing literature confirms these factors' relevance in ensuring uniform growth and reducing competition among seedlings. Despite advancements, significant research gaps persist, notably in integrating traditional practices with modern technologies and understanding replanting's long-term impacts. Future research could explore the implementation of mixed-species plantations or the introduction of nitrogen-fixing species to improve soil quality and nutrient availability, potentially mitigating the negative impacts of monoculture eucalyptus planting and promoting a more resilient ecosystem. Additionally, future studies could investigate the long-term effects of these practices on both water conservation and plantation yields, providing valuable insights for sustainable management. The ecological benefits of such practices, including enhanced biodiversity and ecosystem services, warrant further exploration. The increasing volume of research and identified trends underscore the growing recognition of Eucalyptus replantation's significance for economic and ecological sustainability. By addressing critical gaps and suggesting future directions, this research supports broader environmental and economic objectives, emphasizing the importance of continued research and collaboration in the field.

Keywords: bibliometric analysis, eucalyptus, metadata, plantation, replanting, sustainable forestry

INTRODUCTION

Bibliometric analysis employs statistical methods to explore the extensive literature in a specific field, assessing applications and identifying research opportunities (Wang et al., 2014). This method is particularly effective for evaluating a paper's contributions to the advancement of knowledge (Nugroho et al., 2022). Typically, trend analysis in bibliometrics utilizes indicators such as fields of study, sources of documents, publication outputs, languages, nations, distributions of institutions, leading authors, citation counts, and author keywords (Dong et al., 2012). Recent bibliometric studies provide a precise and objective means to evaluate the impact of scholarly works on the advancement of knowledge (Currie et al., 2008). Bibliometrics, defined in "Introductory Concepts in Information Science" by Melanie J. Norton, involves the measurement of texts and information (n.d.). This technique allows for the exploration, organization, and analysis of large datasets to uncover hidden trends, thereby assisting academics in informed decision-making (Daim et al., 2006).

A bibliometric review offers significant benefits to both the academic community and the general public. It facilitates the transformation of published metadata into maps or visualizations that simplify control and yield insightful information. Examples include mapping the author affiliations of a specific journal, determining a journal's geographic scope, visualizing keywords to detect research themes or clusters within a discipline, and charting institutional and international collaborations to identify emerging technologies (Tanudjaja & Kow, 2018).

Eucalyptus, a genus comprising over 700 species of flowering trees, is widely cultivated worldwide due to its rapid growth, versatility, and economic importance (Wang et al., 2014). Its applications span from timber and paper production to the extraction of essential oils, rendering it an indispensable resource for multiple industries (Cunningham et al., 2015). In locales such as Brazil, eucalyptus plantations have played a crucial role in revolutionizing the forestry sector, with productivity rates significantly improving over the years through enhanced silvicultural practices (IBÁ, 2017). However, the sustainability of these plantations is frequently compromised by the requirements for replanting, which can impact both productivity and ecological equilibrium. The global demand for eucalyptus and its derivatives has been steadily increasing, driven by the need for renewable resources and sustainable forestry practices. As a fast-growing species, eucalyptus offers a viable solution to meet the demands of the timber and pulp industries, which are under pressure to reduce their carbon footprints and reliance on non-renewable resources. Moreover, eucalyptus plantations contribute to local economies by providing employment opportunities and supporting rural development.

Abbad et al. (2024), demonstrated the potential of plant extracts from *Ocimum basilicum* and *Eucalyptus globulus* as effective biostimulants in tomato cultivation. These extracts not only enhance the growth and performance of several plants may improve and offering a sustainable alternative to conventional stimulants. The research underscores the importance of utilizing natural resources to boost agricultural productivity while maintaining ecological balance.

Replanting is an essential silvicultural practice designed to maintain productivity and ecological balance within plantations (Le et al., 2012). This practice involves replacing dead or underperforming seedlings to ensure even stand development. While replanting can increase forest density and productivity, it also presents challenges such as elevated costs and potential delays in achieving full canopy closure (Trindade et al., 2017). Moreover, the timing and techniques of replanting substantially affect the growth outcomes of eucalyptus stands, as delayed replanting can intensify competition for resources among seedlings (Correia et al., 2013). These complexities underline the necessity for a profound understanding of replanting strategies to maximize their benefits and minimize their drawbacks.

Replanting also plays a pivotal role in enhancing freshwater availability by restoring soil water content and is considered an effective approach to halting biodiversity loss and combating climate change (Barbier, 2006). It encompasses a range of practices from establishing fast-growing exotic species for timber plantations to recreating the original forest patterns and structures using indigenous species (Le et al., 2012). Additionally, replanting facilitates the biogeochemical cycling of carbon, oxygen, and nutrients among the atmosphere, biomass, and hydrosphere (Cunningham et al., 2015).

Beyond ecological benefits, replanting contributes to preventing soil erosion, promoting economic development, enhancing carbon sequestration, and improving habitat connectivity (Wolff et al., 2021). However, it can also introduce negative effects such as altered species distribution, spatial arrangements, and dynamic productivity (Luke et al., 2019). Furthermore, replanting may compete for land that could otherwise be used for housing (Jiang et al., 2016). Importantly, replanting offers a mitigative response to the adverse effects of climate change on amphibian populations, which are notably declining in Central and South America (Ramalho et al., 2021).

Horas and Purba (2019) discusses the replanting policies currently implemented in Indonesia that support sustainable development goals. These policies aim not only to generate financial returns but also to offer social and environmental benefits over time. Fitri Nurfahtirani, Rahmwati, Galih Salih, and Heru Komarudin (Nurfatriani et al., 2019) investigated oil palm replanting in Indonesia as a strategy to help smallholders reduce deforestation. Chow (2014) analyzed the effects of replanting on various soil types in Hong Kong, while Huang et al. (2013) explored the impact of growth-promoting techniques on tree replanting in Chinese cypress plantations in subtropical China.

The primary research problem addressed in this study concerns the optimization of replanting strategies for Eucalyptus plantations to enhance growth and yield while minimizing economic and ecological drawbacks. Inadequate management of Eucalyptus replanting can lead to nonuniform growth patterns, increased susceptibility to pests and diseases, and diminished overall productivity (Soares et al., 2016). Additionally, the economic burden of replanting, especially in large-scale operations, necessitates the development of efficient and cost-effective methods to ensure the sustainability of these ventures (Summers et al. 2015).

Xiao et al. (2022) developed a bibliometric analysis of remote sensing applications to monitor spatial variation of plants, characterizing the status, development, and future projections used to quantify the number of replanted plants in a specific area or production unit over a designated period. Gichuru (2015) discussed a strategy for establishing forest plantations called the Pelis strategy, which significantly influences replanting programs. Paul et al. (2016) conducted research on the potential of replanting to increase biodiversity and mitigate the loss of agricultural land. A general solution to these challenges involves developing optimized replanting protocols that consider the timing, frequency, and techniques of replanting. Precise timing for replanting is crucial because early replanting can reduce competition among seedlings and promote uniform growth (Pereira Filho et al., 2020). Additionally, integrating complementary fertilization and advanced monitoring techniques can enhance the growth outcomes of replanted seedlings. These strategies aim to balance economic costs with ecological benefits, ensuring the long-term sustainability and productivity of Eucalyptus plantations.

Recent scientific literature has provided numerous insights into the optimization of eucalyptus replanting strategies. Studies have demonstrated that the timing of replanting critically influences the growth and yield of eucalyptus stands. Filho et al. (2020) observed that longer intervals between initial planting and subsequent replanting result in reduced individual volume of replanted trees, indicating that timely replanting is crucial to minimize competition and ensure uniform growth. Ngai et al. (2024) demonstrated the effectiveness of using constructed wetlands with organic waste, including eucalyptus leaf waste, to neutralize AMD. This innovative method not only improves water quality but also supports ecological balance by utilizing natural resources.

Research on complementary fertilization has explored its potential to enhance the growth of replanted seedlings. Rocha et al. (2013) suggest that while supplementary fertilization can promote initial growth, its long-term benefits are limited, underscoring the need for balanced fertilization strategies that support sustainable growth without causing nutrient imbalances or additional environmental impacts.

Advancements in remote sensing and monitoring technologies have significantly improved the precision and efficiency of replanting operations. Xiao et al. (2022) demonstrated the application of remote sensing in monitoring spatial variations in eucalyptus plantations, providing critical data to optimize replanting schedules and techniques. These technological advances facilitate better resource management in plantations and enhance the implementation of effective replanting strategies.

Florencio et al. (2022) conducted an analysis of the impacts of climate change on Eucalyptus plantations, focusing on adaptive measures necessary for sustainable forestry development. The study employed agroclimatic zoning and Earth System Models to evaluate suitable areas for Eucalyptus cultivation under future climate scenarios. This analysis highlighted potential restrictions and the economic unfeasibility of Eucalyptus plantations in certain regions due to projected changes in climate variables, such as precipitation and temperature, which affect water availability and evapotranspiration. The research underscores the importance of implementing adaptive measures to mitigate these impacts and ensure the sustainability of Eucalyptus plantations. Nilsson et al. (2010) identified the optimal season and conditions for replanting in northern Europe, finding the best period to be from June to March. Trac et al. (2007) studied replanting programs in Southwest China, focusing on natural forest protection and the conversion of sloped land to arable use. Additionally, Abiodun Adeyewa, and Ajayi (2012) developed a model to investigate the potential impacts of replanting on the climate of West Africa in the future.

Despite advancements in replanting strategies, several research gaps remain. For instance, while the timing of replanting is acknowledged as crucial, comprehensive studies on the optimal intervals for different Eucalyptus species under varying plantation conditions are still required (Correia et al., 2013). Additionally, the long-term effects of complementary fertilization on replanted seedlings are not well understood, highlighting the need for further research to establish sustainable fertilization practices (Rocha et al., 2013).

One of the significant gaps filled by the current study is the understanding of soil dynamics in eucalyptus plantations, particularly regarding soil organic carbon (SOC) and nutrient cycling. Research has shown that successive planting of eucalyptus can lead to a decrease in bacterial diversity, which in turn affects SOC dynamics Chen (2023). This finding emphasizes the need for management practices that enhance microbial diversity and soil health (Yao et al., 2023; Xu et al., 2022). Such practices could mitigate the negative impacts of monoculture eucalyptus planting and promote a more resilient ecosystem.

The study also highlights the importance of water-use efficiency (WUE) in eucalyptus plantations, particularly in regions with varying climatic conditions. It has been observed that WUE can fluctuate significantly between planting rotations, influenced by factors such as fertilization and irrigation practices (Yao, 2023; Tan, 2024). Another critical aspect addressed by the current study is the impact of eucalyptus plantations on local biodiversity. The findings indicate that large-scale eucalyptus plantations can lead to homogenization of landscapes, negatively affecting species richness and habitat availability for terrestrial mammals (Pestana et al., 2023; Afonso, 2023). The insights gained from the current study can significantly inform policy development regarding sustainable eucalyptus replanting practices. Individuals responsible for making decision can utilize these findings to create guidelines that promote the adoption of best management practices, such as mixed-species planting and enhanced soil management techniques. This could lead to more sustainable eucalyptus production systems that align with broader environmental and economic goals (Sembiring, 2024).

A significant gap also exists in the need for integrated approaches that blend traditional silvicultural practices with modern technologies. Although remote sensing has proven effective for monitoring plantation health and growth, its integration with ground-based silvicultural practices remains inadequately explored, necessitating further research to develop comprehensive replanting protocols (Xiao et al., 2022). Moreover, more research is required on the ecological impacts of replanting, particularly regarding biodiversity and soil health, to ensure that replanting practices contribute to overall ecosystem sustainability (Le et al., 2012). To date, there has been limited discussion on the bibliometric analysis of replanting strategies in eucalyptus and plantation fields. The primary objective of this study is to develop optimized replanting strategies for eucalyptus plantations that enhance growth and yield while minimizing economic and ecological drawbacks. This study aims to integrate traditional silvicultural practices with modern technologies to formulate effective and sustainable replanting protocols. Therefore, this research seeks to analyze the academic and scientific literature on eucalyptus replanting. The study addresses several questions:

1. Who are the leading authors in the research on replanting eucalyptus worldwide?
2. Which organizations play pivotal roles in research on replanting eucalyptus in plantation fields?
3. How many publications are projected to be published by 2025? and
4. What is the potential for future research in this field?

This bibliometric study evaluates the relationships between publishing trends, prospective research objectives, and global replanting development goals. The novelty of this study resides in its holistic approach, which synthesizes insights from recent scientific literature with practical field applications. In contrast to previous studies that often focused on isolated aspects of replanting, this study aims to provide an integrated solution encompassing timing, fertilization, and monitoring. It utilizes advancements in remote sensing and ground-based monitoring to develop precise and efficient replanting strategies applicable to various Eucalyptus species and plantation conditions. The following contributions of this study distinguish it from other works:

1) The paper enriches the literature on replanting by exploring methods and strategies to enhance the productivity and development of plants within plantation fields or forest management.
2) It investigates optimization and policies for replanting plantations to support smallholder eucalyptus replanting and other plantation types, aiming to minimize deforestation and rehabilitate unproductive land.
3) It examines the interplay between the replanting sector and other agricultural and non-agricultural sectors, highlighting the mutual benefits and economic opportunities for eucalyptus and other farmers.

This study includes a comprehensive review of existing replanting practices, experimental trials to test various replanting protocols, and the application of advanced monitoring technologies to assess outcomes. Conducted in collaboration with forestry experts and plantation managers, this research ensures the practical applicability of the findings. The results are expected to significantly enhance the body of knowledge on eucalyptus replanting and promote the development of more sustainable and productive plantation practices.

The originality of this research lies in its approach of using a comprehensive bibliometric review to examine research trends related to eucalyptus replanting strategies. While previous studies have focused on optimizing replanting strategies, particularly the timing of replanting and balanced fertilization to enhance plantation productivity and sustainability, this research offers a new perspective by analyzing the literature as a whole.

The novelty of this research is in providing a thorough analysis of research trends in this field, which has not been done before. By employing bibliometric methods, this study can identify patterns, developments, and gaps in the existing literature, offering deeper insights for researchers in developing more effective and sustainable eucalyptus replanting strategies.

MATERIALS AND METHODS

This bibliometric study explores the literature concerning eucalyptus replantation in plantation fields and assesses its future research potential. The dataset, obtained from the CrossRef database, underwent performance and networking analyses to identify pertinent research on this topic. This exploration was structured using research documented by scholars including Ospina-Mateus et al., (2019), Solano-Charris & Montoya-Torres (2019), Meza-Peralta et al., (2020), Khan et al., (2021), Gholampour et al., (2019), Guiling et al., (2022), and Martínez et al., (2022), which guided the search strategy.

As detailed in Table 1, the search terms focused on the replanting of eucalyptus, sustainable forestry and plantation fields. The text outlines the keywords and search terms utilized in the exploration of articles related to specific topics. It organizes these terms into clusters to streamline the search process. The first cluster, "Replanting Eucalyptus," includes terms such as "Replanting Eucalyptus," "replanting," "Eucalyptus," "Eucalyptus tree," and "Reseeding," which are employed to locate articles focused on the replanting of eucalyptus trees. The second cluster, "Plantation," comprises terms like "Plantation fields," "Agricultural," "Crops," and "Farm Plantations," aimed at finding articles about agricultural plantations and related subjects. The third cluster, "Sustainable Forestry," uses a combination of search terms that include titles, abstracts, or keywords containing phrases from both the "Replanting Eucalyptus" cluster and terms associated with "Sustainable Forestry," "Agricultural," "Crops," or "Farm Plantations." This approach is designed to identify articles that discuss sustainable forestry practices within the context of eucalyptus replanting and agriculture. To address the issue of articles such as from Google and Elsevier often being repetitive, it is essential to adopt a systematic approach for selecting and organizing them. One effective strategy is to create a database or spreadsheet to track the articles that have already been reviewed. This database should include important details such as the title, authors, journal, and a brief summary of each article's content. Additionally, it is crucial to regularly cross-check this database to ensure that duplicate articles from different sources are not inadvertently selected. This organized method will help streamline the research process and enhance the quality of the selected articles. The CrossRef database was selected for its comprehensive coverage of globally significant and high-impact studies.

From the CrossRef database, a total of 245 articles were identified, spanning the last 22 years. The search ranged from 2000 to 2024, intentionally excluding data from the prior 27 years to focus on recent trends. Ultimately, 218 manuscripts were selected for further consideration.

Table 1. Keywords used in article exploration.

Cluster	Search Items
Replanting eucalyptus	"Replanting Eucalyptus" or "replanting" or "Eucalyptus" or "Eucalyptus tree" or "Reseeding"
Plantation	"Plantation fields" or "Agricultural" or "Crops" or "Farm Plantations"
Sustainable forestry	TITLE-ABS-KEY ("Replanting Eucalyptus" or "Replanting" or "Eucalyptus" or "Eucalyptus tree" or "Reseeding") and TITLE-ABS-KEY ("Sustainable Forestry" or "Agricultural" or "Crops" or "Farm Plantations")

Exclusions were applied to ensure focus and relevance. Notes, book chapters, and conference papers were excluded. Through the second filter, 68 items were removed, leaving 150 documents. The third filter, which eliminated non-English articles – including seven Indonesian, two Brazilian, one Portuguese, and one Thai – resulted in 139 remaining documents. The titles and abstracts of these articles were scrutinized with a fourth filter, leading to the exclusion of 71 articles that did not specifically address eucalyptus replantation in plantation fields. Ultimately, 87 articles were deemed relevant and included for detailed analysis, as summarized in Table 1, utilizing specific keywords to refine the search.

The acquired dataset encompasses a comprehensive range of bibliometric data, including titles, authors, sources, publication years, bibliographic details, abstracts, affiliations, keywords, funding information, publishers, sponsors, publication stages, publication types, and other relevant features. The VOSviewer software was utilized for network visualization, while Excel facilitated data management. Bibliometric mapping enables the visualization of and exploration into the relationships among articles, authors, organizations, nations, citations, and key terms (Zahra et al. 2021). Keyword analysis based on co-occurrence was performed using VOSviewer, with visualization parameters such as size, color, and distance. The research methodology is detailed in Figure 1.

RESULTS AND DISCUSSION

Term analysis

Identifying research trends involves analyzing terms found in the abstracts and titles of articles. The co-occurrence analysis of terms in articles from VOSviewer is presented in Figure 2, where four distinct clusters were identified. The primary cluster includes terms related to plantation activities and features words such as eucalyptus, forest,

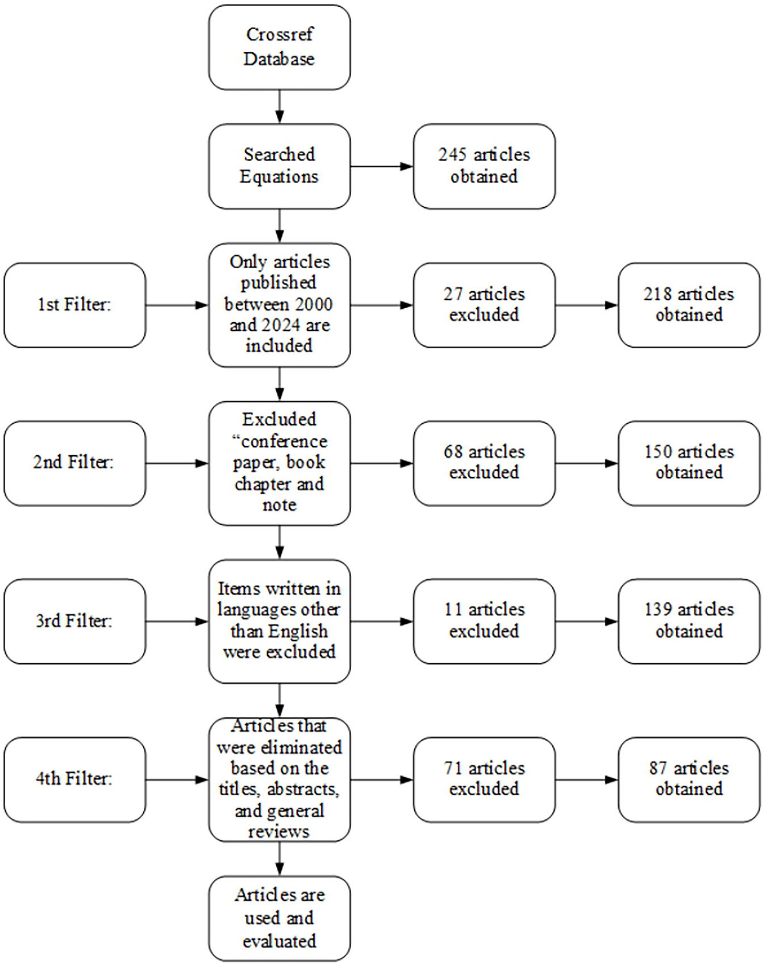

Figure 1. Research methods overview

growth, effect, and variation. The second cluster encompasses productivity, development, study, time, and research. The third cluster includes terms like influences, production, case studies, and replanting. The fourth cluster comprises impact, response, and influence. Figure 3 displays an overlay visualization of the co-occurrence analysis using all keywords. For example, the colors dark blue and light blue correspond to the most frequently occurring terms between 2014 and 2015, which include plantation, eucalyptus, forest, growth, effect, response, and variation. A bibliometric analysis of eucalyptus replanting has revealed key trends and influential contributors within this field. Figures 2 and 3 illustrate the co-occurrence analysis of keywords, emphasizing the main themes and research clusters identified in the literature. The analysis delineates four primary clusters:

- plantation- and growth-related terms;
- studies on productivity and development;
- influence and case studies; and
- analyses of impact and response. These clusters reflect the varied research approaches and areas of focus within the study of eucalyptus replanting (Fig. 2 and 3).

This study identifies the need for integrating traditional silvicultural practices with modern technologies, such as remote sensing, to

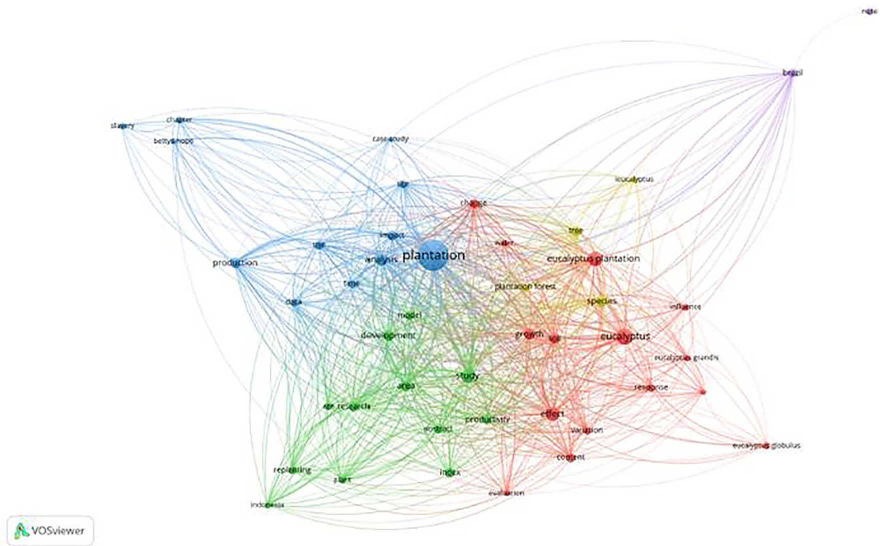

Figure 2. Analysis of terms within the subject area

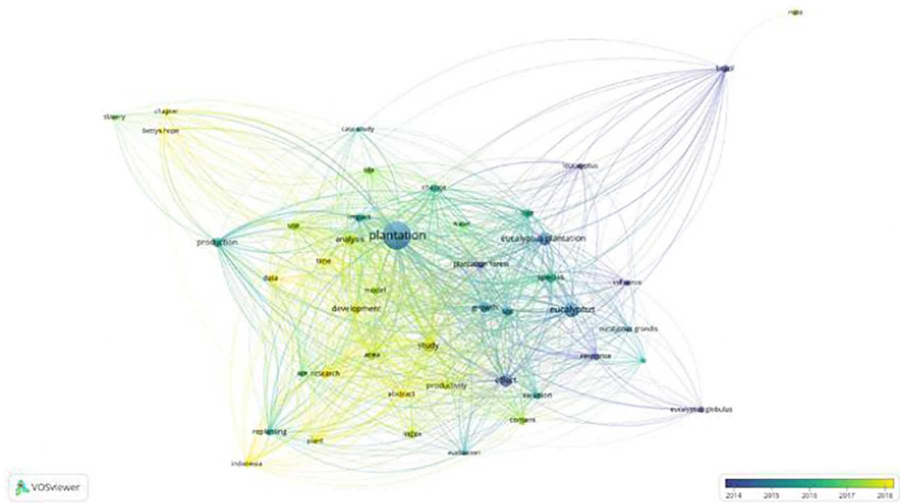

Figure 3. Overlay visualization of keyword co-occurrence

optimize replanting strategies. Additionally, understanding the long-term ecological impacts of replanting, including its effects on soil health and biodiversity, remains a critical area for future research.

Publication by year

Based on the number of articles retrieved during the materials and methods stages, a total of 87 articles were significant to this study. The years 2011 and 2019 featured prominently, each with eight articles, making them the most referenced years.

The year 2010 followed closely with seven articles. Forecasting was also conducted using a linear forecasting method in Excel, projecting the publication of five articles each in 2023 and 2024, and six articles in 2025. Figures 4 and 5 display the number of publications and the cumulative total forecasted through 2025. Moreover, Figures 4 and 5 predict a steady increase in research outputs through 2025, indicating growing interest and investment in eucalyptus replanting studies.

Analysis of authors

Table 2 lists the top ten authors by output, with Jean Paul Laclau and Yann Nouvellon leading with seven publications each on eucalyptus replanting in plantation fields. Auro C. Almeida ranks second with six publications. Sharing third place, Falin Chen, Kai Zhang, Hua Zheng, Geuric Le Maire, Zhiyun Qiyang, Dan Bankley, and Jose Luiz Stape each have four publications. The distribution of publications among the listed authors demonstrates both the geographic diversity and the collaborative nature of research in the field of eucalyptus replanting in plantations. This means that researchers from different countries are actively contributing to this area of study, indicating a wide range of perspectives and international cooperation. Table 2 provides a list of the top 10 authors who specialize in eucalyptus replanting within plantation fields. For each author, the table includes their name, country, and the number of publications they have contributed to this topic. The authors come from various countries, such

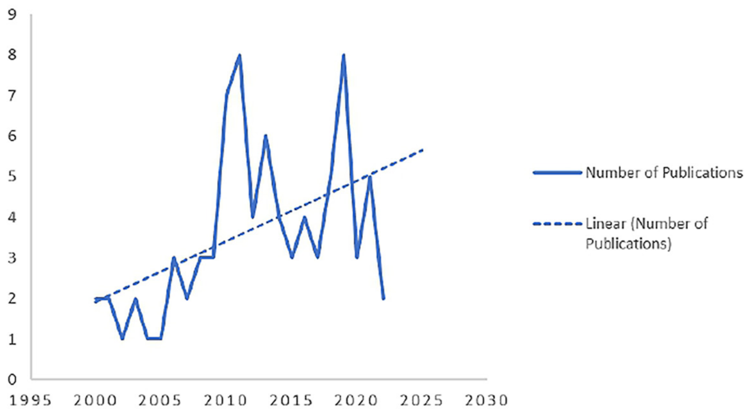

Figure 4. Annual publication trends predicted until 2025

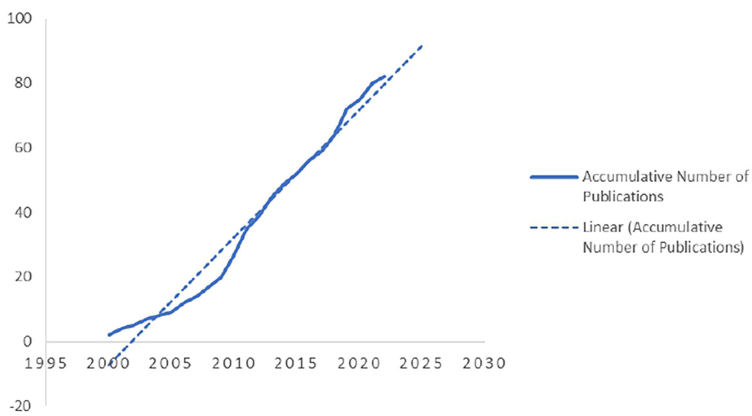

Figure 5. Cumulative number of publications predicted until 2025

as France, Australia, China, the United States, and Brazil, which further highlights the international scope of research in this area. The study of co-authorship using documents obtained via VOSviewer is depicted in Figure 6. An analysis of the connections among various authors shows that Jean Paul Laclau, Yann Nouvellon, and Geuric Le Maire are the most interconnected. The main groupings were divided into four clusters, as detailed in Table 2, based on the affiliations of the authors. The authors' cooperation network for replanting eucalyptus in plantation fields is showcased in Figure 6.

Publication by organizations

Table 3 enumerates the top 10 organizations involved in publishing on the topic of replanting eucalyptus in plantation fields. Nanjing University and the Rochester Institute of Technology lead with 11 publications each. Following closely, the Guangzhou Institute of Geochemistry has produced nine publications.

Trent University, Universidade de São Paulo, and Universidade Federal da Paraíba are tied for fourth place with six publications each. Rounding out the top five, the University of KwaZulu -Natal and Kyoto University each have four publications. The most productive organizations in this field are detailed in Table 3.

Figures 7 and 8 illustrate the distribution of publications by these organizations and depict the organizational cooperation network for replanting eucalyptus in plantation fields. The findings of this study are consistent with those of previous research, which has repeatedly emphasized the importance of optimized replanting strategies for improving productivity in eucalyptus plantations. Consistent with the studies conducted by Correia et al. (2013) and Trindade et al. (2017), our analysis emphasizes the importance of timely replanting to minimize competition

Table 2. Top 10 authors specializing in eucalyptus replanting in plantation fields

No	Name of author	Country	Number of publication
1	Laclau, J.P.	France	7
2	Nouvellon, Y.	France	7
3	Almeida, A.C.	Australia	6
4	Chen, F.	China	4
5	Zhang, K	China	4
6	Zheng, H	China	4
7	Qiyang, Z	China	4
8	Maire, G.L.	France	4
9	Binkley, D.	United States	4
10	Stape, J.L.	Brazil	4

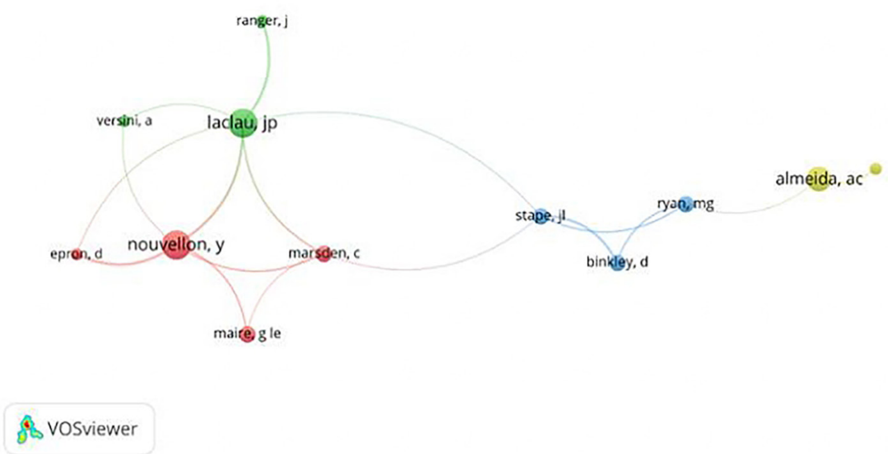

Figure 6. Network of author collaboration on eucalyptus replanting in plantation fields

Table 3. Top 10 most productive organizations in eucalyptus replanting

No	Organizations	Country	Number of publications
1	Nanchang University	China	11
2	Rochester Institute of Technology	United States	11
3	Guangzhou Institue of Geochemistry	China	9
4	Cmpc Celulose Do Brasil Ltda	Brazil	8
5	University of Lavras	Brazil	8
6	Trent University	Canada	6
7	Universidade de Sao Paolo	Brazil	6
8	Universidade Federal da Pariba	Brazil	6
9	University of Kwazulu Natal	South-Africa	4
10	Kyoto University	Japan	4

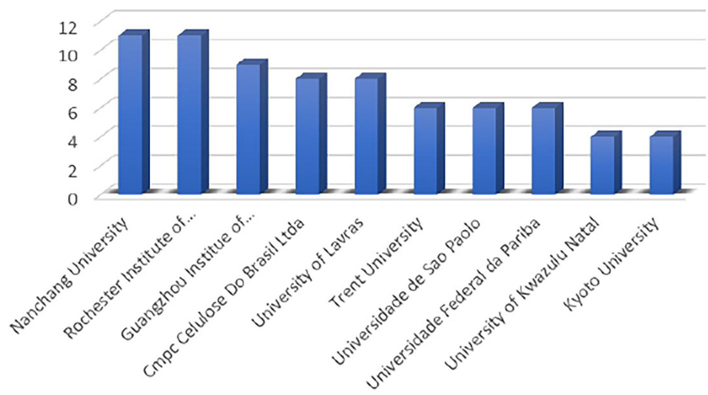

Figure 7. Publication distribution by organizations specializing in eucalyptus replanting

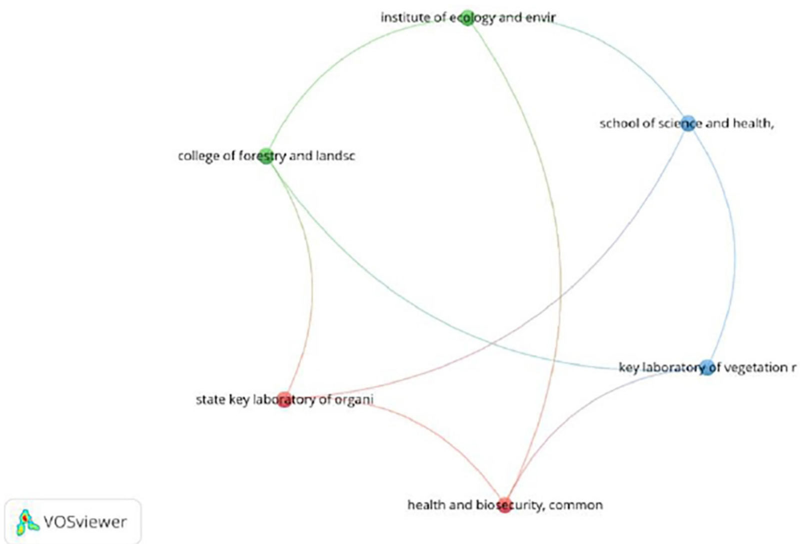

Figure 8. Organizational cooperation network for eucalyptus replanting

and ensure uniform growth. These studies demonstrate that delays in replanting can result in increased heterogeneity in tree size and a decrease in overall stand productivity, findings that align with our observations on the importance of replanting timing. Figure 9 addressing the identified research gaps could significantly contribute to the development of more effective and sustainable Eucalyptus replanting protocols, ultimately supporting broader environmental and economic goals. This aligns with the study's findings, which underscore the importance of timely replanting and balanced fertilization in improving plantation productivity and sustainability. The research emphasizes that replanting during optimal conditions, such as the rainy season, enhances seedling survival and growth due to better soil moisture availability.

Additionally, our findings parallel those of Filho et al. (2020), who noted the significant impact of complementary fertilization on the growth of replanted seedlings. While our study indicates that supplementary fertilization does not significantly improve the volume of replanted trees. This research advances the understanding of eucalyptus replanting by exploring the nuanced effects of different fertilization regimes on long-term soil health and nutrient cycling, aspects that have not been fully addressed in previous studies. Unlike prior research, which primarily focuses on initial growth boosts, this study delves into the sustainability of these practices by considering potential ecological impacts and the need for nutrient balance to prevent soil degradation. This comprehensive approach fills a significant gap in the current literature and provides practical guidelines for plantation managers seeking to optimize growth while maintaining environmental integrity. By integrating modern technologies such as precision agriculture, this study suggests innovative methods for dynamically monitoring and adjusting fertilization practices, thereby enhancing both productivity and sustainability in eucalyptus plantations.

Analysis of citations

Table 4 enumerates the most cited articles in the field of eucalyptus replantation. The study by Le Maire et al. holds the top position, followed by Almeida et al., and Nouvellon et al. in third place.

Additionally, Zhang et al. and Cabral et al. secured the fourth and fifth positions, respectively. Packelen et al. and Marsiden et al. came in sixth and seventh, while the eighth position was occupied by McIntosh et al. Chen et al. and Rocha et al. completed the list in ninth and tenth places, respectively. These top ten publications with the most citations regarding replanting eucalyptus in plantation fields are detailed in Table 4.

Figure 10 presents a citation analysis using VOSviewer, highlighting the pioneering study by Le Maire et al. This analysis delineates four primary groups (clusters) that originate from the work of the aforementioned author and illustrates the connections between the publications and their respective citations. Figure 11 further explores the connections between citations and cited sources.

Analysis of subject categories

Our analysis identified the top five primary research areas concerning replanting eucalyptus in plantation fields. The results showed that 24 papers (34%) fell under the category of forest management. Environmental Science followed with 18 articles (25% of publications), then Technology Development with 14 articles (20% of publications), hydrology represented by 13% of the publications, and Business and Economy,

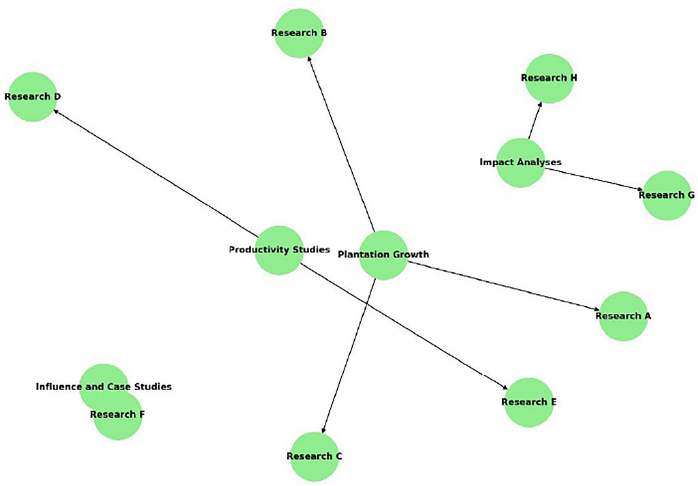

Figure 9. Main research cluster in eucalyptus replanting

Table 4. Top 10 most cited publications on eucalyptus replanting

No	Citation	Times cited	Institution	Country
1	Le Maire et al. (le Maire et al. 2011)	129	Remote S.E	France
2	Almeida et al. (Almeida et al. 2010)	74	Forest ecology and management	Brazil
3	Nouvellon et al. (Nouvellon et al. 2010)	65	Forest ecology and Mgmt	France
4	Zhang et al. (Chen, Zheng, Zhang, Ouyang, Wu, et al. 2013)	63	Journal of soils and sediments	China
5	Cabral et al. (Cabral et al. 2010)	51	Journal of hydrology	Brazil
6	Packelen et al. (Packalén, Mehtätalo, and Maltamo 2011)	49	Annals of forest science	Finland
7	Marsden et al. (Marsden et al. 2013)	47	Forest ecology and management	France
8	Mcintosh et al. (McIntosh et al. 2012)	46	Bioresource technology	Australia
9	Chen et al. (Chen, Zheng, Zhang, Ouyang, Li, et al. 2013)	44	Journal of environmental sciences	China

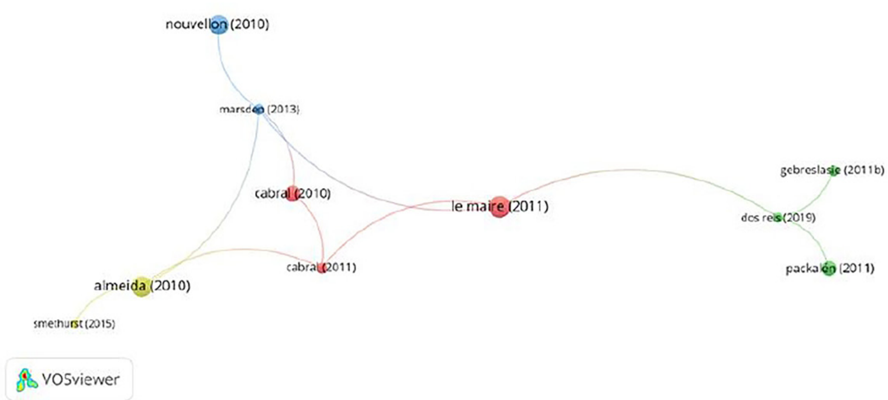

Figure 10. Analysis of co-citations in eucalyptus replanting research

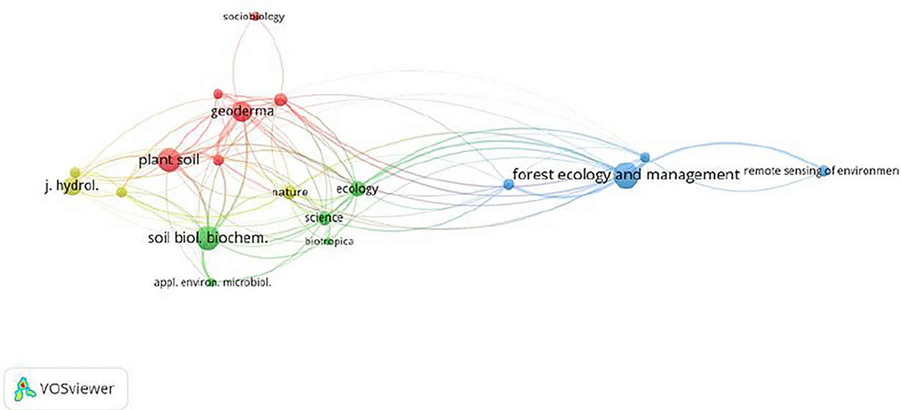

Figure 11. Citation analysis by source in eucalyptus replanting studies

which accounted for 8% of the articles (6 articles in total). Figure 12 visually represents these top five categories using the collected datasets.

Cortez et al. (2014), Zegeye (2010), and Tomé et al. (2021) have documented the areas of land planted with eucalyptus in Brazil, South Africa, Tanzania, and New Guinea, respectively. Paquette and Messier (2010) examined the role of plantations in global forest management. Zhang and Wang (2021) investigated the geographic

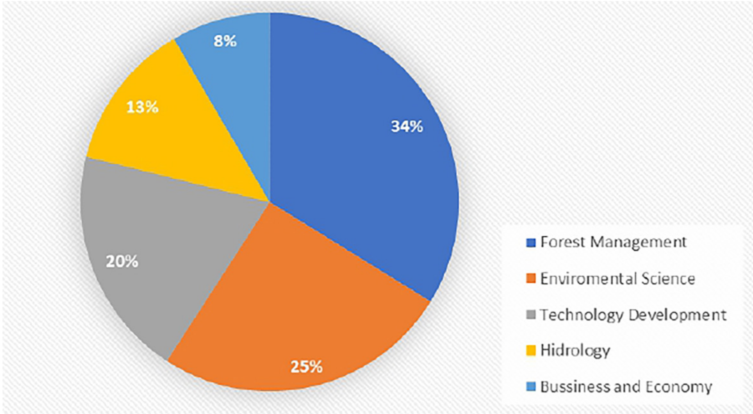

Figure 12. Predominant topics in publications on eucalyptus replanting

distribution of Eucalyptus plantations. By integrating findings from various studies, this research opens up several prospects for future exploration and application in sustainable forestry practices. One of the significant gaps filled by the current study is the understanding of soil dynamics in eucalyptus plantations, particularly regarding soil organic carbon (SOC) and nutrient cycling. Research has shown that successive planting of eucalyptus can lead to a decrease in bacterial diversity, which in turn affects SOC dynamics Chen (2023). Yao et al. (2023) and Xu et al. (2022) underscore the critical need for management practices that enhance microbial diversity and soil health within eucalyptus plantations. These studies highlight that such practices are essential to mitigating the adverse effects associated with monoculture eucalyptus planting, which often leads to reduced biodiversity and compromised soil quality. This approach aligns with broader ecological objectives, aiming to enhance ecosystem resilience and functionality. Nouvellon et al. (2010) analyzed the specific leaf area of Eucalyptus plantations in the Republic of Congo. Le Maire et al. (2011) utilized remote sensing to monitor the biomass of Eucalyptus plantations. Almeida et al. (2010) explored the impacts of climate and soil variability on the productivity of Eucalyptus plantations. Cabral et al. (2010) investigated the water and energy balance of Eucalyptus plantations in southeast Brazil.

The integration of remote sensing technologies, as highlighted by Xiao et al. (2022), marks a significant advancement in the management of eucalyptus plantations. Remote sensing enables precise monitoring of plantation health, spatial variations, and growth patterns, which are essential for optimizing replanting strategies. This technological advancement allows for the collection of real-time data on critical factors such as soil moisture levels, vegetation health, and pest infestations. Consequently, plantation managers can make informed decisions that enhance resource efficiency. By leveraging these insights, managers can implement timely interventions, adjust fertilization schedules, and optimize irrigation practices to improve overall plantation productivity. Additionally, the ability to monitor large-scale plantations remotely reduces the need for extensive on-ground surveys, thereby lowering operational costs and minimizing environmental disturbances.

Several researchers have focused on the growth dynamics of Eucalyptus. Delgado-Matas and Pukkala (2011) compared the growth of six Eucalyptus species in Angola. Forrester (2013) examined growth responses to silvicultural treatments such as fertilization, thinning, and pruning in Eucalyptus plantations, which are crucial for the production of solid wood products. Hubbard et al. (2010) discussed the impact of water use on Eucalyptus plant growth. Mhamdi et al. (2022) analyzed the growth of seven Eucalyptus species in northwestern Tunisia.

Several researchers have investigated the responses of eucalyptus to various environmental challenges. Saadaoui et al. (2017) examined the adaptive responses of Eucalyptus to drought conditions. Naidoo et al. (2014) explored the defense mechanisms of eucalyptus against infections and pests. Laclau et al. (2014) analyzed the photosynthetic and anatomical responses of Eucalyptus to potassium and salt supplementation in a field experiment.

Additional studies have focused on the characteristics of eucalyptus plantations. Prasetyo et al. (2017) described the traits of three Eucalyptus species cultivated for pulpwood in Indonesia. Vieira, Fernández, and Rodríguez-Soalleiro (2016) discussed the nutritional requirements of Spanish Eucalyptus plantations. Harwood and Nambiar (2014) reviewed the productivity of Southeast Asian Eucalyptus plantations, noting that the region now supports at least 2.6 million hectares of acacias and 4.3 million hectares of eucalyptus. Stape et al. (2010) conducted research on the potential productivity of Eucalyptus plantations in Brazil.

Carrijo et al. (2020) proposed a model for predicting the production of Eucalyptus urophylla plantations. Valadares et al. (2018) developed a model to simulate the carbon and nitrogen cycles in the soil of a Eucalyptus plantation. Attia et al. (2019) created a regional-scale model to assess the carbon and water balance of eucalyptus plantations, taking into account the influence of climate, soil, and genotypes.

Eucalyptus plantations are known for producing a wide array of engineered wood products, such as particleboard, plywood, fiberboard, oriented strand board (OSB), laminated veneer lumber (LVL), gluelaminated timber (GLT), and cross-laminated timber (CLT) (Seng Hua et al. 2022). Additionally, ethanol has been produced from thinned eucalyptus plantations.

Several studies have examined the impacts of Eucalyptus plantations. Goded et al. (2019) investigated the effects of Eucalyptus plantations on avian and herbal species in northwest Spain. Graça et al. (2002) researched the impact of Eucalyptus plantations on stream litter, decomposers, and detritivores. Bayle (2019) discussed both the ecological and social impacts of Eucalyptus tree plantations, noting their potential for both positive and negative effects on the environment.

Laclau and Nouvellon emerged as the most prolific authors regarding publications on eucalyptus in plantation fields, with Auro C. Almeida ranking second. Falin Chen, Kai Zhang, Hua Zheng, Geuric Le Maire, Zhiyun Qiyang, Dan Bankley, and Jose Luiz Stape held the third position. The journals Forest Ecology and Management, Bioresource Technology, and the Journal of Environmental Sciences featured the most research on replanting eucalyptus in plantation fields.

Our data reveal that the most frequently cited articles for this study spanned from 2011 to 2019, with a total of eight articles, based on the 68 articles reviewed at the materials and methods stage. The year 2010 was the second most cited, with seven articles. Notably, countries such as China, Brazil, the United States, France, Australia, and Indonesia have been instrumental in developing models for replanting eucalyptus in plantation fields.

The dominant terms in this study included plantation eucalyptus, eucalyptus plantation, effect, growth, research, replanting, and productivity. The CrossRef database was utilized for this research. Table 5 lists the authors of the mostcited papers, with Le Maire et al. at the forefront, followed by Almeida et al., and Nouvellon et al. in third place. Figure 7, which highlights the analysis of citations by source, shows that this article had the highest correlation with VOSviewer. A literature search was conducted using keywords such as eucalyptus, replanting, eucalyptus tree, reseeding, plantation fields, agriculture, crops, and farm plantations.

In this bibliometric study, the leading institutions and universities, as detailed in Table 4, include Nanchang University in China and the Rochester Institute of Technology in the United States. The Guangzhou Institute of Geochemistry in China ranked second, while Cmpc Celulose Do Brasil Ltda and the University of Lavras, both in Brazil, were third.

The research identified trends related to the interactions between eucalyptus plants and various factors, ranging from replanting conditions to forest management, and their relationships with living organisms and the environment.

To examine the impacts of Eucalyptus replantation on living organisms and the environment, it is crucial to establish a causal relationship. Given that different Eucalyptus species exert varied effects, an in-depth analysis of the plant species, including the ideal soil structure and type, is essential for effective replanting.

Optimized replanting strategies for eucalyptus can significantly enhance plantation management by focusing on precise timing and balanced fertilization. The timing of replanting is critical, as it influences seedling establishment and growth rates. Research indicates that replanting during the rainy season can improve survival rates and initial growth due to increased soil moisture availability (Sembiring, 2024). Furthermore, the application of balanced fertilization, which considers the specific nutrient requirements of eucalyptus, can lead to improved growth rates and biomass production. Studies have shown that the application of nitrogen, phosphorus, and potassium in appropriate ratios can enhance tree growth and wood quality, thereby increasing overall productivity (Yao, 2023).

Incorporating modern technologies such as remote sensing and precision agriculture can further optimize plantation management. For instance, satellite imagery can be utilized to monitor vegetation health and soil moisture levels, allowing managers to make informed decisions regarding irrigation and fertilization (Sarto et al., 2022). Additionally, the use of drones for aerial surveys can facilitate the identification of pest infestations and disease outbreaks, enabling timely interventions that can mitigate losses (Sembiring et al., 2022). By integrating these advanced management practices, plantation managers can enhance productivity while ensuring the sustainability of eucalyptus plantations.

The insights gained from optimized eucalyptus replanting strategies can inform those responsible for decision making in developing guidelines for sustainable replanting practices. This individuals can utilize findings from research to create frameworks that promote best practices in eucalyptus cultivation, ensuring that environmental and economic goals are aligned. For example, policies that incentivize the use of genetically modified eucalyptus varieties, which are designed to be more resilient and resource-efficient, can lead to more sustainable plantation practices (Sembiring et al., 2022).

Moreover, the establishment of certification programs for sustainably managed eucalyptus plantations can encourage adherence to best practices among plantation owners. Such programs can promote transparency and accountability, ensuring that replanting efforts contribute positively to local ecosystems and communities (Porto, 2024). Those responsible in decision making can also consider implementing regulations that limit the expansion of eucalyptus plantations into ecologically sensitive areas, thereby protecting biodiversity and ecosystem services (Pinheiro, 2023).

The emphasis on sustainable practices in eucalyptus replanting strategies supports broader ecological objectives, such as biodiversity conservation and climate change mitigation. Eucalyptus plantations, when managed sustainably, can serve as carbon sinks, contributing to efforts to reduce greenhouse gas emissions (Shi et al., 2022). Additionally, integrating native species into eucalyptus plantations can enhance biodiversity by providing habitat for various flora and fauna, thereby promoting ecological resilience (Pestana et al., 2023). From an economic perspective, improved plantation yields resulting from optimized replanting strategies can contribute to local economic development. Increased productivity can lead to higher incomes for plantation owners and workers, while also supporting local industries that rely on eucalyptus products, such as paper and bioenergy (Alemayehu et al., 2023). Furthermore, sustainable eucalyptus plantations can provide ecosystem services, such as soil stabilization and water regulation, which can have long-term economic benefits for surrounding communities (Wang, 2023).

The findings from this bibliometric analysis carry significant implications for future research and practices in Eucalyptus replanting. By highlighting key authors, institutions, and research trends, this study offers a comprehensive overview of the current state of knowledge and potential future directions in this field. The increasing volume of publications and the identification of research clusters indicate a growing recognition of the importance of eucalyptus replanting for both economic and ecological sustainability.

The insights gained from this study can guide researchers in optimizing replanting strategies to enhance plantation productivity and sustainability. Focusing on timely replanting and balanced fertilization practices can lead to more uniform and productive eucalyptus stands, ultimately supporting sustainable forestry and climate change mitigation goals. Additionally, the identification of key research gaps underscores the need for ongoing investigation into the long-term impacts of replanting practices and the development of innovative technologies to support these efforts.

Future research could explore the implementation of mixed-species plantations or the introduction of nitrogen-fixing species to improve soil quality and nutrient availability (Yao et al., 2023; Xu et al., 2022). Such practices could mitigate the negative impacts of monoculture eucalyptus planting and promote a more resilient ecosystem. Future studies could investigate the long-term effects of these practices on both water conservation and plantation yields, providing valuable insights for sustainable management. Future research could focus on the ecological benefits of such practices, assessing their effectiveness in enhancing biodiversity and ecosystem services.

Future studies could evaluate the effectiveness of these policies in real-world scenarios, providing evidence-based recommendations for sustainable forestry practices.

CONCLUSIONS

This study conducts an extensive bibliometric analysis to evaluate the progression of research in Eucalyptus replanting. By providing a comprehensive overview of the current state of knowledge, the study identifies key trends, influential authors, and significant research clusters. The findings underscore the critical necessity of optimized replanting strategies, particularly the timing of replanting and the application of balanced fertilization techniques. Timely replanting is essential to reduce competition among seedlings and ensure uniform growth, while delays can significantly diminish plantation productivity. Although complementary fertilization may enhance initial growth, its long-term benefits remain uncertain and warrant further investigation.

The research fills critical gaps in understanding the ecological and management dynamics of Eucalyptus plantations. It emphasizes the need for integrated approaches that combine traditional silvicultural practices with contemporary technologies, highlighting future directions for improving replanting strategies. This study opens numerous prospects for future exploration, particularly in soil dynamics, water-use efficiency, and biodiversity conservation. Continued investigation in these areas will be essential for developing sustainable Eucalyptus replanting strategies that benefit both the environment and local economies.

The practical implications of optimized Eucalyptus replanting strategies are multifaceted, encompassing enhanced plantation management, informed policy development, and significant ecological and economic benefits. By focusing on sustainable practices, stakeholders can ensure that Eucalyptus replanting contributes positively to both environmental health and local economies.

This research lays the groundwork for future studies aimed at optimizing plantation management practices to enhance productivity and sustainability. The insights gained are invaluable for researchers dedicated to developing and implementing more effective and sustainable practices for Eucalyptus replantation. The growing body of literature and increasing interest in this field signal the potential for further significant advancements, ultimately supporting broader environmental and economic objectives.

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