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Bibliometric survey of forest biomass for Eucalyptus in Brazil

Anny Francielly Ataide Gonçalves[1], Luciano Cavalcante de Jesus França[2,*], Isáira Leite e Lopes[1], Juscelina Arcanjo dos Santos[3], Lorena Oliveira Barbosa[1], Otavio Camargo Campoe[1], José Roberto Soares Scolforo[2]

Abstract
Forest biomass use provides opportunities for implementing strategies to reduce greenhouse gas emissions and global temperature due to its key role in the world carbon cycle. Therefore, this study aimed to provide an overview of advances in forest biomass by focusing on bibliometric analysis. This analysis identified the research fronts involving relationships of forest biomass from the genus Eucalyptus and Corymbia in Brazil. Three hundred thirty-nine publications came from the metadata of scientific articles collected in the Web of Science index. Data processing was performed using the Bibliometrix package in Rstudio. After the selection stage, the analysis yielded 116 articles published in 45 journals and 561 authors. There has been an increasing trend in publications over these years, with a peak of publications in 2020. The Brazilian researcher Jose Luiz Stape (14 publications, h-index:12) stood out with the highest number and the most cited on this topic, followed by the Frenchs (Yann Pierre Nouvellon and Guerric Le Maire). Brazilian authors showed great scientific interest in this topic, which has also been attractive internationally. Our findings revealed gaps in specialized themes in this research line. Therefore, researchers can use these insights to direct new academic research by deepening knowledge in this subject.

Keywords
Carbon — *Eucalyptus* — *Corymbia* — Forest production

[1] *Department of Forest Science, Federal University of Lavras (UFLA), Lavras, Minas Gerais, Brazil*
[2] *Institute of Agricultural Sciences, Federal University of Uberlândia (UFU), Monte Carmelo, Minas Gerais, Brazil*
[3] *Department of Forestry Engineering, University of Brasilia (UNB)*
*__Corresponding author__: luciano.franca@ufu.br

1. Introduction

Population growth and economic development have resulted in a significant increase in energy consumption, mainly due to its indispensability to human activities, which can range from primary and primordial uses (such as food preparation) to advanced and technological uses (high-tech industries) (Ahorsu, Medina, and Constantí 2018; Silva et al. 2018). The world scenario has moved from a historical context of high dependence on fossil fuels towards incorporating alternative and renewable energy sources to diversify the energy matrix. Advances in the development of renewable energies have been encouraged by the growing worldwide concern about energy security and climate change caused by greenhouse gas emissions inherent to the consumption of fossil fuels (Atashbar et al. 2016). Biofuels from biomass have played a key role as one of the leading renewable energy sources globally (Atashbar et al. 2016; Teixeira et al. 2018). The use of plant biomass can adopt strategies to reduce greenhouse gas emissions (Brahma et al. 2021; Santos et al. 2017; Welfle 2017).

Although 2020 was an atypical year with the emergence of the global pandemic caused by the SARS-CoV-2 coronavirus (COVID-19), there was a 2% reduction in the Brazilian domestic energy supply compared to 2019. However, the increase in the supply of biomass associated with reducing the supply of non-renewable energy sources has given Brazil a leading position worldwide, with 48% of the Brazilian energy matrix being from renewable energy (EPE 2021). Compared to other countries, this competitive advantage of Brazil is due to its natural and geographic conditions and wide territorial extension in terms of arable area with soil and climatic characteristics suitable for agricultural activity. In this way, the internal production of biomass is highly linked to the integrated systems of farming, agro-industrial, and silvicultural production (Santos et al. 2017).

Biomass of forest origin comes from forest plantations exclusively for energy use or residues from the productive sector. The use of wood as an energy source in Brazil is

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favored by the high forest productivity of its silvicultural sector. This is because forest plantations in Brazil are commonly carried out with species of the genus *Eucalyptus* and *Corymbia*, which have the highest rates of the mean annual increment (MAI) of wood volume (m^3 ha^{-1} $year^{-1}$) in a reduced period of forest rotation (Silva et al. 2018; Simioni et al. 2018a). Planting clones of these forest species in Brazil results in the highest growth rates in the world, with around 25 Mg ha^{-1} yr^{-1} (50 m^3 ha^{-1} yr^{-1}) (Campoe et al. 2013). The planting of these species represents 77% of the planted forests in the country (i.e., 10,2 million ha) (IBÁ 2024). However, efforts are still needed to improve biomass and carbon estimation in these forest plantations in Brazil (Sanquetta et al., 2018). The critical point that has aroused scientific interest integrates the generation of reliable information from the forest inventory, accurate monitoring of aboveground forest biomass production, and understanding of the role of forests as sinks or sources of atmospheric carbon (Timothy et al. 2016). Using reliable and up-to-date data is strategically valuable for adopting public policies that subsidize investments in the forest sector and also contribute to directing the necessary actions related to the issue of climate change (Sanquetta et al., 2018).

Therefore, the contextualization of state-of-the-art to future directions regarding the progress of scientific research on forest biomass has national and global relevance, and bibliometrics is a justifiable analysis. Bibliometric analysis is based on the statistics and dynamics of literature data, revealing trends and research patterns on the respective topic (Shi et al. 2021). This analysis has been an essential tool in the scientific understanding of numerous forest science topics, such as the use of process-based models (Gonçalves et al. 2021), artificial neural networks applied to biometrics and forest modeling (Chiarello et al. 2019), non-timber forest products in Brazil (Silva et al. 2020), carbon sequestration on a global scale (Huang et al. 2020), forest fires in tropical forests (Juárez-Orozco et al. 2017), among others. The absence of a consolidated and systematic view on the main research fronts, influential authors, trends and thematic gaps in scientific publications involving Eucalyptus and Corymbia forest biomass in Brazil.

The critical question for the development of this study focused on providing an overview of scientific advances in forest biomass in Brazil and insights concerning the challenges and opportunities in this line of research.

The demand for forest biomass as an alternative energy source has significantly increased in recent years, mainly due to the ability of tree species to capture and store greenhouse gases and reduce the emission of pollutants from fossil sources (Sanquetta et al. 2014; Sereghetti et al. 2015). This demand contributes to expanding planted forests, especially fast-growing species that adapt well to different climates and soil conditions (Nardini et al. 2020; Stape et al. 2010). The main species used worldwide in the production of forest biomass for energy purposes are gum tree (*Eucalyptus* sp.), willow (*Salix* spp.), and poplar (*Populus* spp.) In Brazil, *Eucalyptus* has stood out for having desirable characteristics, excellent adaptation to different country regions, and high wood productivity (Stape et al. 2010).

According to Pérez et al. (2011), the final yield is one of the main parameters influencing the choice of energetic tree species. This yield is the result of the interaction of two types of variables: i) variables related to biomass production per species and hectare in short harvesting periods and ii) variables related to the calorific value of the different parts of the plant biomass, namely the specific energy of tree crop (kJ kg^1).

Several studies have been conducted to analyze the forest species with the highest energy potential (Pérez et al. 2011; Silva et al. 2015). Eucalyptus plantations represent most of the planted areas in Brazil (IBÁ 2021). These forests conserve biodiversity and reduce greenhouse gas emissions from carbon storage. The carbon captured from the atmosphere by photosynthesis by plants is transformed into biomass. Estimates indicate that the 9 million hectares of planted trees store approximately 1.88 billion tons of CO_2 equivalent (IBÁ 2020).

Biomass is one of the most promising strategies for renewable energy generation, mainly through residues generated in other transformation processes (Guerra et al. 2015; Lopes et al. 2016). Forest biomass production also contributes to generating employment and income in Brazil, promoting the development and improvement of the population's well-being (Cambero and Sowlati 2014) and reducing deforestation(Simioni et al. 2018b). The proportion of cultivated wood to the total production of forest extraction increased from 17% in 1990 to more than 68% in 2016, while charcoal from planted forests increased from 40% to more than 90% in this period (IBGE 2017). Understanding the potential of tree species for biomass production, opportunities, and bottlenecks is essential for the country's economic, social, and environmental development; therefore, this research is relevant for the forestry sector.

The bibliometric study is one of the most appropriate methods to measure and analyze the evolution of scientific production in a given area of knowledge. Bibliometrics is a statistical analysis of articles, books, and other technical-scientific publications (OECD 2018). The statistical data produced through these analyses measure the contribution of scientific knowledge derived from publications in a given area of research. This data can represent current research trends and identify topics for

future research (Soares et al. 2016).

The bibliometric approach adopts three types of bibliometric indicators: (i) quantitative indicators (measure the productivity of a particular researcher or research group); (ii) qualitative indicators (measure the performance of scientific production of a particular researcher or research group); and (iii) structural indicators (measure the connections between publications, authors, and research areas) (Biancolillo et al. 2020). The methodology used for this analysis is considered practical and flexible and can be applied to different studies (Silva, Hayashi, and Hayashi 2011).

Some bibliometric methods and tools can be used to analyze scientific publications in the most diverse research areas. These methods have proved to be exciting and powerful tools that help researchers and universities assess trends, gaps, and research directions in a given area of knowledge (Arfaoui et al., In the forestry sector, numerous scientific studies have been carried out using bibliometric tools, such as research with biochar (Li et al. 2019), forest bioeconomy (Biancolillo et al. 2020), forest biometrics (Chiarello et al. 2019), forest carbon sequestration (Huang et al. 2020), and models based on processes used in forestry research (Gonçalves et al. 2021).

2. Material and Methods

Bibliometric analysis was used to evaluate the theoretical and methodological development over the years and to identify the research fronts that study the relationships of forest biomass from productive matrices of the genus Eucalyptus sp *Corymbia* spp. in Brazilian plantations. For this purpose, the metadata of research articles indexed in the Web of Science database (WoS, core collection) was collected in this study.

Subsequently, the software R version 4.1.0 (R Core Team 2021) was used to access the bibliometric library and its web interface entitled bibliophily App (Aria & Cuccurullo 2017), which facilitates the use and processing of scientometric and bibliometric analyzes by users who do not have a more excellent knowledge of programming language. The methodological development proposed by Jin et al. (2018) and Gonçalves et al. (2021) was followed. Metadata information was collected from a total of 339 publications (335 scientific articles and four review papers), following the selection criteria shown in Table 1.

English was the predominant language (288), followed by Portuguese (48), Finnish (1), French (1), and Spanish (1). The metadata format of the selected files was BibTeX (.bib), which was later converted into an Excel spreadsheet (.xlsx). The lower limit (Table 1) was not predetermined; we used the WoS indexer's standard limit (1945), while the upper limit refers to articles indexed until July 31, 2021.

Table 1. Description of the information used in the survey of the publications' metadata in the Wos indexer.

Fonte dos dados	WoS
Keywords used	("Forest biomass" AND Brazil OR Brasil) AND (Eucalypt OR Eucalyptus OR Eucalipto OR Corymbia)
Types of documents	Articles and review articles
Languages	All languages
Complete turnaround time for articles	1998 to 2021
Response time after the article's selection	2008 to 2021

The "abstract screening" technique (Shonhe 2020), which consists of reading the abstracts of each article, was applied, which helps in the reliability of the results obtained in the development of this research. This technique validates all articles that fit the thematic area of the research and excludes from the database all articles incompatible with the theme under analysis. After reading the articles' abstracts, we analyzed a set of 116 articles, and the other articles were unrelated to this research's thematic area. The following analyses using the articles' metadata were performed: (i) quantitative analysis of the temporal scientific production; (ii) identification of the most productive journals on the thematic area of this research; (iii) more productive authors with higher h-index; (iv) geographic analysis of the studies; (v) analysis of co-authorship between authors; and (vi) co-occurrence and cluster analysis of keywords.

To prepare the methodological flowchart, identification, screening and inclusion, the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocol was used (Figure 1).

3. Result and Discussion

3.1 General description

The search resulted in the selection of 116 articles published in 45 different journal sources, accounting for the involvement of 561 authors/researchers. Among these articles, only 1 article was authored individually, and after using the abstract screening technique, the literature review works were not selected for this thematic area of study. The average collaboration index calculated was 4.87 authors per scientific article (Table 2).

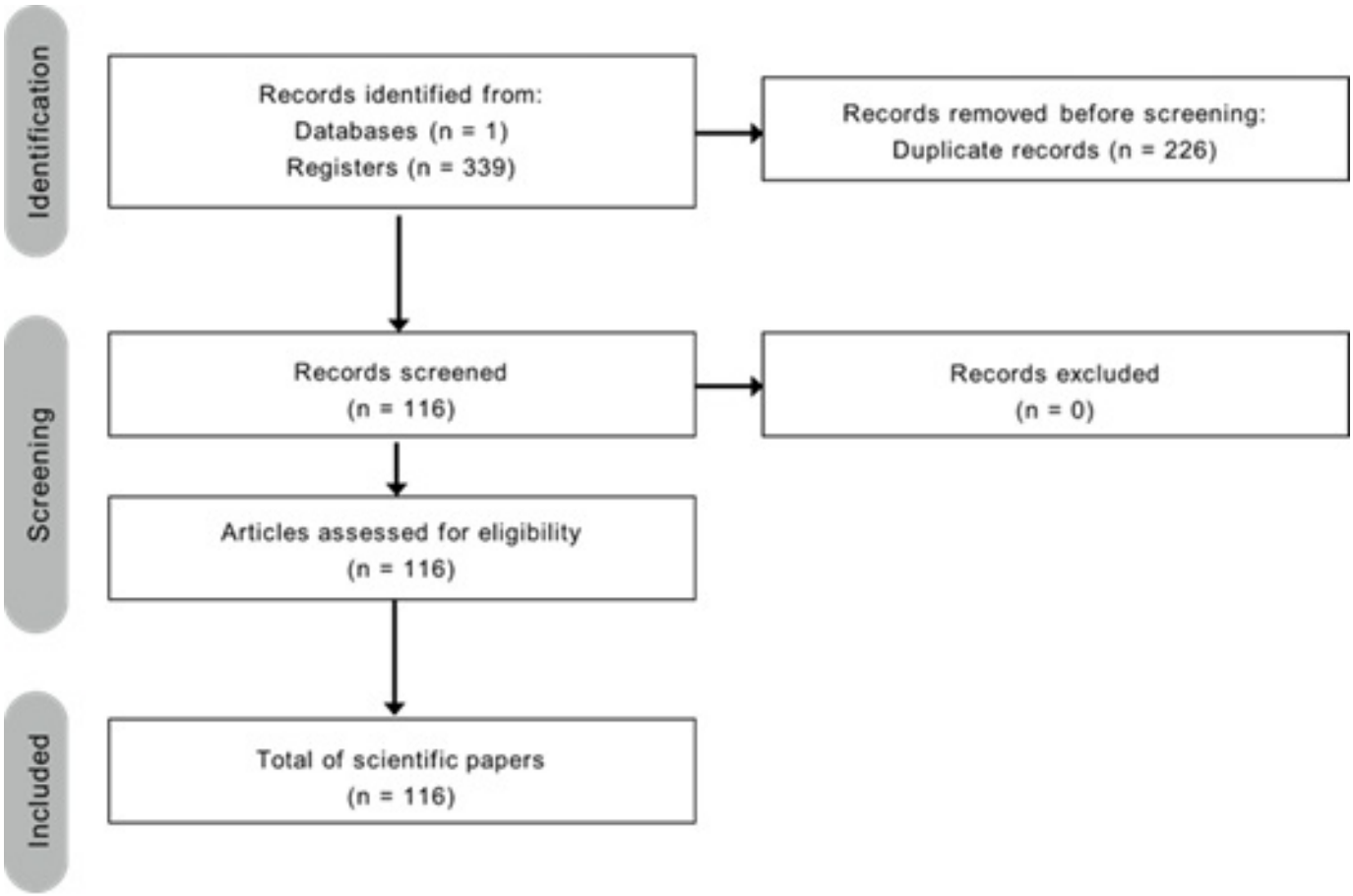

Figure 1. Methodological flowchart of the steps implemented in the study.

3.2 Temporal analysis of scientific production

In general, there was an increasing trend in the number of publications over the years. The most significant number of publications occurred in 2020, with a total of 20 publications (Figure 2). The first three research records investigated Eucalyptus sp. and Corymbia spp forest biomass. Plantations in Brazil took place in 2008 and were published by Ceccon (2008), Lupatini et al. (2008), and Silva et al. (2008).

The subjects addressed in this thematic area were vast and applicable to different areas of scientific knowledge. While the study by Lupatini et al. (2008) investigated the effect of ectomycorrhizal fungi on the growth of *Eucalyptus* spp. in Brazil, research carried out by Silva et al. (2008) investigated volumetric prediction and carbon stock in eucalyptus tree plantations. In turn, Ceccon (2008) evaluated forest biomass production in agroforestry systems that use eucalyptus trees for bioenergy production.

This trend of the annual increase in the scientific production of investigations on biomass from planted forests in Brazil is related to the rise in the use of forest by-products, especially for bioenergy purposes. IBÁ's annual report (IBÁ 2024) indicated an increase in electricity generation based on forest biomass, mainly due to the country's start-up of new pulp and paper production units. Bioenergy systems have great potential to replace fossil fuels worldwide because they reduce greenhouse gas emissions (Briones-Hidrovo et al. 2021).

3.3 Analysis of Research Elite Authors

The authors with the most publications on forest biomass in *Eucalyptus* spp. and *Corymbia* spp. Plantations in Brazil over the years are shown in Figure 3. The size of each circle and the intensity of the colors are equivalent to the number of articles published by each author and the total number of citations they have, respectively. Brazilian researcher Jose Luiz Stape (14 publications) is the leader of publications on forest biomass, followed by Yann Pierre Nouvellon (10 publications, French) and Guerric le Maire (9 publications, French).

The scientific production of the most productive au-

Table 2. Main characteristics of the database and synthesis of the bibliometric survey.

Information	Result
Journals	45
Plus keywords[1]	395
Authors' keywords[2]	440
Return period for articles	2008 – 2021
Average citations per article	11,26
Authors	561
Documents by Author	0,207
Authors per article	4,84
Co-authors per article	6,08
Collaboration Index	4,87
Articles	116
Review	0

[1,2] 'Authors keywords' are words or phrases submitted by authors to provide the exact idea of the article, while 'plus keywords' are words or phrases that often appear in the titles of an article's references but not necessarily in the article title (Jamali et al. 2015).

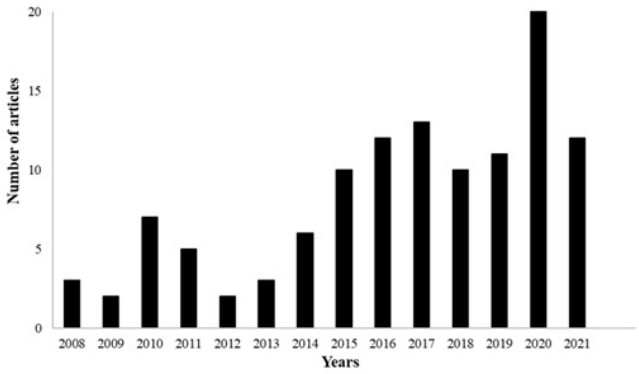

Figure 2. Distribution of annual scientific publications related to the study of forest biomass in Eucalyptus and Corymbia plantations in Brazil.

thors in this thematic area of forest biomass has had greater emphasis since 2010, as can be seen in Figure 2. The highest number of publications over the years is also observed for less productive authors; however, this increase is more evident in recent years, demonstrating the relevance of studies related to some degree to forest biomass in *Eucalyptus* spp. and *Corymbia* spp. Plantations. In addition, such evidence reinforces that the topic has drawn the attention of many researchers and

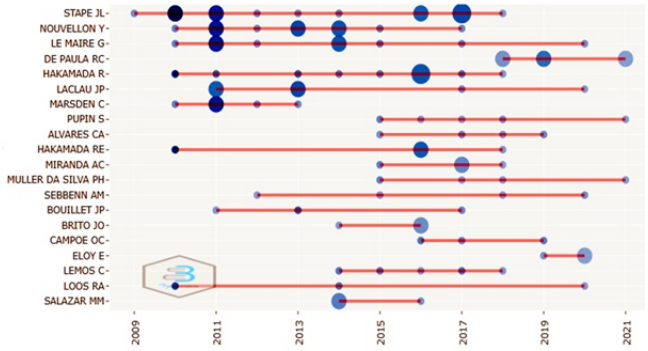

Figure 3. Research elite (y-axis) with their respective numbers of publications over the years (x-axis).

that it is not a topic of occasional occurrence in scientific research.

Another fundamental analysis developed in this study is the evaluation of the h-index of publications. The h-index is an index that combines the number of publications and the number of citations of a given scientific article or researcher, and this index was developed by Hirsch (2005) (Figure 4). The researcher's Stape JL (h-index: 12), Nouvellon YP (h-index: 10), and Guerric le Maire (h-index: 10) are, respectively, the most cited and are the three authors who published the most articles on the topic of forest biomass (Figure 3). This analysis confirms the relevance of the research published by these researchers. The h-index is an efficient metric to assess whether the most productive authors generate productions with a more significant scientific impact. The number of publications and the impact of publications are considered when calculating the h-index. Still, the number of publications is critical, as it is the maximum h-index an author can obtain (Costas and Bordons, 2007).

3.4 Authors' affiliations

Among the 20 primary affiliations of the authors presented in Figure 5, the role of Brazilian universities stands out. UNESP and USP are public institutions in São Paulo, and UFV and UFLA are in Minas Gerais. These states also have Brazil's largest eucalyptus planted area, with approximately 3,136,230 hectares (IBÁ 2020; IBGE 2020). These universities also stand out for their traditional teaching of forest sciences, which helps explain this greater relevance in publications on forest biomass in *Eucalyptus* spp. and *Corymbia* spp. Plantations.

3.5 Corresponding authors' countries

Even if the research is limited to Brazilian territory, we can observe an international interest in studying and

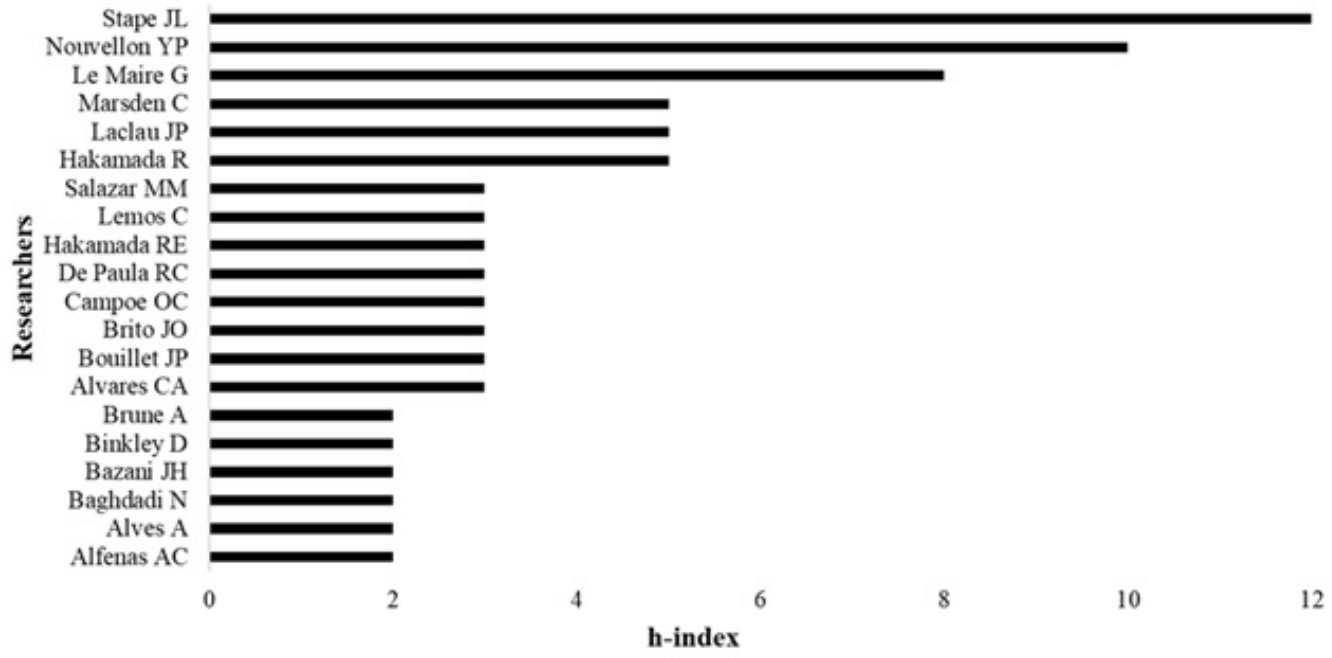

Figure 4. Distribution of h-index by researchers (h-index regarding the publications analyzed.

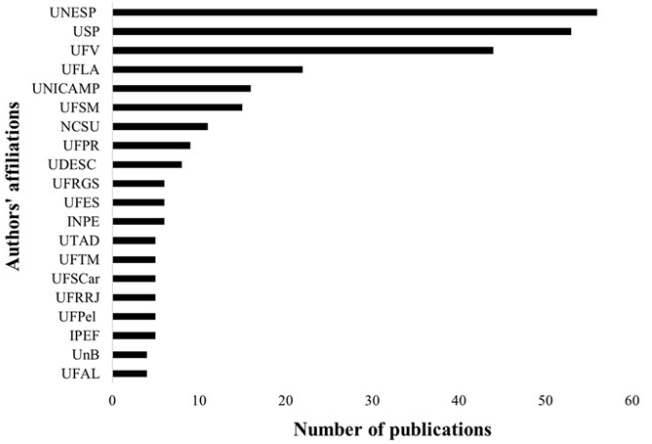

Figure 5. Distribution of authors' affiliations and the number of publications.

understanding the productive behavior of Eucalyptus and Corymbia forest biomass in Brazil (Figure 6): planted forests, especially those established with *Eucalyptus* spp. Trees comprise a relatively large portion of the world economy (Hakamada et al. 2017).

The adoption of good management practices, genetic improvement, and the edaphoclimatic conditions in Brazil led to the worldwide recognition of the high Brazilian productivity, compared to other countries, considering the volume of wood produced per area per year and for having one of the minor cycles between planting and harvesting the world. In 2020, Brazil had an average productivity of 38.6 m^3/ha per year in eucalyptus plantations (IBÁ 2021).

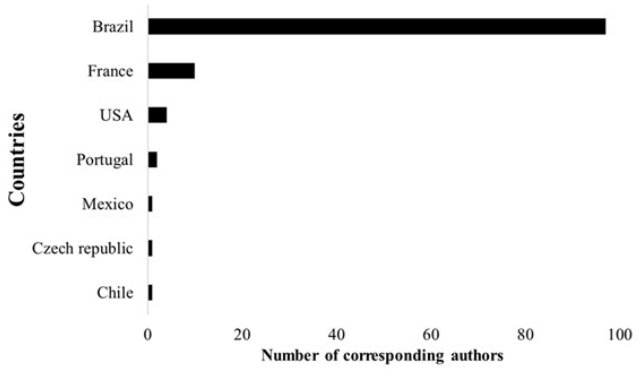

Figure 6. Analysis of the nationality of the corresponding authors in the analyzed articles.

3.6 Authors' Collaboration Network

The collaboration network analysis shows the grouping of the principal authors into seven groups, with each node within the network representing an author and the link between these nodes representing the collaboration between the authors. Such inference reports a co-

authorship relationship between two nodes in order n. The size of each node represents the frequency of collaboration between researchers.

In the cluster in red (Figure 7), we observe the three primary authors with the highest number of publications, the researchers Jose Luiz Stape, Yann Pierre Nouvellon, and Guerric le Maire, who have a solid international contribution network. There is a connection between this group and the pink group, whose primary author is researcher Rodrigo Hakamada. This shows that the relevance of your research group's publications attracts partnerships with other researchers interested in the same topic and who, until then, belonged to another contribution network. The other blue, lilac, orange, and green groups produce separately among their authors without necessarily connecting and collaborating with the different groups. Tracking the principal authors of a given area of research and the relationships between them is an efficient way to understand the productivity and collaboration of authors and research groups (Hissi, 2021).

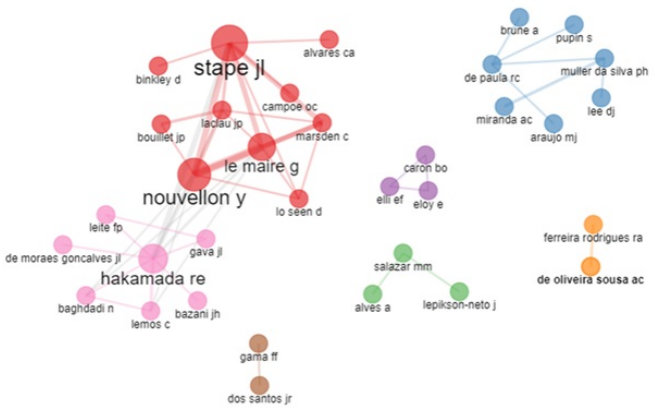

Figure 7. Visualization network based on the co-authorship relation of bibliographic data between authors.

3.7 Keywords and Topics

The co-occurrence analysis of the keywords that stood out the most among the authors is shown in Figure 8. It should be noted that this type of analysis serves to highlight research topics that are on the rise among researchers. Thus, it represents the most discussed topics within a given research area.

The separation of topics by the strategic diagram shows the distribution of the most common topics used in studies on forest biomass in *Eucalyptus* spp. and *Corymbi*a spp. Plantations were divided into four quadrants (Figure 9).

The interpretation of the topic follows the works of Cobo et al. (2011) and Lam-Gordillo, Baring, and Dittmann (2020). Thus, the first quadrant (the upper left) is intended to present highly developed and specialized topics, in which none of the topics were included in this study. This fact may be related to the range of multiple possibilities of research in forest biomass, being it macro representative. This result shows the importance of bibliometric analysis in directing future research strategies on forest biomass to meet the demand for specialization and investigative advances. The lower left quadrant is equivalent to emerging topics, such as *Eucalyptus* spp. and Planted forests, both positively correlated. We find well-developed and essential topics in the upper right quadrant, also called 'engines,' as they are critical for structuring this research area (Eucalypt, Brazil, Soil, Interaction, and Forest Nutrition). The lower right quadrant reports essential but slightly less developed core topics. This group included Plantation, Biomass, Forest, Tree breeding, Forest biomass, and *Eucalyptus*.

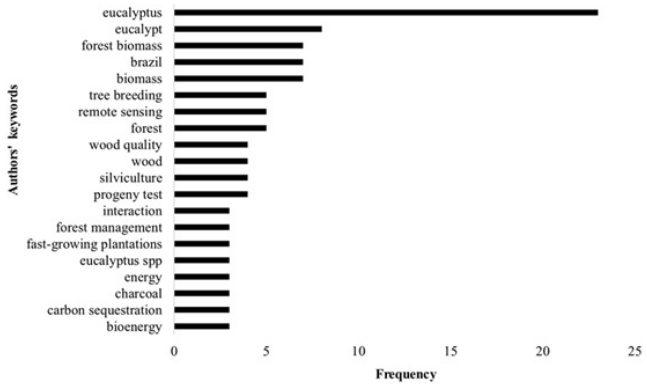

Figure 8. Strategic diagram with the distribution of the most common themes in forestry research that analyze forest biomass in Eucalyptus and Corymbia plantations in Brazil.

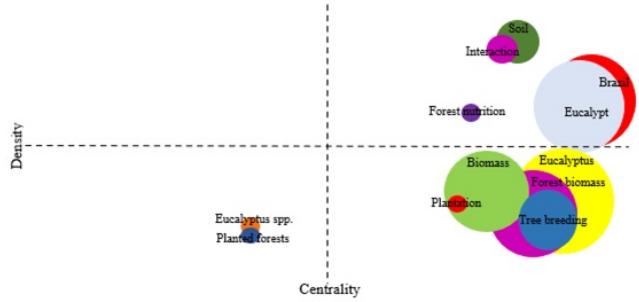

Figure 9. Analysis based on the authors' keywords.

4. Conclusion

Through an extensive bibliometric survey, we report the scientific production in the area of studies on forest biomass in Brazil for statistical characterization of productivity and assessment of challenges and opportunities in this line of scientific research. With an emphasis on the main productive matrices of the genus *Eucalyptus* spp. and *Corymbia* spp. in plantations located in Brazil. It was possible to observe a growing trend in the number of publications over the years, especially with a substantial increase in production in 2020 and the main sets of keywords, authors, institutions, and highlights. In this context, the findings of this study can be used as tools for directing national and international scientific research on the multiple applications of forest biomass from commercial forest plantations.

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Author Statements

✓ No conflicts of interest were declared.

✓ All existing funding sources were acknowledged.

✓ There is no evidence of plagiarism in this article.

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