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Bibliometric Analysis of the Green Gluing Technique (2000–2020): Trends and Perspectives

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Abstract: Wood is a sustainable and renewable material with a lower carbon footprint than other materials. However, its transformation into engineered products industrially, such as glulam, requires kiln drying, which implies energy consumption and loss of wood resources. Recent research has carried out green gluing, a variant of glulam characterized by a reduction of the drying process. Interest in it has increased as a new method of improving the use of wood that does not meet industry standards. It has been accomplished by developing adhesives for wood with high moisture content, but the variables involved are not yet completely understood. Therefore, conducting further research and analyzing the relevant publications is necessary. Bibliometric analysis was the method used, which included documents stored (from 2000 to 2020) in Scopus (Elsevier), Web of Science (Clarivate Analytics), and SciELO Citation Index (Web of Science—Clarivate Analytics) databases. The bibliometric analysis identified three main areas to develop: glue wood, glue properties, and analysis methods. The studies were concentrated on a few countries and research groups. The main progress has been made in synthetic and natural (or environmentally friendly) glue topics. The improvement of technique could enlarge the opportunities for collaboration and innovation in wood material science.

Keywords: bibliometric analysis; glulam; green gluing; sustainability; timber; wood

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1. Introduction

The timber industry is one of the oldest industries in the world. Its development is associated directly with developing countries' economic and social growth, due to the natural resources and territory used to carry it out. The timber industry is experiencing relevant challenges that require developing new techniques and processes. The area that most demands improvement in its performance is the timber harvesting sector, which must balance wood production with sustainability. Due to this, several techniques have been developed to promote wood in construction. The most important technique is glulam, which consists of joining various wood layers using an adhesive.

The glulam technique can be carried out using dry wood or a piece of wood with a moisture content above the Fiber Saturation Point (FSP). Green gluing is a method of gluing unseasoned, freshly sawn timber that has never been dried [1]. It means that the construction of glued laminated timber uses pieces of wood with a high moisture content (or green wood) and an adhesive that works with this level of moisture. Owing to the relevance of the adhesive, some authors mention that green gluing is the development of structural adhesives that can be applied to unseasoned wood above FSP [2]. However, it is necessary to clarify that although developing the green gluing technique required improving several areas, the topic of adhesives was the area that captured attention.

New wood adhesives are continuously being developed and improved, owing to the adhesive bonding quality being strongly influenced by the penetration degree into porous wood [3,4]. One of the most studied adhesives is a synthetic adhesive (one component being polyurethane), which reacts with the water bound to the wood when applied to wet wood, inducing chemical drying. This adhesive is characterized by imparting a lower percentage of wood breakage than other systems, while providing excellent joint strength [5].

In the same way, there is a high tendency to develop environmentally friendly adhesives. This type of adhesive is based on natural compounds, and although the strength of their glue and resistance to water and heat are limited and their periods of application are also short, they meet the requirements of environmental protection and sustainable development [6]. Due to their nature, several types of these adhesives have been developed, such as tannin-based adhesives for the development and industrialization of cold-setting tannin–resorcinol–formaldehyde adhesives for glulam and finger jointing [7,8]. Another area with extensive studies is the lignin-based adhesives, considered a valuable functional raw material. Nevertheless, enhancing performance is a great challenge, because applying significant amounts of lignin to adhesives often reduces the adhesive's performance [9]. To obtain more information, an overview of green adhesives, studies, and methodologies in this field is presented by Moini et al. [10].

The drying process can continue after joining and gluing the pieces of wood of two forms. An option is to dry the wood in the open air without energy consumption, but a disadvantage is the waiting time and uncontrolled conditions of drying. Another option is the kiln-drying process, which can generate internal stresses in the wood pieces, producing defects such as cracks, warps, and fiber collapse if the operational conditions are not appropriate [11]. The use of this technique requires energy consumption. Nevertheless, this process can be done more quickly and efficiently using optimal operational conditions. Industrially, the second option is more often used to reach a moisture content under the FSP.

As mentioned above, green gluing allows for glulam using wood with high moisture content. This situation represents a significant advantage in using the green gluing technique, since it can join pieces of green wood duly prepared without being kiln-dried, as is done traditionally [5,12]. In this form, the pieces of wood that were discarded by the traditional method since greenwood has fewer defects than dried wood, which is close to the FSP, can be used.

Another advantage of green gluing is that it helps dimensionally stabilize the wood [13]. It has become a valuable technique for raw materials typically of lower quality to produce structural elements [4,14]. Different studies in conifer species have shown that the green sizing technique is feasible with moisture contents ranging from 30 to 70%, with an average of 44% [5,15], which contributes to lower energy consumption in wood processing. The technique has also been explored to manufacture plywood with green laminates, demonstrating advantages in evaluating the product's life cycle, due to the lower energy required and the reduction of quality loss [16,17].

The emergent character of green gluing requires an appropriate and critical knowledge of terminology and research groups. In this sense, bibliometric analysis helps decipher and map the cumulative scientific knowledge and evolutionary nuances of well-established fields, by rigorously interpreting large volumes of unstructured data [18]. In recent years, the bibliometric analysis method has been successfully applied to the specific disciplines of engineering and construction, among others, contributing to improving decision-making in the development of each discipline [19–23]. Since the bibliometric analysis summarizes the bibliometric and intellectual structure by analyzing the social and structural relationships among different research constituents [18], this technique provides a comprehensive vision of each discipline and indicates some hot spots in a specific research area.

Bibliometric analysis involves two categories: performance analysis and science mapping. Performance analysis accounts for the contributions of research constituents (e.g., authors, institutions, countries, and journals) and, despite being descriptive, recognizes the importance of different constituents in a research field. On the other hand, science mapping focuses on the relationships among research constituents, which allows for the presentation of the research field's bibliometric and intellectual structures [18]. Both analyses are required to understand the topic under study properly.

This study carried out a bibliometric analysis to identify the actors (researchers and institutions), their level of interaction, and the topics addressed in these investigations related to green gluing. The results will favor research on innovation issues, which guides experiences and allows for reduced development times by finding base variables to continue the explorations in poorly explored areas.

2. Materials and Methods

The bibliometric analysis was limited to the Scopus (Elsevier), Web of Science (Clarivate Analytics), and SciELO Citation Index (Web of Science—Clarivate Analytics) databases. The period of the publications established was from 2000 to 2020. The data were extracted on 5 July 2021. A search strategy was applied to the databases' title, abstract, and keywords fields.

The search strategy included the following descriptors: ((“green glue*” OR “glue* green” OR “green gluing” OR “gluing green” OR “gluing of green” OR “glue* of green” OR “greenwood adhesive*”) AND (*wood OR timber OR lumber OR “finger joint*” OR glulam)). As a result, 77 documents were retrieved with the corresponding bibliographic data, obtaining the following information: Author(s), Document title, Abstract, Index keywords, Source & Document Type, Citation count, and Affiliations. Twenty-five records were excluded because they were not directly related to the field of research “Green gluing”, or lacked the minimum information required to carry out the review, such as not presenting an abstract or being unable to access the full text. Finally, a total of 52 papers were considered for bibliometric analysis.

The bibliometric tools of Clarivate Analytics, Elsevier, and the Centre for Science and Technology Studies (CWTS), such as Web of Science (WoS), Journal Citation Report (JCR), Scopus, and VOSviewer, were used. Each tool contributed specific information to the bibliometric analysis. The Clarivate Analytics tools (Web of Science and JCR) and Elsevier (Scopus) made it possible to determine the impact and productivity of the principal authors, institutions, countries, and documents, according to the following indicators: total papers, times cited, highest quartile, first author, and international collaborations. Additionally, the following metrics provided by the tool were considered: Total Link Strength, Average Citations, Average Publication Year, and Occurrence. The strength of a link indicates that two items (keywords, author, institution, country) are connected, since they appear together in the same document. A positive value represents strength. The higher the value, the stronger the relationship between the two items. Therefore, they are brought together in the same cluster. The Occurrence indicates the number of documents in which an item appears. In this way, a larger circle indicates a more significant presence of the item in the set of documents analyzed. Average Citations and Average Publication Year indicate the average values (citations and year of publication) of a set of documents belonging to a given item.

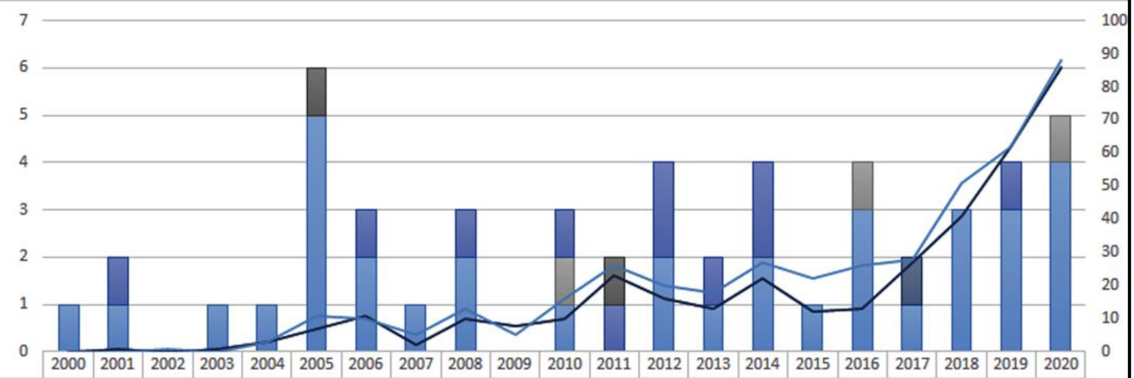
3. Results

This section describes the results of the bibliometric analysis on green gluing of 52 papers published from 2000 to 2020. The results are presented in two sections: bibliometrics analysis and science mapping.

3.1. Bibliometrics Analysis of Research on Green Gluing

3.1.1. Annual Publications

Figure 1 shows the annual distribution of the publications analyzed, classified into the following categories: Article (67%), Review (6%), Conference Paper (21%), Book Chapter (2%), and Editorial Material (4%). There was a sustained and gradual increase in productivity in the thematic field, with 2005 standing out for its high productivity, consisting of five research papers of the Article type and one Editorial Material. The papers published after this date (from 2006 to 2020) correspond to 79% of the production in the studied theme. In addition, this period presents relevant productivity peaks, which double the annual average, equivalent to two publications. These correspond to 2012, 2014, 2016, 2019, and 2020. The impact of citations received in the databases considered is also shown. A similar annual evolution of citations was observed in both WoS and Scopus. These results showed a notorious and growing interest from the specialized scientific community in the last five years, starting in 2016, and reaching 86 and 88 citations in 2020, respectively.



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Editorial Material	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Book Chapter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Conference Paper	0	1	0	0	0	0	1	0	1	0	1	1	2	1	2	0	0	0	0	1	0
Review	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	1
Article	1	1	0	1	1	5	2	1	2	0	1	0	2	1	2	1	3	1	3	3	4
WoS cites	0	1	0	1	3	7	11	2	10	8	10	23	16	13	22	12	13	27	41	62	86
Scopus cites	0	0	1	0	3	11	10	5	13	5	16	26	20	18	27	22	26	28	51	62	88

Figure 1. Annual distribution of papers and the evolution cites from 2000 to 2020.

3.1.2. Leading Publications Contributing to the Research Field

The documents were published in 30 sources, including journals, books, and conference proceedings. Table 1 shows the 10 sources with the highest number of papers published on the subject studied. It can be seen that 80% of these contribute to the OECD No. 2 Engineering and Technology area, allowing the thematic content of the set of documents to be contextualized. Except for the last source, the others have published at least two papers. They are generally located in quartiles (Q) 1 to 3, indicating that they are journals with significant impact, and contribute 62% of the papers retrieved from the period analyzed. In addition, they received 242 citations in Scopus out of 479, corresponding to the total number of papers. According to bibliometric laws, these findings represent the most relevant scientific literature retrieved on the subject (Bradford's law).

On the other hand, there is no clear correlation between the impact of the journal and the number of citations received. For example, the "European Journal of Wood and Wood Products" (Q1) presents eight published papers that have received 64 citations in Scopus, while the "Forest Products Journal" (Q3), with five papers, reports 48 citations in Scopus. Therefore, each published paper should be considered according to its contribution to the scientific field.

Finally, the disaggregation of the topics involved in the studies gives us the first signals of relevant topics to continue working on, such as adhesives, processes, technology, and energy consumed. All of them are related to the improvement of green gluing.

Table 1. Sources with the most significant impact and that publish the most about "Green Gluing".

Ranking	Source Name	Research Area OECD	Total Papers	Highest Quartile	Total Cites	Most Cited Papers
1	European Journal of Wood and Wood Products	Engineering & Technology	8	Q1	64	[24]
2	World Conference on Timber Engineering	Agricultural Sciences	5	N/A	5	[13]
3	Forest Products Journal	Engineering & Technology	5	Q3	48	[25]
4	Wood Material Science and Engineering	Engineering & Technology	3	Q2	30	[5]
5	Journal of Wood Science	Engineering & Technology	2	Q3	0	[26]
6	Rilem Bookseries: Materials and Joints in Timber Structures	Engineering & Technology	2	Q3	8	[27]
7	Journal of Applied Polymer Science	Natural Sciences	2	Q1	29	[28]
8	Bioresources	Engineering & Technology	2	Q2	9	[14]
9	Journal of Cleaner Production	Engineering & Technology	2	Q1	45	[19]
10	ACS Sustainable Chemistry & Engineering	Engineering & Technology	1	Q1	4	[29]

3.1.3. The Leading Country Contributing to the Research Field

Twenty-two countries and 68 organizations were identified as having contributed scientific research on the topic under study. Table 2 presents the ten countries that contributed the highest number of documents. France, China, and the United States are the leading countries, since they concentrate the highest number of citations and their associated institutions, such as the University of Bordeaux, Nanjing Forestry University, and the USA Forest Service. It can also be seen that eight of the ten countries present international collaboration in at least 33% of their papers, indicating that green gluing is a topic of general interest.

Table 2. Countries with the highest productivity in "Green Gluing".

Country	Total Papers	Total Papers (%)	WoS Cites	Scopus Cites	International Collaborations	Organization	Organization Type	References
France	17	33	153	183	47%	University of Bordeaux	Academic	[17]
China	10	19	83	87	70%	Nanjing Forestry University	Academic	[28]
United States	8	15	134	156	50%	USDA Forest Service	Government	[25]
Sweden	7	13	27	36	0%	Linnaeus University	Academic	[4]
South Africa	5	10	26	23	60%	Stellenbosch University	Academic	[30]

Table 2. *Cont.*

Country	Total Papers	Total Papers (%)	WoS Cites	Scopus Cites	International Collaborations	Organization	Organization Type	References
Italy	4	8	38	36	100%	Istituto per la Valorizzazione del Legno e delle Specie Arboree	Research Institute	[14]
Finland	3	6	11	11	33%	VTT	Research Institute	[31]
Greece	2	4	4	13	0%	Technological Education Institute (TEI) of Larissa	Academic	[32]
United Kingdom	2	4	12	10	50%	University of Cambridge	Academic	[33]
Cameroon	2	4	0	0	100%	The University of Yaounde I	Academic	[34]

3.1.4. Principal Authors Contributing to the Research Field

A total of 141 authors were identified who have researched "Green Gluing." Table 3 presents the first ten authors with at least three papers in indexed journals between quartiles 1 to 4. France, Sweden, China, and South Africa were the countries associated with these authors, indicating leadership in the number of publications on Green Gluing. The "First Author" indicator determines an author's position in the list of co-authorships, and is considered a synonym of primary author. Consequently, the authors Pommier, R., Sterley, M., and Na, B. can be considered the leaders in the subject of Green Gluing.

Table 3. Leading authors in "Green Gluing" publication.

Author	Affiliation	Country	Total Papers	WoS Cites	Scopus Cites	First Author	References
Pommier, R.	University of Bordeaux	France	9	19	44	4	[5]
Sterley, M.	SP Technical Research Institute of Sweden	Sweden	7	27	36	5	[15]
Pizzi, A.	University of Lorraine	France	6	131	135	1	[7]
Lu, X.	Nanjing Forestry University	China	5	33	35	0	[28]
Danis, M.	University of Bordeaux	France	4	6	9	0	[35]
Enquist, B.	Linnaeus University	Sweden	4	6	14	0	[27]
Serrano, E.	Linnaeus University	Sweden	4	6	14	2	[13]
Na, B.	Nanjing Forestry University	China	4	30	31	4	[28]
Wessels, C.B.	Stellenbosch University	South Africa	4	26	23	1	[2]
Proller, M.	Stellenbosch University	South Africa	3	14	13	1	[14]

3.1.5. Most Cited Documents

Table 4 presents the ten papers with the highest citations received for the Web of Science and Scopus databases separately. For the documents designed as type Article, it was found that 223 citations have been received in WoS and 249 in Scopus, representing 55% and 52% of the total citations, respectively. One document designed as type Review (Pizzi, 2016) was the document with most citations in both databases for the time of analysis of this study, with a total of 77 citations in WoS and 81 in Scopus. Based on the years of publication of the papers, it is observed that there has been no substantive progress in the area of study, because no continuity was detected in publications with a higher number of citations. It should be noted that the topics evolved from the development of adhesives, moving to energy reduction and then to the product's life cycle.

Table 4. Most cited papers in the discipline.

Document Title	Document Type	Year	Highest Quartile	WoS Cites	Scopus Cites	Source	References
Wood products and green chemistry	Review	2016	Q1	77	81	Annals of Forest Science	[7]
Life-cycle analysis of wood products: Cradle-to-gate LCI of residential wood building materials	Article	2005	Q2	71	100	Wood and Fiber Science	[36]
Reduction of energy consumption of green plywood production by implementing high-efficiency thermal conductive bio-adhesive: Assessment from pilot-scaled application	Article	2019	Q1	28	29	Journal of Cleaner Production	[19]
Durability of one-part polyurethane bonds to wood improved by HMR coupling agent	Article	2000	Q3	27	25	Forest Products Journal	[25]
Comparative wet wood glueing performance of different types of Glulam wood adhesives	Article	2003	Q1	24	23	European Journal of Wood and Wood Products	[24]
One-component polyurethane adhesives for green wood gluing: Structure and temperature-dependent creep	Article	2005	Q1	22	23	Journal of Applied Polymer Science	[28]
Edge and face gluing of green timber using a one-component polyurethane adhesive	Article	2004	Q1	14	13	European Journal of Wood and Wood Products	[15]
LCA (Life Cycle Assessment) of EVP—engineering veneer product: plywood glued using a vacuum moulding technology from green veneers	Article	2016	Q1	13	16	Journal of Cleaner Production	[17]
On the mechanical properties of bovine serum albumin (BSA) adhesives	Article	2008	Q1	12	10	Journal of Materials Science-Materials in Medicine	[33]
The potential of young, green finger-jointed Eucalyptus grandis lumber for roof truss manufacturing	Article	2016	Q2	12	10	Southern Forests	[30]

The documents were published in sources with quartiles between Q1 and Q3. The European Journal of Wood and Wood Products [15,24] and Journal of Cleaner Production [17,19] are highlighted for providing the highest number of critical research articles with the highest impact.

3.2. Science Mapping: Structure of the Research Field

Bibliometric maps are graphic representations of a disciplinary area of knowledge, in which it is possible to identify relationships between the nodes representing the information analyzed [37,38]. They enable a distance-based analysis, where the location of the nodes and their links in a two-dimensional plane indicates the greater or lesser strength of the relationship between them. A node represents the name of an author, institution, country, or word, while a link is a relationship between two nodes, given that they are included in the information of the same papers, for example, two co-authors of a paper or two keywords describing the content of a document.

3.2.1. Main Research Themes: Co-Occurrence of Keywords

According to the literature, keywords are recommended for generating bibliometric maps, allowing recognition of the focus of research in academic articles, since they correspond to indexing terms generated. In addition, they can describe the research better by conceptualizing references that cite a document [23,39–41]. This technique was introduced by Garfield [41], who claimed that it collects a set of mathematical methods and statistics used to analyze and measure publications (i.e., articles, books, and book chapters, among others). It applies statistical methods to establish qualitative and quantitative changes within a given scientific research topic to detect the profile of publications on the topic and pinpoint trends within a discipline.

Analyzing the co-occurrence of terms made it possible to identify those terms used jointly in one or more papers. As a result, 534 keywords were obtained, corresponding to terms reported by the authors and the databases, with at least one occurrence. Normalization was carried out on those incorrectly reported or redundant terms. Figure 2 shows the keywords gathered in three clusters composed of 20 or more keywords each. They are differentiated by color (red, blue, green), showing three thematic clusters predominating in the publications analyzed.

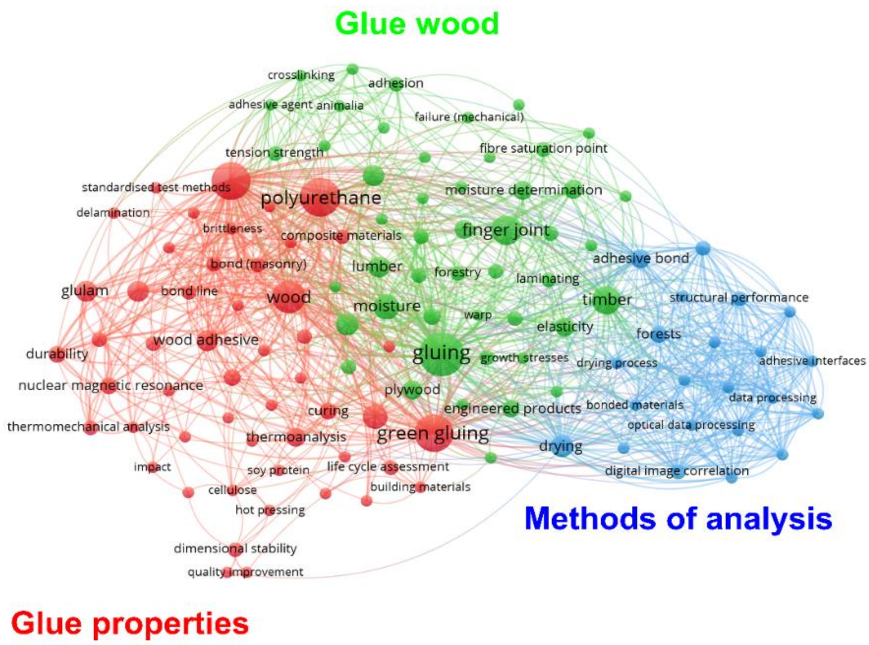


Figure 2. Bibliometric map of keywords consigned in papers on "Green Glued" in network visualization (VOSviewer).

Table 5 presents a selection of keywords with a high value of co-occurrence (equal to or greater than five) or higher, Total Link Strength. This indicator determines the number of links between the nodes of a network. That means that when the number of links is high, there is a high presence of words (node), so this node has a greater weight and strength concerning the network obtained.

Table 5. Top Keywords with the most significant presence in the bibliometric map on "Green Gluing".

Keyword	Occurrences	Total Link Strength	Cluster	Avg. Pub. Year	Avg. Citation
gluing	26	410	2	2012	5
polyurethane	21	262	1	2009	8
adhesives	20	314	1	2013	10
green gluing	20	279	1	2011	6
wood	15	275	1	2011	20
finger joint	12	120	2	2010	5
timber	11	182	2	2010	4
moisture	9	132	2	2011	7
wood products	8	133	1	2016	19
drying	7	128	3	2014	1
strength properties	7	94	2	2011	13
glue	6	112	2	2011	9
wood adhesive	6	102	1	2014	3
lumber	6	91	2	2011	7
strength	6	87	1	2012	7
glulam	6	69	1	2010	6
elasticity	5	101	2	2010	5
adhesive bond	5	93	3	2012	2
plywood	5	87	2	2017	10
thermoanalysis	5	85	1	2018	8

The terms with most citations above average were highlighted. These were wood, wood products, strength properties, adhesives, and plywood predominate, with a value higher than 10 for Average Citation, indicating that they are fundamental for constructing an article. Also, research topics were identified which are trending and have been predominant in the last five years, using the indicator Avg. Pub. Year. The terms "thermoanalysis", "plywood", "wood products", and "drying" stand out.

Moreover, a detailed analysis can be seen in Table 5, with a concatenated development line, with the first topic being adhesives, then species studies, and finally, products obtained from green gluing.

3.2.2. Scientific Collaboration Network (Co-Authorship Analysis): Prominent Investigators

Figure 3 shows the result of the analysis of co-authorship networks of the authors of the analyzed publications differentiated by color. The network indicates several research groups with clear boundaries. Those authors with more co-authorships (link) have a larger size. In this regard, several independent clusters are observed, highlighting those led by Pommier, R. (blue cluster), Sterley, M. (red cluster), and Wessels, C. (green cluster), and three clusters related to each other led by Pizzi, A. (yellow cluster)—Wang, Z. (purple cluster)—Zhang, W. (brown cluster).

A detailed analysis of the annual evolution of co-authorship corresponding to a subsample of authors with at least four publications (high production) is considered in the "Main authors contributing to the research field." Those authors with higher production have a greater weight than the others studied. Thus, 60 nodes were recovered (Figure 3) comprising four differentiated clusters, showing a close collaboration network in the period 2005–2020, according to the indicator of Av. Pub. Year. The lower cluster is led by R. Pommier (France), published around 2015. It should also be noted that they relate to a subcluster led by V. Makomra, a new research group from Cameroon, with a joint publication in 2020 [34].

Regarding the other clusters shown in Figure 4, the one at the top stands out, led by A. Pizzi (Italy), whose network is connected, through X. Lu, with a new research cluster in China [29]. The cluster on the left side of the figure, led by M. Sterley (Sweden), corresponds to a research group that does not maintain international collaboration. Finally, the cluster on the right of the figure stands out, led by C.B. Wessels (South Africa), who maintained a recent collaboration between 2015–2020 with Italian researchers led by M. Nocetti and M. Brunetti.

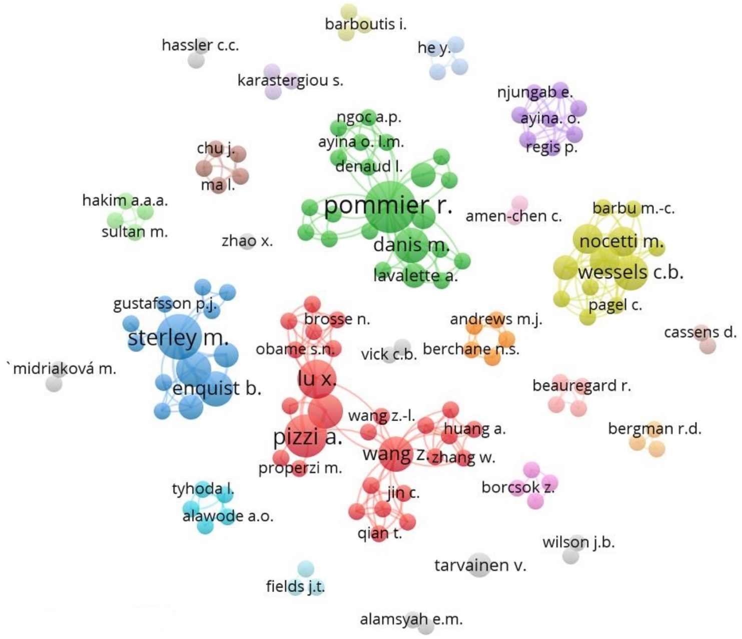


Figure 3. Network of co-authors of researchers in network visualization (VOSviewer).

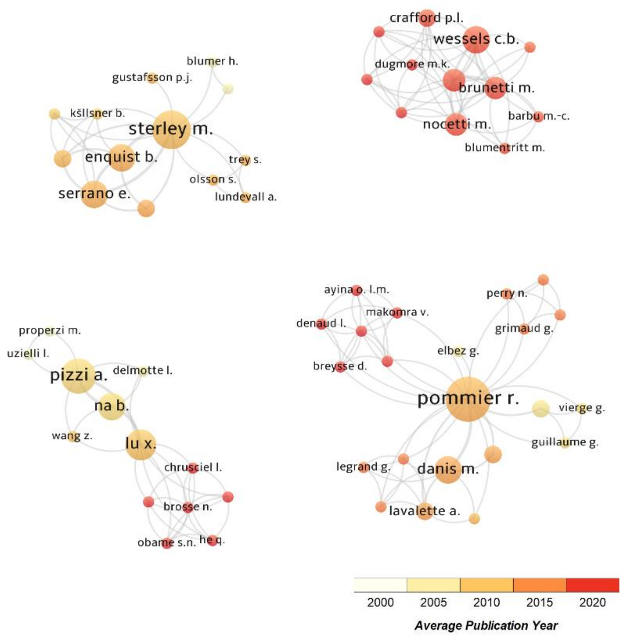


Figure 4. Co-author network of leading researchers in "Green Glued", in overlay visualization (VOSviewer). The timeline accounts for the average publication year of each author through a color scale from 2000 to 2020, where 2020 is represented with the most intense color (red).

3.2.3. Network of Top Countries and Institutions

Figure 5 shows the result of the co-authorship analysis for 22 countries associated with the universe of papers co-authors. Those countries with more associations present a larger node size. Several independent clusters are observed. However, a collaboration network formed by France-China-United States-Italy (central cluster) stands out in the center of the image.

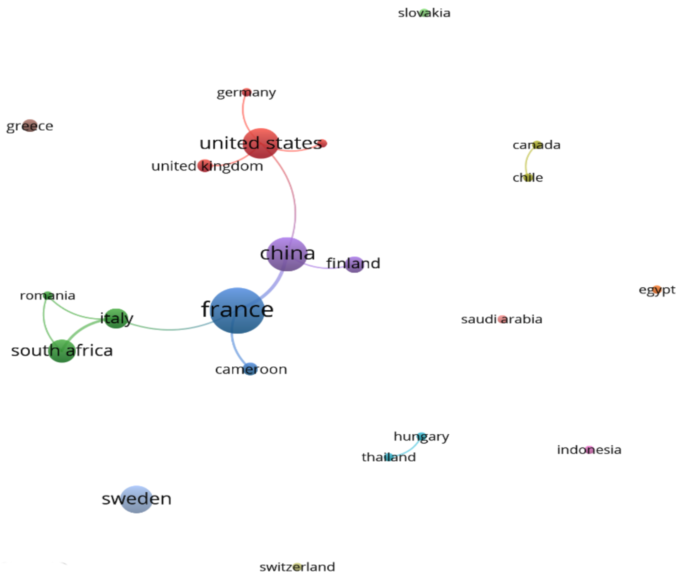


Figure 5. Collaboration network of countries according to papers analyzed in network visualization (VOSviewer).

A focused co-authorship analysis was generated with countries presenting the highest number of published documents, and corresponding to the previously identified leading authors. Figure 6 shows the featured collaboration network between France, China, and Italy [24,28,42,43], who recently collaborated in a 2018 Avg. Pub. the year of 2018, with countries such as Cameroon, South Africa, and Romania.

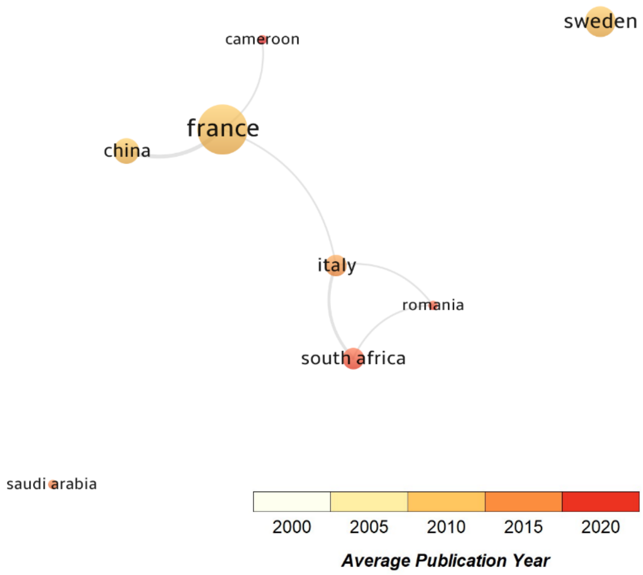


Figure 6. Collaboration network of leading countries in "Green Glued" in overlay visualization (VOSviewer). The timeline accounts for the Average Publication Year of each country through a color scale from 2000 to 2020, where 2020 is represented with the most intense color (red).

A co-authorship analysis of organizations allowed the identification of the most relevant organizations in the network (larger nodes), given the number of links (TLS) reported in the VOSviewer platform. Thus, relevant clusters were observed, for example, Forest products society and VTT Rakennus, who predominate in the graph in Figure 7. However, a network of co-authorizes limited was established for the institutions and nations highlighted in Section 3.1.3.

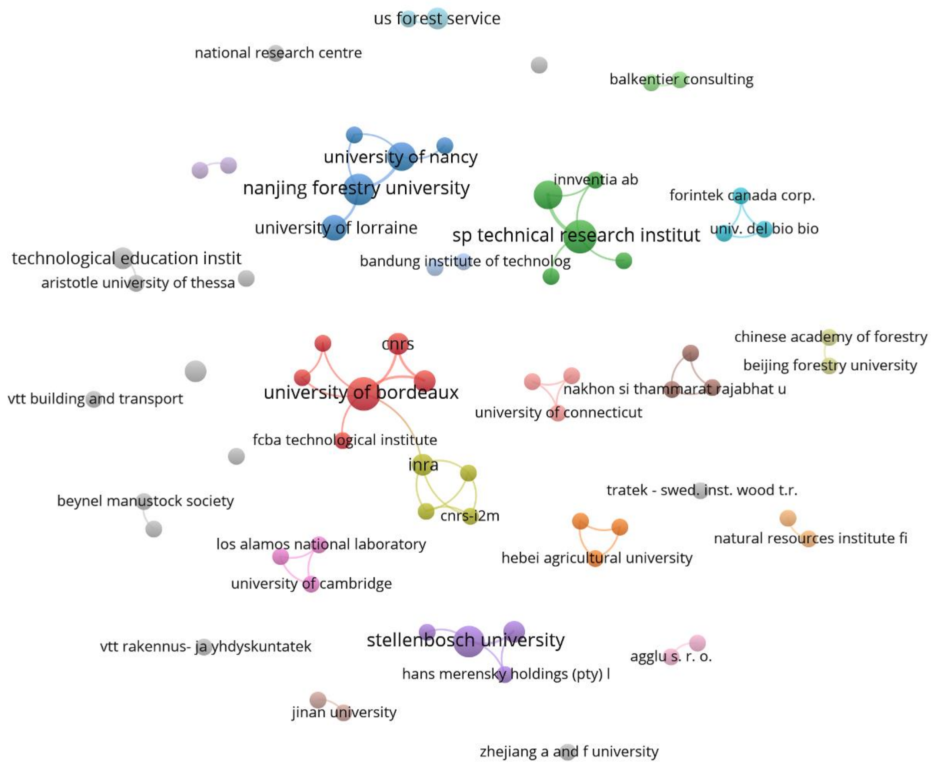


Figure 7. Analysis of co-authorship of institutions in network visualization (VOSviewer).

3.3. Qualitative Interpretation—Identification and Interpretation of Clusters

Figure 2 shows the interrelation among the keywords considered in the bibliometric analysis. The appearance of the net is like a cloud or ball of wool, where the different keywords are related within one of them. The closeness between the clusters suggests that the topics addressed in this literature review partially overlap, even though they provide different concepts and approaches to green gluing. Nevertheless, it is possible to identify three clusters involving three relevant topics: glue of wood, analysis methods, and glue properties. The decision to maintain the original number of clusters was consistent with our purpose of discovering the areas of interest in order to discuss the possible future heat points in this study field.

Researcher co-authorship networks shown in Figures 3 and 4 reveal a reduced number of research groups, where the expertise area and location could have allowed network development or collaboration.

4. Discussion

The bibliometric analysis of the last twenty years of research into green gluing is shown in this work. The bibliometric analysis showed an increment of interest in green gluing topics, which is reflected in the growing number of citations, as Figure 1 showed. This increment in interest can be attributed to the effort of the industry and market to be sustainable.

Moreover, the bibliometric analysis revealed that the topics related to glue wood, glue properties, and methods of analysis are the areas most developed (Figure 2). These results are expected, particularly given the importance of glue in carrying out the green gluing technique. However, it should be mentioned that the green gluing technique involves topics other than glue.

The analysis of the clusters found in this research can be segregated into the following form: (i) Glue wood: refers to products and construction obtained using the green gluing technique. (ii) Glue properties: this cluster involves green adhesive (sustainable adhesives, environmentally friendly adhesive, or natural adhesive) and synthetic adhesive used to develop the green gluing technique. This field has more research due to a continuous search to improve the modification process and reduce costs [6]. As was mentioned, the development began by using adhesive with a synthetic composition base, as one component of polyurethane adhesive [24], moving to an eco-friendlier adhesive with a base of lignocellulose [44] and other compounds. (iii) Methods of analysis: this cluster is associated with the method of drying and pressing the different types of wood. The improvement in this area has relevance to the industry since, during the drying process, it can create defects, with arguably the highest value implications [2].

A global analysis of results suggests that the research requires a multidisciplinary group. This situation could create difficulty in developing green gluing, since professionals in different areas such as chemical, material, and construction must have a common language to present a global result with different points of view on how or what to resolve first.

A critical point about common language was detected from the bibliometric analysis. The results revealed a strong need to define and distinguish the concepts related to green gluing, such as differentiating between sustainable adhesives and greenwood glued. These considerations were relevant in the bibliometric analysis because it was necessary to increase the filters applied, since its success depends on a specific word or concept. At the same time, the combination of words is not initially associated with a clear concept because there are no precise term definitions, as mentioned above. This difficulty was approached by unifying terms in this work, with the final purpose of correcting and avoiding bad assignments. A wider redefinition of the green gluing term could probably be an excellent proposal to consider, owing to the multifactorial components of the technique. The new definition could incorporate the green adhesive and join with the high moisture content. The points mentioned become relevant when considering the results of Sterley et al., where different parameters affect an appropriate green gluing technique [4]. An incorrect concept will create confusion and hinder the research. Under those circumstances, a high reduction of documents after applying all the filters occurred. Finally, 52 of 77 documents were assigned as related to green gluing in this work, owing to this situation.

Considering the above could explain why the articles of Puettmann and Wilson [36] and Pizzi [7] are the most cited papers. In these, it is possible to find a clear definition of fundamental concepts and a broad vision of diverse edges of green gluing. Without limiting the preceding, the analysis of the last decade also showed constant work on the topic related to adhesives, showing a high number of occurrences and Avg. Citation, as is seen in Table 5. The continuous work indicates the relevance of this area in developing green gluing. Other components were studied, such as wood characteristics and the influence of moisture content [4,15], as described in Table 5.

On the other hand, the bibliometric review identified a limited amount of literature and knowledge on green gluing, focusing on productive wood countries. The hub of collaborative networks on green gluing is France, with contacts with China, Italy, and Cameroon. These results are detailed in Table 2, where the France percentage of participation reached 28% approximately. It should be mentioned that the total paper summation was higher than 52, since the articles were developed in collaboration with different institutions, whereby the same article could be counted more than once.

The local regulations and the different uses of wood in structural buildings or as design material probably promote France's high amount of research. The interest in developing green gluing techniques or related topics is probably associated with searching for the increase in the value of various quality woods, considering the high market that could cover. In the same way, the countries where the wood industry has a strong presence have developed green gluing to improve energy conservation, focusing on reducing the energy of drying processes and production energy, as Puettmann et al. [36] mentioned.

The interest in green gluing has increased since 2016, when many citations were counted (Figure 1). Probably, environmental and energetic issues have given an impulse to the interest in green gluing. As was mentioned, the green gluing technique has also been explored in the manufacture of plywood with green laminates, which has shown advantages in the product's life cycle assessment, owing to its lower energy requirement and less quality loss [16,17].

Despite specific difficulties, the bibliometric analysis identifies the critical aspect of the green gluing study. Such information having been provided, we can begin from a good starting point to plan the experimental design and, at the same time, to find or create networking with the leader of each field that involves green gluing. Furthermore, this type of analysis will facilitate research on innovation issues and reducing development times, by finding essential variables for further assessment.

5. Conclusions

The bibliometric analysis carried out in this work highlighted the relevance of understanding and distinguishing the terms associated with the green gluing technique. Likewise, the technique's development emphasizes an improvement that involves all the components of green gluing, such as green wood, glue properties, and the methodology associated with it. Adhesives and their properties are the most studied, due to their central role in the green gluing technique. Finally, a multidisciplinary research staff could help to achieve the best performance in the green gluing approach.

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