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Analysis of the delignification process influence on the dimensional stability of densified wood: a systematic review

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: One of the challenges in the development of densified wood products is maintaining their dimensional stability. Several treatment methods are employed to achieve this stability, including the delignification process. This paper analyzes the efficiency of the delignification process on the improving of the densified wood dimensional stability through a systematic literature review. This research was based on the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and conducted using Scopus, Web of Science and Google Scholar databases. After the eligibility criteria application and bias analysis, the systematic search sample resulted in 54 articles. The meta-analysis was conducted through a narrative synthesis, including the densification process, wood species, apparent density, delignification process, other wood treatments, and dimensional stability.

Results: The delignification process was used in approximately 26% of the 54 articles analyzed and these numbers occurred after 2018. Of the studies that related dimensional stability to delignification, sodium hydroxide (NaOH) was used as a reagent in 50% of the cases. The combination of NaOH and Na_2SO_3 in the alkaline treatment of wood was the most used (28.5%). The treatments used proved effective in the partial removal of lignin and hemicellulose, improving the dimensional stability of the species analyzed.

Conclusion: The increasing number of publications in China indicates that the Chinese market has a significant demand for densified wood. Although partial removal of lignin and hemicellulose improves the dimensional stability of densified wood, some studies have shown that excessive removal of lignin can negatively impact the mechanical characteristics of the material.

Keywords: Wood densification; wood modification; set-recovery; thickness swelling.

HIGHLIGHTS

Partial lignin and hemicellulose removal enhance impregnation treatment effectiveness.
Studies show that excessive lignin degradation can negatively affect mechanical properties.
Most studies combined NaOH and Na_2SO_3 for the delignification process.
Furfuryl alcohol, tung oil and biochar stands out like stabilization methods.

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INTRODUCTION

One of the challenges in producing densified wood is the loss of densification, which may occur due to the elastic memory of wood components and the interaction of wood with water. This instability manifests through the partial loss of densification and, consequently, the physical and mechanical properties of the material (Pertuzzatti, 2018; Sotayo et al., 2020).

According to Navi and Heger (2004), the elastic recovery of densified wood is primarily caused by the elastic strain energy stored in semicrystalline microfibrils, hemicellulose, and lignin. On the other hand, set-recovery occurs when densified wood is exposed to moisture, leading to reversible and irreversible volume expansion. The reversible swelling is attributed to the hygroscopic nature of wood, while the irreversible swelling is caused by the elastic recovery of the wood structure (Kutnar and Sernek, 2007).

Some techniques are commonly employed to mitigate the elastic recovery of densified wood. Thermal treatment and synthetic polymers (phenol-formaldehyde and epoxy) impregnation like one. However, these techniques may present limitations or impacts, as evidenced by Pelit et al. (2018), where thermally treated densified samples led to a decrease in mechanical properties (MOR and MOE), and according to Karthäuser et al. (2023), the impregnation of wood with petroleum-derived polymers, such as phenol-formaldehyde, results in the release of toxic compounds that pose risks to human health.

Recently, the delignification process before densification has emerged as a promising alternative to enhance the dimensional stability of densified wood (Song et al., 2018). Partial lignin removal facilitates densification at lower pressures, reducing processing costs and minimizing defects (Wang et al., 2021). Furthermore, delignification helps reduce elastic recovery as lignin plays a significant role in the shape-memory mechanism of wood (Song et al., 2018).

The degradation of hemicellulose and the partial depolymerization of lignin can enhance the stabilization of the densified structure. This process reduces the amorphous fraction of wood components, which decreases their hygroscopicity and promotes greater dimensional stability, characterized by lower expansion and contraction due to moisture (Dwianto et al., 1999).

To achieve this, alkaline treatments using NaOH solutions can partially degrade and dissolve hemicellulose, cellulose, and lignin, reducing the amount of these amorphous regions and, consequently, moisture absorption. Thus, alkaline treatment before densification can improve dimensional stability and mitigate the set-recovery effect (Nawawi et al., 2023).

Based on this context, this study presents a systematic literature review analyzing research on the relationship between the delignification process and the dimensional stability of densified wood. The objective is to identify the evolution of studies in terms of volume and geographical distribution and examine the main methods and materials used. The results are also analyzed to support future research aimed at improving the stability of densified wood.

MATERIAL AND METHODS

For this research, a systematic literature review was chosen to ensure the rigorous and impartial collection and analysis of relevant scientific evidence about the theme. The systematic review synthesizes studies using predefined criteria to identify, select, and evaluate methodological quality, guaranteeing reliability in data interpretation. Unlike narrative reviews, the systematic review follows a standardized and transparent protocol, which enhances the reproducibility of the research and minimizes the risk of presumption. Furthermore, the systematic review can include a meta-analysis, which combines the results of multiple studies, increasing statistical power and the accuracy of estimates.

The databases used were Scopus and Web of Science due to their extensive scope and high quality in indexing scientific journals, particularly in forestry and wood science. Web of Science indexes approximately 200 journals in these areas, while Scopus indexes over 300. The selection of these databases ensures the inclusion of high-impact and relevant studies over this research topic.

Additionally, Google Scholar was utilized as a grey literature database to extend the scope of the review and capture studies that may not be indexed in traditional databases. Moreover, Google Scholar covers a substantial amount of academic literature, including theses, dissertations, books and articles published in open-access journals.

To this systematic review, the strategy search was carefully designed to ensure the identification of all relevant studies on the topic. Initially, the following research question was defined:

"Can the delignification process influence on the densified wood dimensional stability?"

Based on the research question, the PICO acronym (Population, Intervention, Comparison, Outcomes) was used to structure the search as follows:

- Population: Densified wood
- Intervention: Delignification process
- Comparison: Compressed wood (or untreated, non-delignified wood)
- Outcomes: Dimensional stability

The PICO acronym definition helped to identify the initial keywords. To complement the keywords, an exploratory search was conducted in the Scopus database using the term "densified wood." This search allowed the identification of synonyms and related terms based on the bibliometric analysis. This strategy was adopted according to the difficulty of finding appropriate terms in specialized thesauruses.

With the keywords and their synonyms defined, the search string construction began combining terms with Boolean operators (OR, AND, and AND NOT). Several combinations were tested until it was obtained a string that returned an initial comprehensive sample, but also specific enough to avoid the inclusion of irrelevant studies.

The search was conducted in May 2024 across the three selected databases, resulting in an initial sample of 459 articles. To refine the search, articles and citations about review were excluded during the initial screening. The search string used, and its construction process are presented in Table 1.

The process of selecting articles, from the initial search to the final sample (Table 1), is demonstrated in the flowchart in Figure 1. The flowchart was developed based on the recommendations PRISMA protocol and supplies a detailed overview of the selection stages, including the number of articles identified in each database, the number of duplicates removed, the inclusion and exclusion criteria applied, and the final number of articles included in the systematic review.

After searching and exporting data to the reference management software Mendeley and Zotero, duplicated articles were removed using Mendeley's duplicate identification feature. This measure ensured that each study was considered only once in the review, avoiding overestimating the sample size and the intention in the results analysis.

Then, a preliminary reading of titles and abstracts of each article was conducted to exclude those not aligned with the scope and research question of this study. This investigation reduced the number of articles for full-text reading, optimizing time and resources. Specific eligibility criteria were defined to guide the selection, as presented in Table 2.

During the selection process, eligibility criteria were developed based on the PICO acronym previously defined. The rigorous application of the eligibility criteria ensured the selection of relevant studies and the focus of this systematic review.

After the selection stage, the final sample consisted of 102 articles. Based on these studies, a scientometric analysis was conducted to identify the main themes and research trends in the field. This analysis considered the frequency and interrelationship of keywords, the number of articles published per year, and the geographical distribution of the studies, providing a comprehensive context for the research.

To assess the methodological quality of the studies and minimize the risk of bias in the systematic review, a bias analysis was conducted for each of the 102 articles. This analysis was based on a questionnaire adapted from the Joanna Briggs Institute, using the checklist for quasi-experimental studies as a reference. The choice of this checklist is justified by the predominantly experimental nature of the studies included in the sample, most of which presented non-random data.

Table 1: Process of defining the search string.

Objective / Problem	**Can the delignification process influence dimensional stability in wood densification?**			
Acronym	**P**	**I**	**C**	**O**
Extraction	densified wood	delignification	compressed wood	dimensional stability
Combination	densified wood; wood densification	delignification; delignificated; delignified wood	compressed wood, mechanical densification	dimensional stability; dimensional stabilization; set recovery; springback
Construction	(“densified wood” OR “wood densification”)	(delignification OR delignificated OR “wood modification” OR lignin)	(“compressed wood” OR “mechanical densification”)	(“dimensional stability” OR “dimensional stabilization OR “set recovery” OR springback)
Use	(“densified wood” OR “wood densification”) OR (delignification OR delignificated OR “delignified wood”) AND (“dimensional stability” OR “dimensional stabilization” OR “set recovery” OR springback OR “wood deformation”) NOT (veneer$ OR “surface densification” OR biomass OR celulose OR feed)			

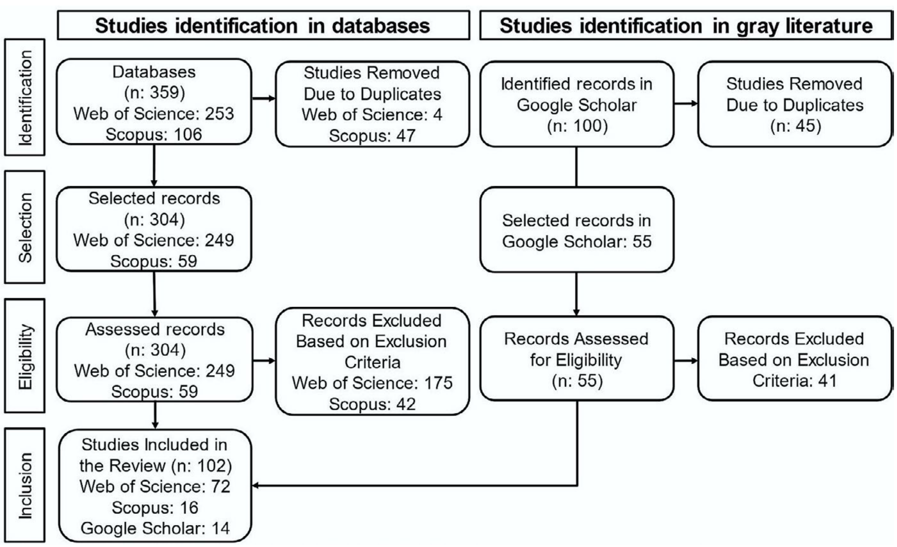

Figure1: Flowchart of the selection, eligibility, and inclusion process of the reviewed studies.

According to Barker et al. (2024), this stage aims to assess whether specific measures have been implemented to minimize the risk of bias and address other factors related to the validity or quality of the articles to be analyzed. In addition, the study exclusion based on critical appraisal assumes that only high-quality studies should be synthesized.

Table 3 presents the questions that guided the bias analysis, each with a maximum score of 10 points. The score assigned to each study reflected its methodological quality and scientific rigor, allowing for a critical evaluation and the identification of potential biases in the results.

The methodological bias analysis was conducted based on a scoring system adapted from the Joanna Briggs Institute and proposed by Stefani et al. (2021). This scoring system, combined with the questions presented in Table 3, allowed the classification of the articles into four categories:
• High quality (score: 10.0): Studies with a robust design, rigorous bias control, and low risk of systematic errors.
• Moderate quality (score: 7.0): Studies with an adequate design but some methodological limitations that may increase the risk of bias.
• Low quality (score: 4.9): Studies with a weak design, high risk of bias, and significant limitations that may compromise the reliability of the results.
• Not applicable (score: 0.0): Studies that do not meet the evaluation criteria or present serious methodological flaws.

At this stage, a cutoff score of 49 points was established. This minimum score ensured that only studies with moderate or high quality were included in the final analysis, minimizing the impact of biases on the systematic review results.

After applying the scoring criteria on the bias analysis, the final sample consisted of 54 articles subjected to data extraction. The following information was collected from each study:
• Year of publication, author(s), and article title;
• Parameters of the densification process: temperature, time, and pressure;
• Degree of compaction achieved;
• Wood species used (common and scientific names);
• Apparent density of the wood before and after densification;
• Description of the delignification process (occurrence, reagents, and methods);
• Results on dimensional stability and other properties;
• Other treatments applied to wood.

The meta-analysis phase, that aims to synthesize the results of the studies included in the systematic review, was conducted through a narrative synthesis. The choice

Table 2: Eligibility criteria.

Inclusion Criteria
Case studies on the densification of solid wood
Research focusing on laboratory tests on the dimensional stability of densified wood
Research that correlates the delignification process of densified wood and dimensional stability
Exclusion Criteria
Research that involves biomass densification studies for fuel production
Research focused on the delignification process for cellulose production
Research focused on densification of other materials (such as bamboo)
Research focused on the densification of wood veneers or surface densification
Research focused on numerical modeling of densified wood data
Research focusing on chemical analysis of the delignification process

Table 3: Bias analysis questionnaire.

Questions	Authorship
Is a relationship established in the study between delignification and the dimensional stability of densified wood?	Adapted from JBI
Did the comparison process, in the case of samples with different species, follow the same test method?	Adapted from JBI
Does the work provide any other analysis of other properties and their influence on the dimensional stability of densified wood?	Adapted from JBI
Are numerical data from laboratory tests presented?	Authors
Does the research analyze other properties such as MOR, MOE, hardness, density?	Authors
Was there a reference sample?	JBI
Were there multiple outcome measurements before and after the intervention/exposure?	JBI
Was follow-up complete and, if not, were differences between groups in terms of follow-up adequately described and analyzed?	JBI
Were results measured, compared and analyzed reliably?	JBI
Was appropriate statistical analysis used?	JBI

of the narrative synthesis is justified by the methodological heterogeneity of the studies, which employed different approaches and methods despite addressing the same topic. This heterogeneity made it impossible to perform a statistical meta-analysis, which requires data standardization and direct comparison between studies.

Finally, the systematic review was accomplished with various computational tools, which optimized the process and ensured greater methodological rigor. The Parsifal platform was used to assist in study selection and bias analysis, enabling the recording of eligibility criteria and the scoring of each study, which facilitated decision-making and task automation.

The Vosviewer software was employed for scientometric analysis to visualize and interpret the relationships between the most frequent keywords in the analyzed articles. This analysis enabled the identification of the main themes and research trends in the field, providing context for the study and guiding the discussion of the results.

Reference management tools, Mendeley and Zotero, were used to organize, store, and manage the bibliographic references. In addition to facilitating the reading and annotation of the articles, these tools enabled the identification and removal of duplicate studies, ensuring the quality and integrity of the systematic review.

Microsoft Excel software was used to organize and analyze the data extracted from the studies included in the systematic review. The spreadsheets and charts generated supported the scientometric analysis, the data collection from the final sample, and the visualization of results, facilitating the interpretation and communication of information.

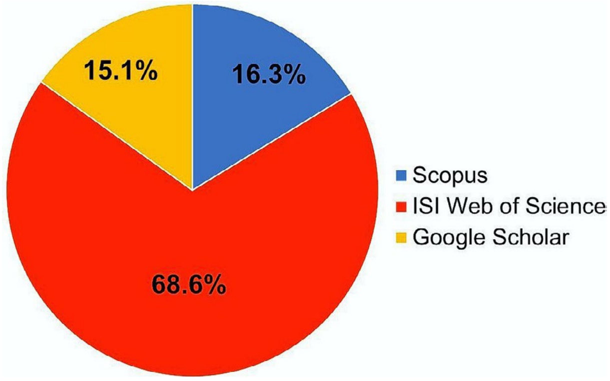

Figure 2: Distribution of percentage of articles per database after removal due to duplication.

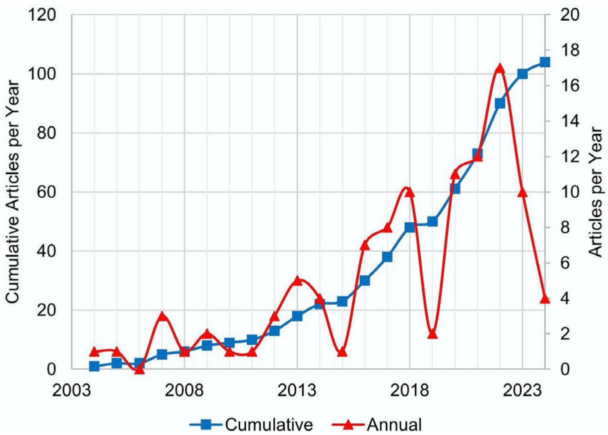

Figure3: Annual and cumulative distribution of articles in Sample 1.

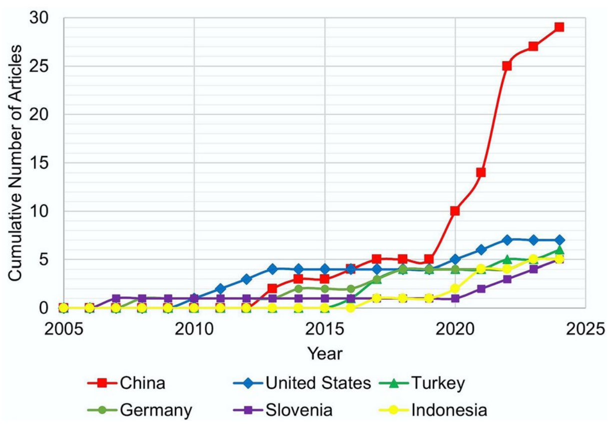

Figure 4: Distribution of publication numbers by country over the years.

RESULTS

Scientometric analysis

After applying the eligibility criteria, the intermediate sample totaled 102 articles distributed among the databases (Scopus, Web of Science, and Google Scholar). The distribution of articles by database is shown in Figure 2.

The annual distribution of publications was analyzed from the 102 articles selected after the eligibility stage. This analysis identified trends and publication patterns, highlighting the scientific community's interest in the subject (Figure 3).

The cumulative curve shows a significant increase of publications between 2015 and 2018, and again between 2019 and 2022. Combining the publications from the latter period results in 40 publications, representing approximately 38% of the sample of 102 articles.

Figure 4 illustrates the six countries with the most publications since 2005. It is evident that until 2019 there was a predominance of articles produced primarily in Europe and North America, which together still account for 51% of the sample. Then, in 2019, there was a significant increase in the number of publications originating from China, reaching 29 articles.

Using the Vosviewer software, a co-occurrence analysis of the most frequently cited keywords in the analyzed studies was conducted. Six clusters were identified: red, blue, cyan, green, yellow, and purple. The red, green and blue clusters contain the highest number of terms and exhibit the greatest interrelation as indicates the Figure 5.

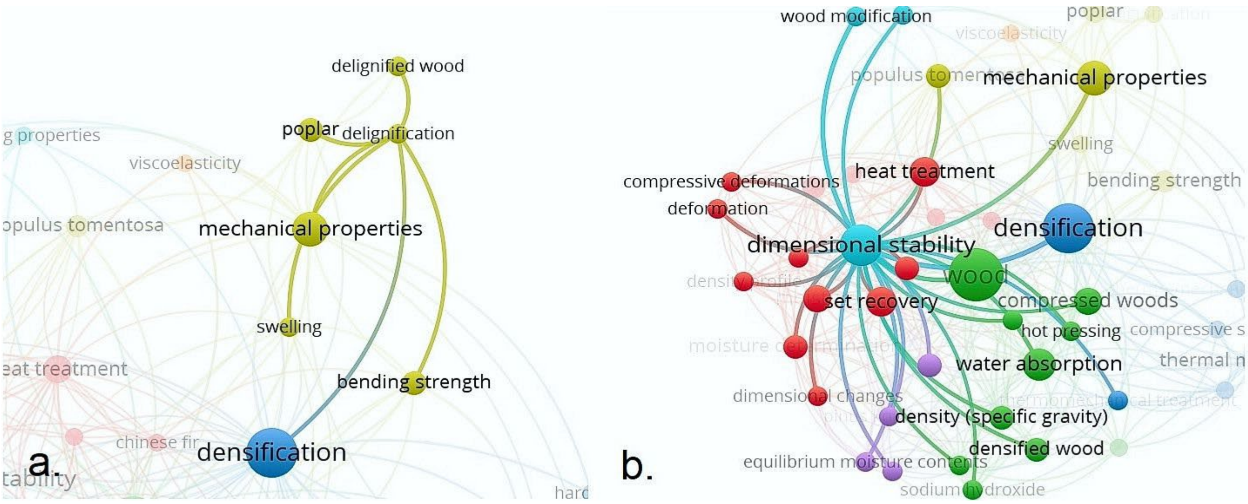

Figure 5: Co-occurrence networks of keyword in research on densified wood. (a) Co-occurrence network highlighting the keyword "delignification". (b) Co-occurrence network highlighting the keyword "dimensional stability".

By selecting the term delignification at the top of Figure 5 (a), it is observed that its proximity is limited to a small number of terms, indicating a weak relationship between the delignification process and the understanding of the wood's dimensional stability.

In Figure 5, by selecting the term dimensional stability, a strong connection is observed with keywords such as set-recovery, densification, and water absorption. Regarding the treatment types, there is a closer association of the term dimensional stability with heat treatment, that is situated within the red cluster.

In contrast, the term delignification appears more distant and located in a separate cluster, without a direct link. This suggests that, even before extracting data from each article, although the term delignification is related to the study of dimensional stability, until the time of this research, other treatment methods, such as heat treatment and impregnation, occur more frequently in the literature than the delignification process.

Meta-analysis of the wood species and densities data

Following the bias assessment, the final sample consisted of 54 articles sourced from the Scopus, Web of Science, and Google Scholar databases, as listed in Table 4. The data used for the meta-analysis and the synthesis of the systematic review findings were extracted from these articles.

Based on the data collected, several aspects of the densification process were able to be identified in the 54 articles included in the sample. Among these data, the most significant ones highlighted in this paper are the most used species and their densities shown in Table 5.

Table 5 and Figure 6 show that the *Populus* was the most used genus, accounting for 31% of the total genera studied. Additionally, a variety of species were utilized, like: *Populus deltoides*, *Populus alba* L., *Populus euramevicana*, *Populus deltoides* Bartr. ex Marsh × *Populus Nigra* L., *Populus tomentosa*, *Populus trichocarpa*, *Populus cathayana* Rehd.. Other genera, mainly from Europe, North America, and Asia, such as *Picea*, *Pinus*, and *Fagus*, also stand out among the most used and account for around 64% of the species utilized in the studies analyzed in this research.

In Figure 7, the frequency histogram of the densities of the wood species in g/cm^3, gathers the densities in constant intervals.

The densities were ranged from a minimum of 0.25 g/cm^3 to a maximum of 0.91 g/cm^3. However, most of the species, 77,1%, had an apparent density between 0.4 to 0.6 g/cm^3, with an average value of 0.476 g/cm^3. The density range above 0.6 g/cm^3 occurred in approximately 16.9% of cases, while below 0.4 g/cm^3 it accounted for around 6,0%.

Meta-analysis of the delignification and dimensional stability data

Among the 54 analyzed articles, only 16 (29.6% of the total sample) did not apply any treatment to improve the dimensional stability. In contrast, 38 studies, i.e. 70.4%, employed one or more pre- or post-densification treatments. Among the methods used to reduce elastic recovery effects such as springback, set-recovery, and thickness swelling, the thermal treatment was the most common, accounting for 56% of the processes reported, followed by impregnation methods with 43%. Among the impregnation treatments, the substances that stood out were furfuryl alcohol, polymeric resins like phenol-formaldehyde, epoxy, and ammonium polymethacrylate, as well as certain acids like succinic acid, acetic acid, and boric acid, as illustrates Figure 8.

The delignification process was employed in approximately 26% of the 54 analyzed articles, totaling 14 studies. The main objectives of the authors in these studies were to increase the compaction degree of the samples and reduce the elastic recovery effect – springback and set-recovery. Table 6 lists the articles that utilized the delignification process, the chemical reagents used, as well as the solutions and concentrations applied. Research about the delignification method has shown significant growth since 2019.

Table 4 – Final sample of articles selected after bias analysis.

Authors	DOI
Augustina et al., 2022	10.3390/f13020293
Augustina et al., 2021	10.37763/wr.1336-4561/66.5.762776
Augustina et al., 2020	10.5658/WOOD.2020.48.4.458
Bao et al., 2017	10.1007/s10086-017-1661-0
Boonstra e Blomberg, 2007	10.1007/s00226-007-0140-y
Buchelt et al., 2014	10.1515/hf-2013-0049
Cai et al., 2013	10.1080/07373937.2013.775147
Esteves et al., 2017	-
Fu et al., 2016	10.15376/biores.11.4.8844-8859
Gabrielli e Kamke, 2010	10.1007/s00226-009-0253-6
Guo et al., 2022	10.3390/f13101620
Hajihassani et al., 2018	10.4067/S0718-221X2018005011001
Han et al., 2022	10.1080/17480272.2022.2133631
Huang et al., 2024	10.3390/16070939
Kuai et al., 2022	10.1016/j.conbuildmat.2022.128282
Kuai et al., 2024	10.1016/j.ijbiomac.2023.128572
Kumar et al., 2019	10.19182/bft2019.341.a31758
Laine et al., 2016	10.1007/s00226-016-0835-z
Langella et al., 2024	10.1007/s00107-023-02032-4
Laskowska et al., 2018	10.15376/biores.13.4.9005-9019
Laskowska et al., 2021	10.3390/coatings11121528
Lee e Lee, 2018	10.5658/WOOD.2018.46.5.471
Li et al., 2013a	-
Li et al., 2013b	10.15376/biores.8.4.5279-5288
Liu et al., 2021	10.1016/j.indcrop.2021.114029
Ma et al., 2023	10.1016/j.conbuildmat.2023.133484
Maturana et al., 2023	10.1038/s41598-023-41342-8
Nawawi et al., 2023	10.5658/WOOD.2023.51.2.133
Pelit et al., 2016	-
Pelit e Yorulmaz, 2024	10.22320/s0718221x/2024.09
Pelit et al., 2018	10.1007/s00107-017-1182-y
Popescu et al., 2014	10.1007/s00226-013-0588-x
Ran et al., 2023	10.1016/j.cej.2023.144476
Sargent et al., 2023	10.22382/wfs-2023-13
Schwarzkopf, 2021	10.1080/17480272.2020.1729236
Skyba et al., 2009	-
Taghiyari et al., 2017	10.1007/s11676-016-0321-3
Tenorio e Moya, 2020	10.15376/biores.15.4.8065-8084
Tenorio et al., 2023	10.1007/s00107-022-01890-8
Tu et al., 2014	10.15376/biores.9.3.3846-3856
Wang et al., 2021a	10.3390/ma14195709
Wang et al., 2022	10.1016/j.indcrop.2022.115645
Wang et al., 2021b	10.1016/2021.123395
Wang et al., 2020	10.1007/s10853-020-05034-2
Wehsener et al., 2018	10.1007/s00107-017-1278-4

Continue...

Table 4 – Continuation.

Authors	DOI
Wehsener et al., 2023	10.1080/17480272.2022.2134049
Welzbacher et al., 2008	10.1007/s00107-007-0198-0
Xu et al., 2022	10.1080/17480272.2021.1924857
Xu et al., 2020	10.37763/wr.1336-4561/65.2.293302
Xu et al., 2021	10.1007/s10853-021-06194-5
Yahyaee et al., 2022	10.1007/s00107-021-01756-5
Yan et al., 2020	10.15376/biores.15.2.2691-2707
Yang et al., 2022	10.1007/s10853-022-07581-2
Yu et al., 2020	10.1186/s10086-020-01892-1

Table 5: Wood species used and their densities.

Genus	Scientific Names	Standard Density (g/cm³)	Occurrence (%)	Average density (g/cm³)
Abies	*Abies alba; Abies* balsamea *(L.) Mill.; Abies bornmulleriana Mattf.*	0.42	5%	0.476
Acer	*Acer saccharum*	0.73	1%	
Alnus	*Alnus acuminata*	0.42	2%	
Brasimum	*Brosimum utile*	0.44	1%	
Carapa	*Carapa guianensis*	0.51	1%	
Ceiba	*Ceiba pentandra*	0.25	1%	
Couratori	*Couratari spp.*	0.694	1%	
Cunninghamia	*Cunninghamia lanceolata*	0.40	2%	
Dipteryx	*Dipteryx oleifera*	0.91	1%	
Eucalyptus	*Eucalyptus fastigata; Eucalyptus nitens*	0.61	2%	
Fagus	*Fagus sylvatica L.*	0.63	7%	
Fraxinus	*Fraxinus excelsior L.*	0.66	1%	
Melia	*Melia dubia*	0.39	1%	
Mezzetia	*Mezzettia leptopoda*	0.47	4%	
Milicia	*Milicia excelsa (Welw.) C.C. Berg*	0.564	1%	
Palaquium	*Palaquium lanceolatum*	0.45	4%	
Picea	*Picea abies Karst.; Picea asperata Mast.*	0.44	8%	
Pinus	*Pinus radiata D. Don.; Pinus sylvestris L.; Pinus pinaster Ait.; Pinus koraiensis*	0.50	8%	
Populus	*Populus deltoides.; Populus alba L.; Populus euramevicana; Populus deltoides Bartr. ex Marsh × Populus Nigra L.; Populus tomentosa; Populus trichocarpa; Populus cathayana Rehd.*	0.44	31%	
Quercus	*Quercus rubur L.*	0.64	2%	
Schima	*Schima wallichii*	0.34	4%	
Tilia	*Tilia cordata Mill.; Tilia grandifolia Ehrh.; Tilia spp.*	0.47	4%	
Vochyisia	*Vochysia guatemalensis; Vochysia ferruginea*	0.41	5%	

Among the 14 evaluated articles that applied the delignification process, sodium hydroxide (NaOH) was the most used reagent for lignin and hemicellulose removal, appearing in 85.7% of the studies. In 7 out of the 14 articles, sodium hydroxide was combined with sodium sulfite (Na_2SO_3) at varying concentrations. Four of these articles, i.e. 28.5% of the sample, employed the same concentration used by Song et al. (2018): 2.5M NaOH and 0.4M Na_2SO_3.

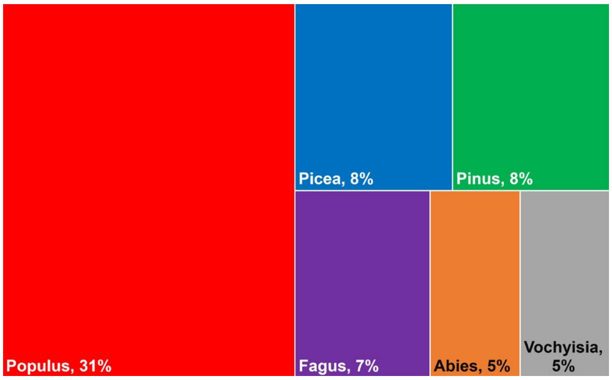

Figure 6: Main genus and species used in studies.

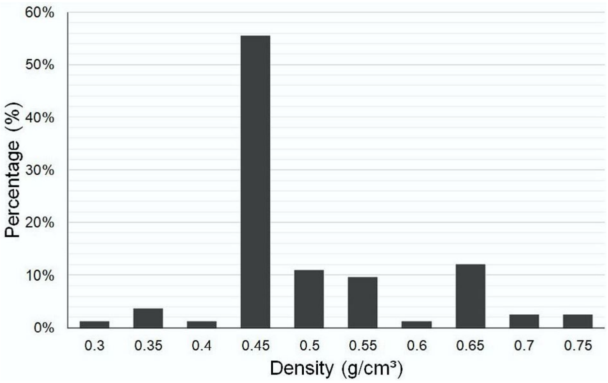

Figure 7: Distribution of the most used densities in the studies.

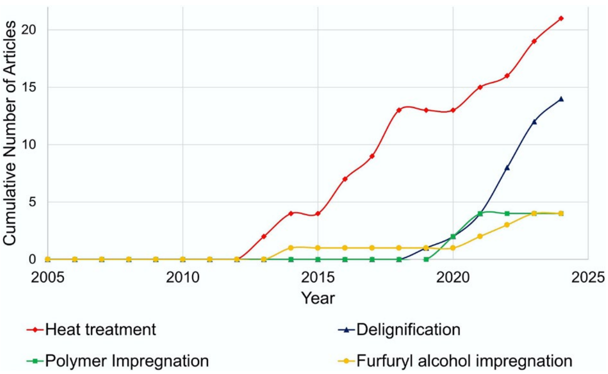

Figure 8: Annual evolution of the type of treatment to combat dimensional instability.

DISCUSSION

This section analyzes the results of the systematic review based on established scientific knowledge. Arguments, comparisons, and discussions are presented to contextualize the findings, highlighting the relationship between the delignification process and the dimensional stability of densified wood. Possible causes of the variability in results among the studies are also investigated, along with the practical implications and future research prospects in the field.

Scientometrics

The results of the scientometric analysis indicate that studies on densified wood have gained significant attention in the last ten years. This may be related to the interest of major global powers, such as China and the United States. According to Zhou et al. (2016), China focuses on its application in renewable fuel production to reduce carbon emissions and diversify its energy matrix. According to Espinoza (2020), the growth in the use of engineered wood, combined with the expansion of forest biomass for energy generation, especially in the production of pellets exported to Europe, demonstrates the search for sustainable alternatives. In addition, advances in nanocellulose and wood-derived bioproducts indicate new high-performance applications. These factors may indicate the US interest in densified wood.

Another finding is that despite the large number of articles originating from Europe and North America in the total sample, it is notable that the number of studies produced in China has grown over the past five years.

This is explained by China's recent prominence in the wood industry. According to Barbu and Tudor (2021), China has become the leading force in global forestry and wood, transitioning from a major importer of raw materials to the top producer and exporter of value-added wood products. Over the past decades, its industry expanded rapidly due to technological advancements, government policies, and rising domestic demand. Despite resource limitations, China has become the largest manufacturer of wood-based panels, furniture, and flooring, influencing international trade.

Moreover, it was observed from the co-occurrence analysis of keywords that, among the analyzed studies, the delignification process is still underexplored as a method to increase the dimensional stability of densified wood, with heat treatment being more strongly associated with reducing set-recovery. However, this scenario is changing due to the prominence given to the work of Song et al. (2018) which gained recognition in the scientific community, due to its remarkable results.

This hypothesis is supported by the fact that this same article is cited in a total of 40 articles, including 20 articles from the sample among the works published between 2019 and 2022.

Species and densities

The choice of low-density species, between 0.4 and 0.6 g/cm^3, can be explained by the fact that these species exhibit faster growth and, consequently, a commercial production potential. At the same time, this choice aligns with the technical potential, as their porosity allows for significant gains in the densification process. The frequent use of species such as poplar, spruce, and pine in the evaluated studies may be related to the geographical distribution of the research, which, in most cases, was conducted in regions where these species are found.

Table 6: Studies that applied the delignification process, the main reagents used, and concentrations.

Authors	Chemical reagents	Solution/temperature/time
Kumar et al., 2019	NaOH - Na_2SO_3	2:1 (NaOH:Na_2SO_3) / 100°C / 4h
Wang et al., 2020	NaOH and Maleic acid	1, 2 and 6% / 155°C / 30min
Wang et al., 2021	NaOH	1, 2 and 6% / 155°C / 30min
Xu et al., 2021	NaOH - Na_2SO_3	2.5 M NaOH and 0.4 M Na_2SO_3 / 3 days
Kuai et al., 2022	NaOH - Na_2SO_3	1mol/L NaOH; 0.4 mol/L Na_2SO_3 / 95°C /10 h
Yahyaee et al., 2022	NaOH - Glycerol	350g glycerol, 5 g NaOH and 140g H_2O / 170 °C / 7 bar / 4h
Augustina et al., 2022	NaOH	10% NaOH (w/w) - 1, 2 and 3h
Wang et al., 2022	Na_2CO_3	0, 60.4, 93.5 g/L a 155°C/30min
Ran et al., 2023	Citric acid ($C_6H_8O_7$) - Choline chloride	Solution 1:1 / 60°C 70% H_2O. 90°C /14h
Maturana et al., 2023	NaOH - Na_2SO_3	2.5 M NaOH - 0.4 M Na_2SO_3 / 90 °C / 7h
Nawawi et al., 2023	NaOH	Solution 1.25 N NaOH / boiled / 1, 3, and 5h
Wehsener et al., 2023	$NaHSO_3$ - NaOH	2.5 M NaOH - 0.4 M Na_2SO_3 / 100°C, 130°C, 150°C / 4h
Kuai et al., 2024	NaOH - Na_2SO_3	NaOH - Na_2SO_3 solution/ 95°C / 10h
Huang et al., 2024	NaOH - Na_2SO_3	M NaOH - 0.4 M Na_2SO_3 / 110°C / 10h

Some articles demonstrate that the use of densification in low-density species obtain possible gains in its physical and mechanical properties. For example, Kuai et al. (2022) used the species Populus tomentosa with a densification process at a temperature of 180°C and a pressure of 10 MPa for 120 minutes, where the samples were previously subjected to a delignification step using a NaOH and Na2SO3 solution. The initial samples had an apparent density of 0.503 g/cm³ and achieved values up to 1.333 g/cm³, representing an increase of approximately 165%.

In contrast, Bao et al. (2017), using the same species without applying the delignification process and compressing the samples at 160°C with different compaction rates (50%, 60%, 70%, and 75%), started with a reference sample density of 0.41 g/cm³, achieving values that ranged between 0.75 g/cm³ and 1.13 g/cm³, depending on the degree of compaction applied.

Delignification and dimensional stability

The increasing use of the delignification process in research involving the dimensional stability of densified wood may be related to the excellent results achieved by Song et al. (2018). Supporting this hypothesis is the fact that all the studies that used delignification were published after 2019. Moreover, the frequent use of similar concentrations of NaOH and Na_2SO_3 further reinforces the influence of this work in recent years.

As an example of NaOH and Na2SO3 use, Kumar et al. (2019) related dimensional stability to the delignification process in densified wood of Melia dubia samples. With lower elastic recovery (2.97% to 5.22% range) for delignified samples compared to samples that did not undergo the delignification process (38.05% to 48.47%).

In a study by Kuai et al. (2024), the aim was to use an alkaline pre-treatment (NaOH/Na_2SO_3) with sodium silicate impregnation to increase the dimensional stability of densified Poplar wood. Changing the lignin content from 22.7% to 7.9% and hemicellulose content from 17.1% to 6.5%, representing reductions of 69.2% and 66.3%, respectively. The results showed a significant increase in mechanical properties and excellent dimensional stability, with no swelling after 30 days of exposure to moisture and only 1% swelling after 72 hours of immersion in water.

Huang et al. (2024), using 2.5 M NaOH and 0.4 M Na_2SO_3 on basswood, reduced lignin content from 18.37% to 8.52% and hemicellulose content from 23.27% to 4.59%. Delignified wood demonstrated better compaction during pressing, resulting in a reduction of the voids between the fibers. However, excessive lignin removal weakened the bond between cellulose fibers, making the material more brittle. After delignification, cellulose underwent structural rearrangements, increasing the crystallinity (from 86.02% to 88.36%), indicating that removing lignin and hemicellulose facilitated better alignment of the cellulose chains.

Wehsener et al. (2023) conducted a study on poplar wood (*Populus nigra* L.) using 2.5 M NaOH and 0.4 M Na_2SO_3 at different times and temperatures for delignification. The results showed a substantial reduction in hemicellulose content, reaching up to 80%. Lignin removal reached 99%, and in the most degraded samples, decreased cohesion between cellulose fibers reduced internal bonding capacity, leading to interlaminar failures. The optimal condition was attained with partial delignification, removing 44% at 130°C, followed by densification at the same temperature, resulting in high mechanical strength and dimensional stability.

These results demonstrate the potential of the reagents used by Song et al. (2018), regardless of the analyzed species and the varied densification methods, with different compression times and temperatures.

Not only did the combination of NaOH and Na_2SO_3 yield positive results in the delignification process of densified wood, but the isolated use of sodium hydroxide also had a beneficial impact on improving its dimensional stability.

In research conducted by Nawawi et al. (2023), it was found that densification in kapok wood [Ceiba pentandra (L.) Gaertn] with an alkaline pre-treatment, using a 1.25 N NaOH solution in boiling water for 3 hours, was essential for degrading hemicellulose and, to a lesser extent, cellulose. Lignin remained relatively stable, and its relative increase was due to the reduction of hemicellulose and cellulose. Furthermore, the NaOH treatment reduced holocellulose by 21.81%, resulting in a 63.24% increase in Anti-Swelling Efficiency (ASE), indicating a significant improvement in dimensional stability by reducing the amount of hemicellulose and amorphous cellulose, thereby lowering hygroscopicity.

The potential for the isolated use of NaOH in the delignification process was also evidenced by Augustina et al. (2022), where samples of Pisang putih (Mezzettia spp.), Nyatoh (Palaquium spp.) and Sepetir (Sindora spp.) underwent delignification with NaOH and impregnation with succinic acid during the pre-densification stage. The alkaline treatment removed a significant portion of hemicellulose and lignin fragments, as evidenced by the disappearance of the 1736 cm^{-1} peak in the FTIR. In addition, it converted type I cellulose to type II, which can increase dimensional stability.

The increase in voids, caused by the alkaline treatment, favored the impregnation of the samples with succinic acid ($C_4H_6O_4$). The setting recovery tests showed a recovery of 75.04% in untreated samples, decreasing to 42.91% with the treatment with NaOH and 22.46% with the combined treatments.

On the other hand, Ran et al. (2023) did not focus on the delignification process but rather on the in situ modification of lignin to improve the dimensional stability of densified wood. The study used a deep eutectic solvent (DES) based on choline chloride (ChCl) and citric acid (CA) in a 1:1 molar ratio to treat the Pinewood (Pinus radiata) samples. This treatment increased the hydroxyl content of lignin, enabling its participation in condensation processes and the formation of crosslinked structures during densification. Lignin modification, along with hemicellulose deacetylation, improved the dimensional stability of densified wood by promoting crosslinking and reducing material recovery.

Yahyaee et al. (2022) performed delignification using a solution of glycerol, sodium hydroxide (NaOH), and water, removing lignin while preserving hemicelluloses, essential for bond formation during densification. The samples were impregnated with glycerol and maleic anhydride and densified. Lignin removal was 55%, preserving lignin between the microfibrils, while hemicelluloses were almost completely retained. The polymerization formed esters, enhancing the mechanical properties. Dimensional stability was affected by cavities, allowing water penetration and partial shape recovery. The polymerized samples showed a 68% reduction in dimensional recovery and a 37% increase in tensile strength.

Besides delignification, other methods address the set-recovery effect. Thermal treatment, a common approach, forms acetic acid from hemicellulose, catalyzing carbohydrate cleavage and reducing polymerization. These reactions enhance wood's dimensional stability and lower its hygroscopicity (Kariz et al., 2017). Additionally, thermal treatment is cost-effective and environmentally friendly (Gong et al., 2010).

Impregnation with eco-friendly materials like furfuryl alcohol, tung oil, and biochar has also been explored. Furfuryl alcohol has shown strong potential, with Bucheldt et al. (2014) reporting a reduction in recovery from 75% to less than 5% in densified samples. Similar trends were observed by Yang et al. (2022) and Tenório et al. (2023), with furfuryl alcohol lowering set recovery from up to 80% to below 10%. Langella et al. (2024) found significant differences between untreated and biochar-treated samples, with 1% biochar showing the best performance despite high set-recovery.

CONCLUSIONS

The systematic review method implemented on this paper proved efficient by enabling the careful selection of studies, avoiding methodological bias, excluding articles with low relevance to the topic, and guiding the selection of data for analysis.

One challenge in this review was the difficulty of in-depth statistical analyses due to methodological heterogeneity in delignification methods, densification processes, and wood species. This variability hindered direct comparisons and statistical meta-analyses, limiting the study to narrative synthesis and descriptive analysis.

The increase in Chinese researchers dedicated to this study is related to China's prominent role in the wood industry and the investments made in the development of this sector, a trend that is expected to continue in the coming years.

The study found consistent evidence linking the increase in studies on delignification, reflecting the growing interest in its potential to improve the dimensional stability of densified wood between 2019 and 2024, to the results obtained by Song et al. (2018).

Studies indicate that delignification has a significant influence on improving the dimensional stability of densified wood. The removal of lignin and hemicellulose, in appropriate amounts, reduces swelling and increases the mechanical strength of the wood, directly contributing to its greater stability under humid conditions.

The combination of delignification and impregnation methods has proven to be an effective strategy for improving the dimensional stability of densified wood. The partial removal of lignin and hemicellulose creates a more porous structure, facilitating the penetration of modifying compounds—such as polymers, organic acids, and cross-linking agents—that promote cross-linking between fibers, increasing cohesion and minimizing swelling.

In parallel, some research focuses on enhancing the dimensional stability of densified wood while reducing environmental impact. Synthetic polymer-based impregnation is being replaced by alternatives like furfuryl alcohol, tung oil, and biochar. Thermal treatment remains the most common method, with furfuryl alcohol showing promising results. However, further studies are needed to evaluate the effectiveness of biochar and tung oil.

Based on the results and discussion of the systematic review, the following recommendations for future research can be proposed:

a) Encourage studies that use standardized methodologies for delignification and densification processes, to enable direct comparison of results and facilitate meta-analyses.

b) Control variables that may influence the dimensional stability of densified wood, such as wood species, initial moisture content, temperature, and densification pressure.

c) Investigate the influence of different delignification methods, like chemical, biological, enzymatic, on the dimensional stability of densified wood.

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