WCTE 2020
WORLD CONFERENCE ON TIMBER ENGINEERING
SANTIAGO, CHILE | 24 - 27 AUGUST

NATIVE WOOD REVALUATION THROUGH GREEN GLUING: A SYSTEMATIC REVIEW

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ABSTRACT: The objective of this study is to identify more representative variables that can be considered during the gluing process of wood from native forests in Chile with the green gluing technique, given that it has the potential to produce structural elements for the construction industry from fine woods that are currently undervalued. In order to do so, the methodology consisted of applying a Systematic Literature Review (SLR) and a bibliometric mapping of scientific publications (2000-2019) indexed in the Scopus database. As a result of the analysis, 3 thematic lines were established: "Environmental Impact", "Performance" and "Variable-Influenced Performance". Based on these lines, the most representative variables that determine the production of wet glue laminated wood, were extracted. These identified variables will be the basis for the elaboration of a green gluing methodology that has been adapted to the native timber gluing process.

KEYWORDS: Glulam, Green gluing, Moisture content, Moisture curing, Timber, Wet wood, Wood waste, Systematic Literature Review.

1 INTRODUCTION

1.1 THE REALITY OF CHILEAN NATIVE FORESTS

The Coigüe (*Nothofagus dombeyi*), Lenga (*Nothofagus pomilio*), Raulí (*Nothofagus nervosa*) and Oak (*Nothofagus obliqua*) broadleaf species make up the Lenga, Roble-Hualo, Roble-Raulí-Coigüe and Coigüe-Raulí-Tepa forest types [1]. These species are well represented within Chile's native forests, with more than 6 million hectares combined [2], along with a potential volume to be exploited of 25 million m^3 [3].

According to Chauchard et al. only 2% of Chilean exports are based on native forest resources [4]. The productive use of Chilean native forests is currently marginal in the area of exports but has significant importance in the area of timber production. It is estimated that approximately 9 million cubic meters of timber are harvested annually [5], constituting nearly 80% of annual native wood production [6,7]. Together with the above, timber exploitation is mostly done informally [8,9], without sustainable management, thus becoming the primary factor of native forest degradation in Chile.

Due to the large proportion of the native wood species in Chile being sold in the form of timber, its favourable mechanical behaviour and durability is being put to waste, with only its calorific potential as fuel being taken advantage of.

1.2 THE OPPORTUNITY TO RECOVER UNDERVALUED TIMBER

As it has been historically compiled by the Instituto Forestal de Chile (INFOR), the forementioned native species present better durability characteristics, modulus of elasticity (MOE) and rupture (MOR) in relation to Insignis Pine [10]. As can be seen amongst the information in Table 1, these characteristics are presented as materials with favourable mechanical behaviour, those of which are currently not being used massively to produce structural elements.

Concerning the uses that are given to these species currently, it can be observed that, despite being sold as sawn timber in some cases, there is no massive development of structural products of higher demand, as it so happens in the case of Insignis Pine, with which glued laminated wood elements have been generated and distributed at both national and international levels [11,12].

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1.3 THE OPPORTUNITY TO CARRY OUT GREEN GLUING WITH NATIVE WOOD

Green gluing seeks to take advantage of the natural durability and mechanical properties of these native woods that are superior to those of the Insignis Pine, as shown in Table l.

Table 1: *Mechanical characteristics of Pinus radiata and native species. Source: INFOR, 2010.*

Wood Species	Scientific Name	MOE MPa	MOR MPa	Density kg/m3
Insignis Pine	*Pinus radiata*	8.359	65	448
Raulí	*Nothofagus nervosa*	9.780	77	448
Coigüe	*Nothofagus dombeyi*	10.339	76	604
Roble	*Nothofagus obliqua*	12.113	82	624
Lenga	*Nothofagus pomilio*	9.927	86	520

Green gluing is the process of joining pieces of wood that have been properly prepared but in its green state -without being previously dried in a kiln, as traditionally done- [13, 14]. The traditional kiln-drying process produces internal tensions in the wood pieces, generating defects such as cracks and collapsed fibre. Consequently, green wood, that is, with a high degree of humidity as well as being near to the Fibre Saturation Point (FSP), has fewer defects than dry wood. In addition, the green gluing process has proven to dimensionally stabilize the wood that has been used [15], becoming a useful technique to add value to raw materials that are typically of lower quality, and allow it to be utilized in the elaboration of structural elements [16, 17].

Furthermore, it is a technique that can help with:

- Revaluating species: opening up new markets, manufacturing products with greater added value and price.
- Eliminating the kiln drying process: green gluing does not require an oven drying process, avoiding the associated environmental impact, the purchase and maintenance of equipment and infrastructure needed, along with other related costs.
- Improving efficiency in the use of raw material: by avoiding the kiln-drying process and gluing wet wood, the appearance of defects in the latter is reduced.
- Sustainably using our forest ecosystems, and improving raw material management processes, opening up opportunities for more than 50,000 small and medium native forest owners that exist in the country, which is equivalent to 7.5 million hectares [18], and who currently do not have access to management, production and market alternatives that allow them to give value to their forest resources. Thus being why it is so important to find new products and non-conventional production processes.

1.5 INFORMATION RETRIEVAL AND ANALYSIS METHODOLOGY

In order to identify, evaluate and synthesize the primary research findings that respond to the field of study, the application of a Systematic Literature Review (SLR) was considered. This methodology aims to conduct an analysis with clear and established criteria, avoiding bias or prejudice in the decisions made during the process.

Additionally, a bibliometric mapping was done so that the key thematic lines for the set of publications could be acknowledged.

2 METHODOLOGY

2.1 SYSTEMATIC LITERATURE REVIEW

A Systematic Literature Review (SLR) was conducted that considered high impact scientific publications indexed in the Scopus (Elsevier) database. This methodology was submitted to the structured protocol of Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) so that it could define inclusion/exclusion criteria. Its process is detailed in Figure 1:

The problem was approached through the following research question:

- What are the most representative variables for gluing Glulam over the Fibre Saturation Point (FSP) and in what ranges should they be controlled to achieve a favourable performance?

Criteria were established to avoid bias while selecting scientific literature. These correspond to:

Criteria for inclusive documentation:
- Being indexed in Scopus as an article (A), review (R) or conference paper (C).
- Being in English, Spanish and/or Slovak.
- Having full text access.
- Addressing some aspect of the green glued technique, according to performance, variables that influence performance, as well as its environmental impact.

Criteria for exclusive documentation:
- Duplicate documents presenting the same author(s) and body of research, with special attention to the results and conclusions.
- Not being related to the field of study, when reviewing title, abstract and full text.

A window of time that would allow a broad and historical overview of the field of study, from 2000-2019, was considered. The data were extracted in January 2020.

The Scopus (Elsevier) database was chosen to account for peer-reviewed and high-impact publications of articles, reviews and conference papers. These are part of the international scientific literature, used and cited in the generation of new original research.

According to the research topic, the following search strategy was structured and applied, to the title, summary, and keywords of the documents in Scopus:

(("green glue*" OR "glue* green" OR "green gluing" OR "gluing green" OR "gluing of green" OR "glue* of green" OR "green wood adhesive*") AND (*wood OR timber OR lumber OR "finger joint*" OR glulam))

To start with, 51 documents met the initial criteria, meaning, with indexing, publication date, document typology, language, and keywords, being present in the considered metadata.

Eighteen documents were excluded since they were found to be duplicated and/or not related to the field of research according to the review of bibliographic information and/or full text.

Finally, 33 documents were considered for the qualitative synthesis. This contemplated a subclassification that determined the specific focus of each investigation. Thus, Table 2 presents the results obtained from applying the criteria and the following subclassifications: life cycle assessment (LCA), adhesive conditions (AC), wood conditions (WC), manufacturing conditions (MC), mechanical performance (MP), appearance of defects (AD), surface qualities (SQ) and glue-line performance (GLP).

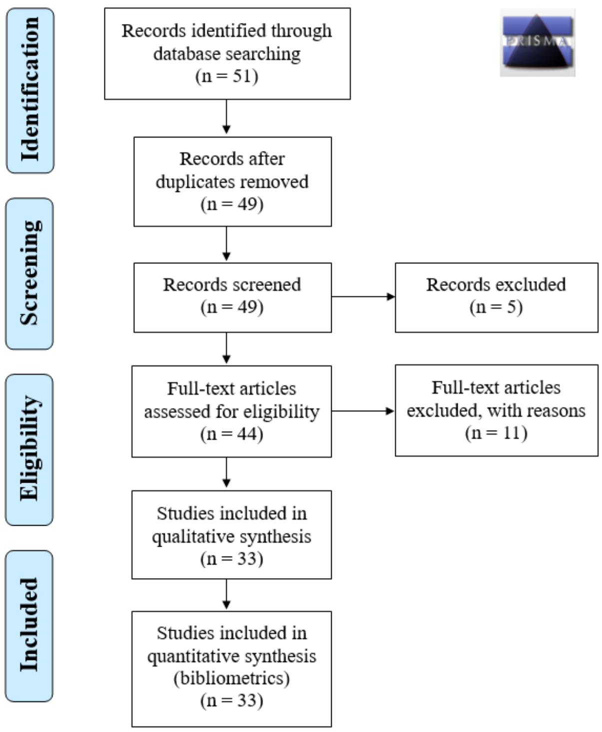

Figure 1: *PRISMA flowchart of literature search and review.*

2.2 BIBLIOMETRIC MAPPING

Additionally, the VOSviewer platform from the Centre for Science and Technology Studies (CWTS) was used to generate a bibliometric mapping that allowed research topics to be detected and the classification established during the final selection of the literature to be validated. In order to do this analysis, standardised keywords (Index keywords) proposed by the database were used. These were improved through manual processing of information consisting of standardizing similar terms and/or refining singular/plural terms.

The resulting map (Figure 2) led to the interpretation of three thematic clusters: "Performance" (green), "Variable-Influenced Performance" (red) and "Environmental Impact" (blue), whose composition is determined by the strength of the links and the occurrence of their labels (keywords). The strength of a link indicates that two labels are connected, since they appear together in the same document. The strength is represented by a positive value. The higher the value, the stronger the relationship between the two labels. Therefore, they are brought together in the same cluster. The occurrence indicates the number of documents in which a keyword appears. In this way, a larger circle indicates a greater presence of the keyword in the set of documents analysed [19].

This analysis provided the definitive validation of the key thematic lines addressed in the final selection of the literature section.

Afterwards, each document was reviewed to determine its focus and be able to classify them according to their main lines of research.

Based on these lines of research, or thematic lines, the documents were then reviewed in order to identify a set of minimum specific variables that would allow the green gluing process to be described in detail. With these variables being identified, it is hoped that in a future stage the process will be able to be replicated with species originating from Chile's native forests.

3 RESULTS

3.1 THEMATIC LINES AND THEIR ASSOCIATED PAPERS

So that the new gluing and testing methodology could be created, a review of the publications already filtered through the systematic review and PRISMA methodology was performed, leading to the development of certain thematic lines being detected, allowing the publications to be separated according to the main issues addressed in each one.

This division, which seeks to facilitate the analysis of the selected literature about green gluing, considers three key thematic lines: Environmental Impact, Variable-Influenced Performance and Performance.

The first thematic line, Environmental Impact, allows the positive attributes of the green gluing technique, in relation to life cycle assessment (LCA), to be distinguished. The second thematic line, Variable-Influenced Performance, provides information on the variables related to the production of laminates by means of green gluing that affect the mechanical performance and stability of the parts manufactured. The third thematic line, Performance, focuses on the validation of the green gluing technique through the analysis of mechanical tests, as well as through the analysis of the observable quality of the green glued laminated products.

In turn, each thematic line is made up of thematic sub-lines retrieved from the reviewed publication content. Thus, the first thematic line, Environmental Impact, considers the life cycle assessment (LCA) as a sub-theme. The second thematic line, Variable-Influenced Performance, considers the following three sub-themes: adhesive conditions (AC), wood conditions (WC) and manufacturing conditions (MC). The third thematic line, Performance, considers the following four sub-themes: mechanical performance (MP), appearance of defects (AD), surface qualities (SQ) and glue-line performance (GLP).

Table 2: *Review and classification synthesis.*

Ref.	**Doc. Type**	**Wood Type**	**Environ. Impact**	**Variable-Influenced Performance**			**Performance**			
			LCA	AC	WC	MC	MP	AD	SQ	GLP
[20]	A	Sw	-	-	-	-	-	+	-	-
[21]	A	Hw	-	-	-	-	-	-	-	+
[22]	A	Sw	-	-	-	-	+	-	-	-
[23]	A	Hw	-	-	-	-	+	-	-	-
[24]	A	Hw	+	-	-	-	-	-	-	-
[25]	A	Hw	-	-	-	-	+	-	-	-
[26]	A	Hw	-	-	-	-	+	-	-	-
[27]	A	Hw	-	-	-	-	-	-	-	+
[28]	A	Sw	-	-	-	-	-	+	-	-
[29]	A	Hw/Sw	-	-	-	-	-	-	+	-
[30]	A	Sw	-	-	-	-	+	-	-	-
[31]	A	Sw	-	-	-	+	-	-	-	-
[32]	C	Sw	-	-	-	-	+	-	-	-
[33]	A	Hw	-	-	+	-	-	-	-	-
[34]	A	Sw	+	-	-	-	-	-	-	-
[35]	C	Sw	-	-	-	-	+	-	-	-
[36]	C	Sw	-	-	-	-	+	-	-	-
[14]	A	Sw	-	-	-	-	-	-	-	+
[37]	A	Hw	-	-	-	+	-	-	-	-
[38]	A	Hw	-	+	-	-	-	-	-	-
[39]	A	N/A	+	-	-	-	-	-	-	-
[40]	A	Sw	-	-	+	-	-	-	-	-
[41]	C	Sw	-	-	+	-	-	-	-	-
[42]	A	Hw	-	-	-	-	-	+	-	-
[43]	A	Hw	-	+	-	-	-	-	-	-
[44]	A	Sw	-	-	-	+	-	-	-	-
[45]	A	Sw	-	-	-	-	+	-	-	-
[46]	A	Sw	-	-	-	-	+	-	-	-
[47]	A	Hw	-	-	-	+	-	-	-	-
[48]	A	Sw	-	-	-	-	-	-	-	+
[49]	A	Sw	-	-	-	-	+	-	-	-
[50]	R	Sw	-	-	-	+	-	-	-	-
[51]	A	Sw	-	-	-	-	-	+	-	-

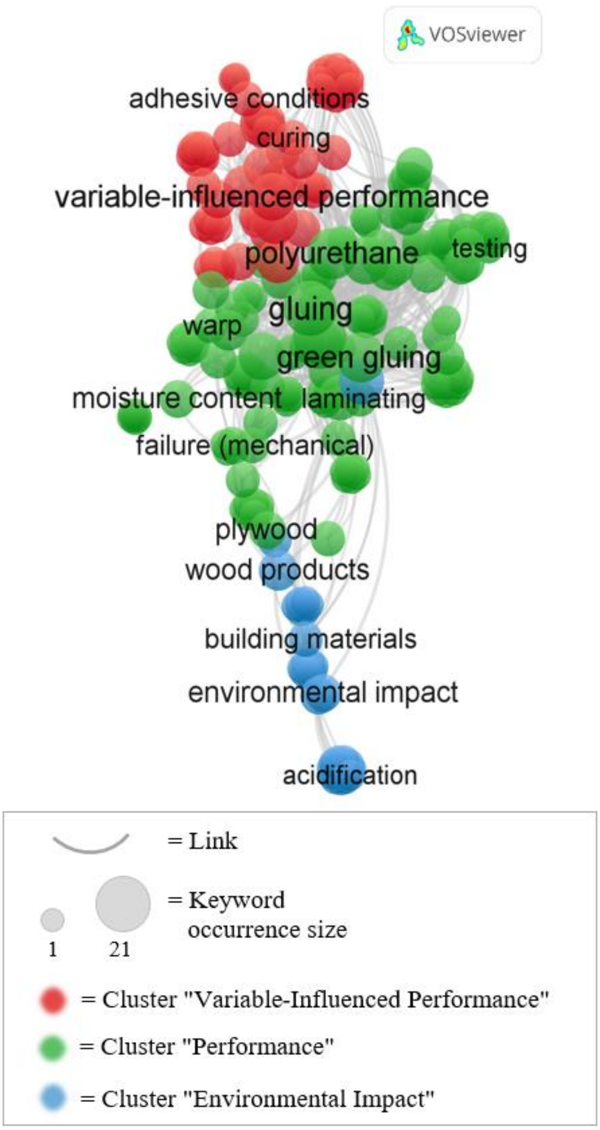

Figure 2: *Bibliometric Mapping of research fields.*

The thematic lines already detected serve to identify the key objective of each publication. However, in this case, publications from the Variable-Influenced Performance, as well as Performance thematic lines, are included, showing the production of green-glued elements.

From the total of 33 documents analysed, those dealing with the production of glued laminates (Glulam) are selected, with the declared information about the manufacturing conditions being extracted from them. With the variables being identified, the basic conditions are then established for the design of a gluing methodology that allows the validation of the green gluing technique with the four selected native wood species.

The manufacturing variables identified are: type of adhesive, type of wood, wood density, moisture content at gluing (MC), adhesive spread rate, press time, clamping pressure, and temperature at gluing.

Table 3: *Analysis of the data reported by each variable.*

Ref.	Adhesive	Wood Type	Density kg/m3	Moisture Cont. (% MC)	Adhesive spread rate g/m2	Gluing pressure MPa	Gluing hours	Gluing temp. °C
[22]	PRF	Sw	450	55	N/A	N/A	2	20
[28]	1 C PUR	Sw	N/A	>30	N/A	N/A	N/A	N/A
[35]	1 C PUR	Sw	N/A	30 and 70	N/A	1	24	N/A
[37]	1 C PUR	Hw	435 - 575	30 and 60	150 and 250	0,6 and 1	20	20
[40]	1 C PUR	Sw	N/A	N/A	200 and 250	0,5 and 1	1	N/A
[41]	1 C PUR	Sw	450	15	200	0.9	1.5	N/A
[42]	SA	Hw	N/A	80 - 90	500	N/A	24	N/A
[46]	1 C PUR	Sw	310 and 430	110 and 150	200	1	2	20
[48]	1 C PUR	Sw	310 and 405	N/A	250	1	3	20
[49]	1 C PUR	Sw	520	35 - 130	N/A	0,5 - 1	1 and 2	20
[51]	1 C PUR	Sw	N/A	N/A	150 and 200	N/A	0.5	N/A

PRF: Phenol Resorcinol Formaldehyde
1C PUR: One-Component Poliuretane
SA: Soybean Adhesive
Sw: Softwood
Hw: Hardwood
N/A: Not available

The data analysis reported by each variable allows to establish intervals within those that can be defined by the gluing methodology that will be designed.

When concerning adhesives, three possible types that can be used are identified: Phenol Resorcinol Formaldehyde (PRF), One-Component Polyurethane (1C PUR) and Soybean adhesive (SA), with 1C PUR being the most recurrent. Given the positive results with respect to the use of this type of adhesive in this technique, the lower quantity of Volatile Organic Compounds (VOC) and their availability on the market, makes it the adhesive with the greatest advantages.

Respecting the type of wood, the use of softwood (Sw) and hardwood (Hw) is observed, so, in principle, the technique would not be limited to a particular type.

The gluing humidity is diverse amongst analysed publications, with a wide interval being observed that accepts the gluing occurring from the sawing onwards. This allows flexibility with respect to the moment in which the wood can be glued.

The adhesive spread rate between 150 g/m^2 and 250 g/m^2 used in the studies corresponds to ranges specified by 1C PUR manufacturers, indicating that green gluing would not require a variation in the amount of adhesive.

The gluing pressure between 0.5 MPa and 1 MPa, used in the investigations studied corresponds to the standard pressure recommended by 1C PUR manufacturers.

With regard to the reported gluing temperature, it corresponds to standard conditions in all reviewed cases.

4 CONCLUSIONS

The Systematic Literature Review (SLR) provided a process to use on the evaluation of the existing evidence, allowing to focus the reading and analysis on findings relevant to the subject of the present study. At the same time, this has limitations. Given the coverage of years, languages and sources of information considered in the criteria, it is likely that some new and relevant studies will be excluded. In this respect, the low presence of Latin American research is evident, given the scarce percentage of journals in Spanish in the field of Civil Engineering and Construction in the Scopus database.

On the other hand, bibliometric mapping allowed the recognition and validation of trends and specific thematic classification aspects that had been carried out, by using predominant keywords from the set of analysed publications. With this said, the Environmental Impact cluster included the keywords: "wood", "wood products", "life cycle assessment", "building materials", and "veneers", the Variable-Influenced Performance cluster included the keywords: "moisture", "lumber", "strength properties", "elastic moduli", and "elasticity", whereas the Performance cluster included the keywords: "gluing", "polyurethane", "green gluing", "adhesives", and "finger joint".

Regarding the reviewed publications, the following technical conclusions have been drawn, allowing a green gluing methodology to be defined for the selected native Chilean species:

Given the majority use of 1C PUR in green gluing and its environmentally favourable characteristics compared to other massively used adhesives, the use of this adhesive is proposed.

The green gluing technique is not limited to softwood type woods since in the review the use of hardwood is also observed. This opens up the possibility of using selected native Chilean woods since all four correspond to the hardwood type.

The wide range of moisture content between 15% and 150%, gives flexibility when concerning the manufacture and the conditions in which the wood can be glued. However, there may be other considerations that condition the limits of this variable, for example the productive aspect that could be affected by the drying speed of the product in the stage immediately after the gluing process.

During the first stage, the standard gluing pressure recommended by the adhesive manufacturers will be used. Variations in pressure can be studied in later stages to determine the influence that the pressure has on the gluing line performance.

The gluing time, mostly under two hours, should not only ensure the adhesion characteristics between the wood sheets, but also consider other related factors such as production speed.

Since the gluing temperature detected in the publications reviewed corresponds to standard conditions, the trend will be followed, not considering this parameter as a new variable.

Continuing this research will address the mechanical characterisation of the Chilean native species that will be used in order to reduce the uncertainty related to their gluing and to verify that the green gluing technique is feasible with each of them. Within the characterisation, shape stability is considered relevant since it could affect the performance of the glued product.

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