

## REVIEW ARTICLE

# Intelligent modeling of thermal processes in wood: a systematic review

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All data will be shared on request.

**Institutional Review Board Statement**

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**Conflicts of interest**

The authors declare no conflict of interest.

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**Abstract**

This study mapped the state of knowledge on the applicability of Neuro-Fuzzy approaches to wood thermal modification through a Systematic Literature Review (SLR) reported according to PRISMA recommendations. Searches were performed in major databases and, after screening and eligibility assessment, 26 peer-reviewed articles were included. The evidence shows that Neuro-Fuzzy methods are widely applied to industrial modeling and optimization; however, no studies were identified that directly apply Neuro-Fuzzy/ANFIS to the specific process of wood thermal modification within the scope of this review. This finding indicates an evidence gap and supports a research agenda focused on reproducible data pipelines (e.g., Python) and integrated databases of thermally modified wood properties to enable future Neuro-Fuzzy modeling and optimization in the forestry sector.

**Keywords**ANFIS; Artificial Intelligence; *Neuro-Fuzzy*; PRISMA; Thermal Modification.

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**Introduction**

Silviculture plays a fundamental role in the Brazilian economy, being responsible for boosting the production of wood and its derivatives, in addition to generating employment and income in several regions of the country (IBA, 2024). In 2023, the Brazilian production of logs from planted forests exceeded 200 million cubic meters, while the value of sector exports reached approximately 12 billion US dollars, with emphasis on pulp, paper, and wood panels (IBGE, 2024).

These figures place Brazil among the main global exporters of forest products, highlighting the strategic importance of silviculture for national economic development. In the State of São Paulo, silviculture also stands out as one of the main agribusiness activities. According to data from (IBA, 2024), São Paulo's production of logs from planted forests reached approximately 22.4 million cubic meters in 2022, significantly contributing to the gross value of the state's agricultural production (FLORESTAR, 2024). According to the same authors, furthermore, the sector has a significant share in generating direct and indirect jobs, boosting the regional economy and fostering productive chains linked to wood, pulp production, and the furniture sector. Silviculture is defined as the branch of science that studies and applies techniques aimed at the cultivation, management, and restoration of forests, with economic, environmental, and social objectives (BLOIS et al., 2017).

This area ranges from selecting the most suitable species for a given climate and soil, through planting, tending, harvesting, and monitoring forest growth, to the recovery of degraded areas and the promotion of ecosystem sustainability

(FARIA, 2012). In the Brazilian context, the main species used in silviculture are eucalyptus and pine, with eucalyptus often chosen for the production of pulp, charcoal, and energy, while pine is widely used for sawn wood, furniture, and panels (SILVA & ROCHA, 2010). Other native species are also gaining ground in restoration and sustainable management projects, increasing the diversity and economic potential of the sector.

The Brazilian wood industrial park is robust and technologically advanced, allowing the transformation of forest raw material into items that supply both the domestic market and exports. With this industrial efficiency and effectiveness, there are many benefits that contribute to this sector, such as: income generation, technological innovation, and the consolidation of the country as a highly relevant sector in the international forest products market (FLORESTAR, 2024; IBA, 2024). Among the technologies applied to wood, thermal modification stands out. This is a process in which wood is subjected to high temperatures in a controlled atmosphere, altering its physicochemical properties (FERREIRA et al., 2019a).

Thermal modification provides greater dimensional stability, resistance to fungi, reduced hygroscopicity, and improved thermal insulation, expanding the range of commercial uses for the treated wood (FERREIRA; RANGEL & CAMPOS, 2018). These changes increase the added value of the product, making it more competitive against conventional materials and expanding its potential market. The search for greater efficiency and sustainability has led to the optimization of production processes in the wood industry. Strategies based on automation, statistical control, computational simulations, and intelligent data integration

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promote cost reduction, quality improvement, waste minimization, and rational use of resources (NUNES et al., 2018).

In this context, modern techniques such as *Neuro-Fuzzy* systems have been successfully applied in industrial production processes, including in the wood sector (GODINHO et al., 2024). These systems combine the learning capacity of neural networks with the flexibility and interpretability of Fuzzy systems, allowing for the modeling of complex processes, prediction of results, and decision-making in environments of high uncertainty (ALAHMED & ALMUHAINI, 2020). The *Neuro-Fuzzy* model integrates artificial intelligence concepts to approximate human knowledge (through Fuzzy rules) and automatic learning based on data (BATISTELA; SABBATINO & SIMÕES, 2020). By applying *Neuro-Fuzzy* in industrial processes, it is possible to optimize production parameters, identify patterns, predict behaviors, and adapt systems in real-time, contributing to more efficient, intelligent, and sustainable production processes (EHTERAM et al., 2019). Given this context, the objective of this chapter is to identify how the state of knowledge regarding the applicability of *Neuro-Fuzzy* in wood thermal modification is configured.

It should contextually and theoretically delimit the subject addressed, present the guiding questions and the justifications that generated the research, as well as, in the end, present the precise objectives of the study.

## Literature Review

Wood Thermal Modification is a thermochemical process in which wood is subjected to high temperatures, typically between 160°C and 260°C, in an environment with controlled or absent oxygen (FERREIRA et al., 2019b). Heating causes changes in the molecular structures of the main wood components, especially hemicellulose, cellulose, and lignin (FERREIRA; RANGEL & CAMPOS, 2018).

Chemically, the thermal modification process promotes hydrolysis, depolymerization, and condensation reactions among wood constituents (PERTUZZATTI et al., 2016). Hemicellulose is particularly sensitive to heat, degrading into by-products such as acids and simple sugars, which in turn catalyze new reactions and promote the process's autocatalysis (GODINHO; CANEPPELE & GASPAROTTO, 2021). According to the same author, cellulose undergoes slight degradation, losing some glucose units from its side chains, while lignin is less affected but undergoes restructuring and condensation, becoming more complex and contributing to the increased chemical and biological resistance of the treated material.

Thermal treatment tends to reduce wood density due to the degradation and mass loss of hemicelluloses, release of volatile compounds (such as water, organic acids, and light gases), and reduction of equilibrium moisture content (FERREIRA et al., 2019a). Although the material's volume remains relatively constant, its mass decreases, leading to lower apparent density. This reduction may vary depending on the treatment intensity and wood species but is generally considered moderate.

The greatest advantage of thermal modification lies in the remarkable improvement of wood's dimensional stability. This process significantly reduces the number of hydrophilic

groups (especially in hemicellulose), making the wood less prone to absorb water and undergo swelling or shrinkage in response to ambient humidity variations (BARREIROS et al., 2022). As a result, thermally modified wood shows altered hygroscopicity, greater biological durability, and resistance to decay, which expands its potential for use in outdoor and humid environments, according to the same authors.

Moreover, the breakdown of polymer chains, combined with reduced density and lower hygroscopicity, also affects wood's thermal conductivity. In general, thermally modified wood presents slightly lower thermal conductivity than natural wood, offering better performance in applications requiring thermal insulation (BARREIROS et al., 2022).

Mathematical modeling is essential in raw material modification processes, especially wood, whether to describe thermal, chemical, or mechanical transformations, allowing prediction and optimization of the material's final properties (IMAI et al., 2020).

Traditional methods rely on linear and statistical models, such as linear regression, analysis of variance, and differential equations to simulate phenomena like heat transfer, density variation, and mechanical properties after treatments such as thermal modification or carbonization (PEIXOTO, 1996).

However, many stages of wood processing exhibit high complexity, natural variability, and nonlinear behaviors that are difficult to capture with classical techniques (HORST, 2013). According to the same author, the final properties of the material are often influenced by multiple interactive factors, such as species, moisture content, processing time and temperature, and anatomical characteristics, which challenge conventional statistical models.

Fuzzy modeling and *Neuro-Fuzzy* hybrid systems stand out, in particular, for their ability to handle uncertainties, input linguistic rules based on expert knowledge, and adapt to incomplete or imprecise information (GODINHO et al., 2023). This translates into practical advantages: these systems can model phenomena where no explicit mathematical knowledge exists or when there is high data variability (GODINHO; CANEPPELE & GASPAROTTO, 2022).

In practice, while traditional models are recommended for controlled situations and well-understood systems, approaches based on artificial intelligence—especially Fuzzy modeling—offer greater flexibility, accuracy, and adaptability in industrial and research environments marked by uncertainties and nonlinearities (MARRO et al., 2010). Fuzzy systems can be quickly adjusted to different conditions, and their rules are easily interpretable, favoring more assertive decision-making in wood modification and valorization (ASGHAR; TALHA & KIM, 2017).

## Materials and Methods

Considering the research problem presented, which addresses the use of the *Neuro-Fuzzy* approach in wood thermal modification, it is observed that, as highlighted by Godinho and Caneppele (2022), the central discussion revolves around the relevance of advanced methods to optimize biomass conversion processes aimed at renewable energy production. Following the guidance of these authors, the hypothesis was formulated that the application of *Neuro-Fuzzy* systems can be optimized through the analysis of data available in the literature, using a systematic literature review

to support and enhance the efficiency of the wood thermal modification process.

The methodological approach adopted in this study, as described by Godinho, Gasparotto, and Caneppele (2022), was based on the systematic search and analysis of documents from scientific publication repositories. According to these authors, this strategy requires the researcher to conduct a rigorous and critical evaluation, selecting relevant information, performing systematic data recording, and applying robust procedures to ensure the reliability of the interpretations. Therefore, grounded in these principles, the Systematic Literature Review (SLR) was adopted as the methodological framework of this study.

The Systematic Literature Review (SLR) this SLR was reported following PRISMA recommendations for transparent reporting of identification, screening, eligibility, and inclusion, supported by a flow diagram and reproducible exclusion criteria (GALVÃO; PANSANI; HARRAD, 2015; PAGE et al., 2022).

This method involves defining protocols, executing structured steps, and employing specific methodological tools to develop a consolidated analysis of the subject in focus (CONFORTO, AMARAL & SILVA, 2011).

Due to its systematized nature, the SLR requires the formulation of a well-defined research question, from which search strategies are developed, along with rigorous criteria for the selection, exclusion, and analysis of the consulted documents, ensuring the quality and relevance of the information considered (ANTONIAZZI & GODINHO, 2023).

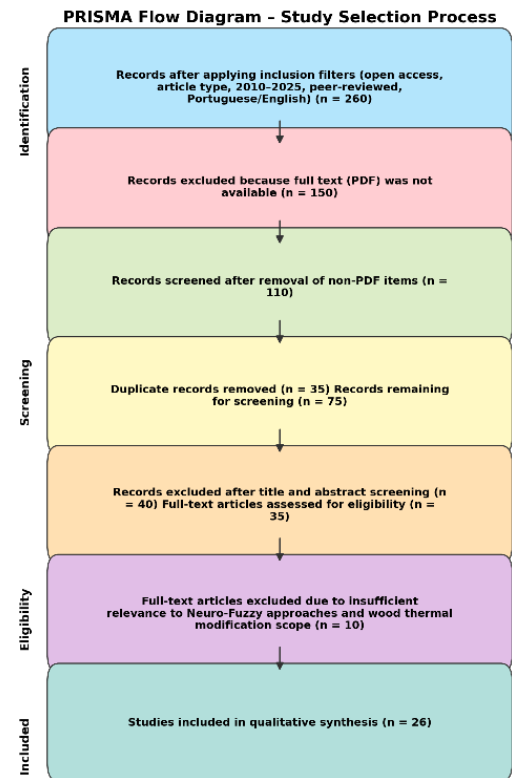
To support the purpose of this study, the SLR was applied following a structured procedure divided into three main stages: Input, Processing, and Output, as also described by FERNANDES et al. (2016).

The input stage consists of clearly defining the research problem that the SLR intends to address, including the delimitation of objectives, the establishment of criteria for including and excluding documents, and especially the formulation of search strings.

Next, during the processing phase, the actual searches are conducted, followed by the initial screening of materials through careful reading and evaluation. Finally, in the output phase, the selected documents are organized and stored, facilitating subsequent analyses and the processing of data necessary for synthesizing the results obtained.

#### PRISMA flow and selection

Study selection and quantitative exclusion criteria. After applying the six inclusion filters (open access; article type; 2010–2025; national/international coverage; peer-reviewed; Portuguese/English), 260 records remained for screening. Subsequently, the following sequential exclusion steps were applied: (i) records not available for PDF download ( $n=150$ ); (ii) duplicate records ( $n=35$ ); (iii) title/abstract screening excluding studies without sufficient proximity to the guiding question and keywords ( $n=40$ ); and (iv) full-text eligibility assessment excluding studies without methods/results relevant to Neuro-Fuzzy approaches, wood properties, thermal treatment processes, or closely related modeling/optimization contexts ( $n=10$ ). The final sample comprised 26 included studies. A PRISMA flow diagram summarizing these steps is provided as Figure 1.



Note: Flow diagram reported according to PRISMA guidelines. Numbers reflect the sequential screening and eligibility steps of this study.

**Figure 1.** PRISMA flow diagram of the study selection process.

The diagram illustrates the identification, screening, eligibility, and inclusion stages of the Systematic Literature Review, reported according to PRISMA guidelines. After applying inclusion filters, 260 records were identified. Subsequent exclusions resulted in 26 studies included in the qualitative synthesis.

Critical appraisal (qualitative assessment). Each included article was appraised for: (1) study type (experimental/modeling/review); (2) transparency of inputs/datasets; (3) clarity and reproducibility of the modeling pipeline (e.g., algorithm/parameters); and (4) validation strategy (train/test split, cross-validation, external validation). This appraisal supported an analytical thematic synthesis rather than a purely descriptive summary.

#### Input

The research problem this study aims to investigate was: “What is the current state of knowledge regarding the applicability of *Neuro-Fuzzy* modeling in wood thermal modification?” Thus, the objective of this Systematic Literature Review (SLR) was to identify the current state of knowledge on the application of *Neuro-Fuzzy* modeling in the wood thermal modification process.

The selection of databases was based on their relevance to the field of study, using access provided by the CAPES Journal Portal of the Federal Government, through the institutional login of UNESP, which allows direct and unrestricted access to platforms such as ScienceDirect®, Scopus®, Web of Science®, Scielo®, and SpringerLink®. This institutional connection, made through the university email, ensures full access to the scientific content required for the research.

After an initial survey of keywords and the creation of search strings, a total of five strings were defined for the first exploratory search, as presented in Table 1. The search was conducted on July 7, 2025.

**Table 1.** Example of table and position of table title.

id	Strings	CAPES®
1	"Thermowood modification"	30
2	" <i>Neuro-Fuzzy</i> "	14.598
3	"Physical Properties of Wood"	44
4	" <i>Eucalyptus urograndis</i> "	371
5	"Wood Strength"	43
Total		15.086

During the document search phase, the search strings were combined progressively, initially joining two terms at a time ("Thermowood modification" AND "*Neuro-Fuzzy*"; "Thermowood modification" AND "Physical Properties of Wood"; "Thermowood modification" AND "*Eucalyptus urograndis*"; "Thermowood modification" AND "Wood Strength"; "*Neuro-Fuzzy*" AND "Physical Properties of Wood"; "*Neuro-Fuzzy*" AND "*Eucalyptus urograndis*"; "*Neuro-Fuzzy*" AND "Wood Strength"; "Physical Properties of Wood" AND "*Eucalyptus urograndis*"; "Physical Properties of Wood" AND "Wood Strength"; "*Eucalyptus urograndis*" AND "Wood Strength"), then three by three ("Thermowood modification" AND "*Neuro-Fuzzy*" AND "Physical Properties of Wood"; "Thermowood modification" AND "*Neuro-Fuzzy*" AND "*Eucalyptus urograndis*"; "Thermowood modification" AND "*Neuro-Fuzzy*" AND "Wood Strength"; "Thermowood modification" AND "Physical Properties of Wood" AND "*Eucalyptus urograndis*"; "Thermowood modification" AND "Physical Properties of Wood" AND "Wood Strength"; "Thermowood modification" AND "*Eucalyptus urograndis*" AND "Wood Strength"; "*Neuro-Fuzzy*" AND "Physical Properties of Wood" AND "*Eucalyptus urograndis*"; "*Neuro-Fuzzy*" AND "Physical Properties of Wood" AND "Wood Strength"; "*Neuro-Fuzzy*" AND "*Eucalyptus urograndis*" AND "Wood Strength"; "Physical Properties of Wood" AND "*Eucalyptus urograndis*" AND "Wood Strength"), and so on, using the recommended Boolean connective AND to link the keywords.

The use of the AND operator is essential to ensure that the results return only documents containing all the searched terms simultaneously, increasing the accuracy and relevance of the articles found, as applied by (CONFORTO, AMARAL & SILVA, 2011). However, after these more specific and complex combinations, it was observed that no relevant results were returned in the consulted databases, indicating a scarcity or absence of scientific publications directly addressing the topic under this specific configuration.

This lack of documents suggests that the application of *Neuro-Fuzzy* modeling in the thermowood modification process is still a little-explored field in the scientific literature, reinforcing the importance and originality of the present research.

After performing the initial search using the defined keywords, 15,086 scientific articles related to the topic were found. Given this large volume of results, it was decided to narrow the research using six specific filters: open access; resource type restricted to articles; publication year between 2010 and 2025; coverage of both national and international

productions; peer review; and language limited to Portuguese and English. These criteria were established to ensure the quality, timeliness, and relevance of the selected documents for analysis, making the study more focused and consistent.

Table 2 presents the number of articles with the inclusion of the cited filters. After applying the six established inclusion filters (open access, resource type restricted to articles, publication year between 2010 and 2025, national and international coverage, peer review, and language in Portuguese and English), the number of available scientific documents was reduced to 260 articles. This filtering allowed focusing the analysis on a more qualified set aligned with the research objectives, facilitating the selection of relevant materials for the study.

**Table 2.** Example of table and position of table title.

id	Strings	CAPES®
1	"Thermowood modification"	13
2	" <i>Neuro-Fuzzy</i> "	56
3	"Physical Properties of Wood"	21
4	" <i>Eucalyptus urograndis</i> "	147
5	"Wood Strength"	23
Total		260

From the 260 articles found after applying the initial filters, a further exclusion step was performed to refine the material for analysis. Initially, 150 articles that were not available for PDF download were discarded, followed by the exclusion of 35 duplicate documents. Then, a filter based on keywords and abstract analysis was applied, eliminating another 40 articles that did not show sufficient proximity to the central theme of the research. Finally, a more in-depth reading led to the exclusion of another 10 articles, resulting in a total of 26 articles selected for detailed analysis, as shown in Table 3. This rigorous screening ensured that only the most relevant studies aligned with the research objective were considered.

**Table 3.** Example of table and position of table title.

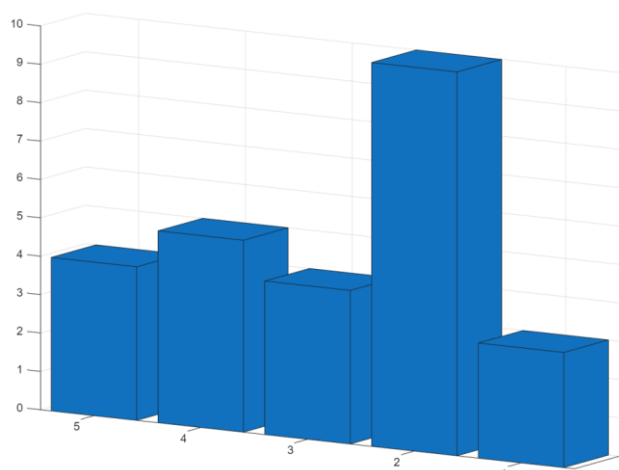
id	Strings	CAPES®
1	"Thermowood modification"	3
2	" <i>Neuro-Fuzzy</i> "	10
3	"Physical Properties of Wood"	4
4	" <i>Eucalyptus urograndis</i> "	5
5	"Wood Strength"	4
Total		26

## Results and discussion

### Processing

With the documents selected using the criteria applied in the Input stage, the Processing began, during which 26 documents were exported from the database and imported into the management software Mendeley®. The distribution of documents by theme was as follows: "Thermowood modification" (3), "*Neuro-Fuzzy*" (10), "Physical Properties of Wood" (4), "*Eucalyptus urograndis*" (5), and "Wood Strength" (4), as illustrated in Figure 2.

After a thorough analysis and the application of specific filters, the articles that supported this research were selected, ensuring the relevance and quality of the material examined.



**Figure 2.** Distribution of included studies by primary search theme (Thermowood modification = 3; Neuro-Fuzzy = 10; Physical Properties of Wood = 4; *Eucalyptus urograndis* = 5; Wood Strength = 4). **Legend:** (1) Thermowood modification; (2) *Neuro-Fuzzy*; (3) Physical Properties of Wood; (4) *Eucalyptus urograndis*; (5) Wood Strength.

**Output**

After downloading and reading the 26 articles in full, a table was prepared presenting the author(s), article title, and its main contribution to the academic community. This organization facilitated a comparative analysis of the studies,

allowing identification of trends, gaps, and relevant advances in the research area. This way, it was possible to systematize the available knowledge and guide the next steps of the work with greater foundation, as listed in Table 4.

Table 4 presents the complete list of the 26 articles selected for this research, highlighting the specific contribution of each to the advancement of the academic community. The study reports that the physical-mechanical properties of *Araucaria angustifolia* vary across phytosociological strata, indicating that wood performance depends on growth conditions and forest structure. For future data-driven modeling (including Neuro-Fuzzy), this supports the need to control for provenance and contextual covariates when predicting wood properties relevant to processing and thermal treatment outcomes (Beltrame et al., 2010).

The authors show that carbonization gas combustion does not change gravimetric charcoal yield but affects by-products (partially carbonized wood and fines), illustrating operational trade-offs in thermal processing of lignocellulosic material. Although not ThermoWood modification, the work is relevant as adjacent evidence on how thermal process conditions influence output streams and efficiency metrics (Cardoso et al., 2010). This article identifies chemical constituents and ecotoxicological effects of *Eucalyptus urograndis* leaf volatile oil, highlighting that eucalyptus-derived compounds may have environmental impacts.

**Table 4.** Example of table and position of table title.

<b>Id</b>	<b>Author</b>	<b>Title</b>	<b>Contribution</b>
1	(Beltrame et al., 2010)	Physical-Mechanical Properties of <i>Araucaria angustifolia</i> Wood in Three Phytosociological Strata	The article demonstrated that the physical-mechanical properties of <i>Araucaria angustifolia</i> wood vary according to the phytosociological stratum, being superior in the middle and upper strata.
2	(Cardoso et al., 2010)	Effect of Carbonization Gas Combustion on the Gravimetric Yield of <i>Eucalyptus</i> sp. Wood	The study showed that combustion of carbonization gases did not alter charcoal yield but reduced the amount of partially carbonized wood and increased fine particle production, helping optimize the carbonization process.
3	(Araújo et al., 2010)	Chemical Constituents and Ecotoxicological Effect of Volatile Oil from <i>Eucalyptus urograndis</i> Leaves (Myrtaceae)	The study identified the main constituents of volatile oil from <i>Eucalyptus urograndis</i> leaves, highlighting ortho-cymene and 1,8-cineole. It showed the leached oil can cause toxic effects on aquatic organisms such as <i>Daphnia laevis</i> and <i>D. similis</i> .
4	(Gonçalves; Leta, 2010)	Macroscopic Rock Texture Image Classification Using a Hierarchical <i>Neuro-Fuzzy</i> Class Method	The study presented a hierarchical <i>Neuro-Fuzzy</i> method based on binary space partitioning (NFHB-Class) capable of classifying macroscopic rock textures with over 73% accuracy, automating the extraction of interpretable Fuzzy rules, aiding petroleum reservoir exploration.
5	(Vivian et al., 2010a)	Strength of <i>Canafistula</i> Wood ( <i>Peltophorum dubium</i> ) under PSF and Equilibrium Moisture	The main contribution was demonstrating how varying moisture levels significantly affect the impact and static bending strength properties of the wood.
6	(Stangerlin et al., 2010)	Static Bending Properties of <i>Carya illinoensis</i> Wood under Two Moisture Conditions	The article showed that water presence in <i>Carya illinoensis</i> wood significantly reduces its elasticity and static bending strength.
7	(Vivian et al., 2010b)	Effect of Pretreatments on Drying Rate of <i>Hovenia dulcis</i> Thunb. Wood	The article demonstrated how different pretreatments significantly influence the drying rate of Japanese raisin tree wood ( <i>Hovenia dulcis</i> Thunb.).
8	(Andrade et al., 2011)	Site Evaluation and Productivity of a 3-Year-Old <i>Eucalyptus urograndis</i> Stand in São Paulo	The article provided an integrated evaluation of silvicultural, chemical, and physical aspects of an <i>Eucalyptus urograndis</i> plantation in Brazil, offering important insights for sustainable forest management.

9	(Viera; Schumacher; Liberalesso, 2011)	Growth and Productivity of Monospecific and Mixed Plantations of Eucalyptus and Black Acacia	The article showed that interplanting <i>Eucalyptus urograndis</i> with <i>Acacia mearnsii</i> , a nitrogen-fixing leguminous tree, did not negatively impact growth or total wood productivity compared to monocultures.
10	(Balbinot; Favieiro, 2013)	A <i>Neuro-Fuzzy</i> System for Characterization of Arm Movements	The article contributed by developing and validating a system based on myoelectric signal analysis acquired via surface electrodes to characterize human arm movements.
11	(Furlong et al., 2013)	Estimating Daily Biomass Concentration of Microalgae <i>Synechococcus nidulans</i> Using <i>Neuro-Fuzzy</i> Network	The article presented a <i>Neuro-Fuzzy</i> estimator to predict biomass concentration of microalga <i>Synechococcus nidulans</i> from initial batch concentrations aiming at daily productivity estimation.
12	(Almeida et al., 2014)	Comparison Between Experimental and Calculated Values of Embedding Strength of <i>Pinus taeda</i> Wood	The article significantly contributed to understanding connection design in wooden structures with metal pins by analyzing the adequacy of the Brazilian standard ABNT NBR 7190:1997 recommendations.
13	(Silva et al., 2014)	Wheat Yield Estimation Related to Nitrogen Fertilization Using <i>Neuro-Fuzzy</i> Modeling	The article demonstrated the feasibility of using adaptive <i>Neuro-Fuzzy</i> inference systems to predict wheat yield under different nitrogen fertilization regimes.
14	(Freitas et al., 2015)	Anatomical and Physical-Mechanical Characterization of <i>Liquidambar sp.</i> Wood	This article provided a comprehensive characterization of anatomical and physical-mechanical properties of wood from eight-year-old <i>Liquidambar sp.</i> trees.
15	(Leonardi et al., 2015)	<i>Eucalyptus urograndis</i> Stem Proteome Response to Short-Term Cold Stress	The article presented an initial characterization of molecular responses of <i>Eucalyptus urograndis</i> to heat stress, especially cold, through stem proteomic analysis.
16	(Chiarello et al., 2016)	Production of Cellulosic Ethanol from Steam-Exploded <i>Eucalyptus urograndis</i> and Sugarcane Bagasse at High Total Solids and Low Enzyme Loadings	The article made a significant contribution by demonstrating advances in cellulosic ethanol production from lignocellulosic biomass using steam-exploded <i>Eucalyptus urograndis</i> and sugarcane bagasse.
17	(Medeiros Neto; Paes; Segundinho, 2016)	Determination of Modulus of Elasticity and Rupture of Woods by Non-Destructive and Destructive Methods	The article showed the viability of using non-destructive techniques based on longitudinal and transversal vibration frequencies and stress wave to assess stiffness and strength of woods from four forest species: eucalyptus ( <i>Corymbia citriodora</i> ), black laurel ( <i>Cordia alliodora</i> ), massaranduba ( <i>Manilkara sp.</i> ), and brazilwood ( <i>Caesalpinia echinata</i> ).
18	(Xavier et al., 2016)	Effect of Moisture Content and Loading Direction on the Strength of Nailed Joints in Plantation Woods	The article significantly evaluated how loading direction (parallel or perpendicular to fibers) and moisture content affect the strength of nailed joints in <i>Corymbia citriodora</i> , <i>Eucalyptus pellita</i> , and <i>Eucalyptus paniculata</i> woods.
19	(Jadidi et al., 2019)	Short-Term Electric Power Demand Forecasting Using NSGA II-ANFIS Model	This article made a significant contribution to enhancing load forecasting in electric smart grids by proposing a hybrid algorithm combining artificial intelligence techniques and evolutionary optimization methods.
20	(Silva; Silva, 2020)	Fuzzy Modeling Using Fuzzy Clustering Techniques and <i>Neuro-Fuzzy</i> Structures	The article presented the development and evaluation of a fuzzy modeling process for complex systems, using fuzzy clustering techniques (FC-Means and Subtractive Cluster) followed by optimization in a <i>Neuro-Fuzzy</i> system.
21	(Stefenon et al., 2021)	Hybrid Wavelet Stacking Ensemble Model for Insulator Contamination Forecasting	This article contributed to predictive fault detection in 13.8 kV porcelain pin insulators in electrical systems, using ultrasound equipment combined with modern machine learning techniques.
22	(Nogueira et al., 2023)	Experimental Study on Full-Scale Glulam Beams Manufactured with <i>Eucalyptus urograndis</i>	The article demonstrated the viability of using hybrid <i>Eucalyptus urograndis</i> in the production of glued laminated timber, highlighting its promise as a raw material for wood products.
23	(Godinho; Frigo; Caneppele, 2023)	<i>Neuro-Fuzzy</i> Modeling in Alcoholic Fermentation	This article presented a relevant contribution by applying mathematical modeling based on Fuzzy Logic and <i>Neuro-Fuzzy</i> Artificial Intelligence to optimize the alcoholic fermentation process of sugarcane must.
24	(Godinho et al., 2024)	Modeling Evaluation of Methods for Determining Basic Wood	The article made an important contribution applying <i>Neuro-Fuzzy</i> systems, particularly ANFIS (Adaptive

		Density in Forest Species Using a <i>Neuro-Fuzzy</i> Inference System	<i>Neuro-Fuzzy</i> Inference System), to predict basic density of various tree species influenced by multiple factors.
25	(Godinho; Caneppele; Floriano, 2024)	Application of <i>Neuro-Fuzzy</i> to Elephant Grass Production Process: A Systematic Bibliographic Review	Through a Systematic Literature Review, the study mapped opportunities and identified that integrating <i>Neuro-Fuzzy</i> systems in laboratory and industrial processes allows more precise and efficient predictive and control models for the bioenergy sector.
26	(Godinho; Fermino; Barreiros, 2025)	Kinetic Modeling and <i>Neuro-Fuzzy</i> Application in Ethanol Production	The article's main contribution was the integrated use of kinetic modeling and <i>Neuro-Fuzzy</i> techniques, specifically the ANFIS system, to optimize ethanol production from sugarcane juice.

While not focused on wood thermal modification, it strengthens the rationale for monitoring chemical by-products and potential ecotoxicity in thermal processes involving eucalyptus materials (Araújo et al., 2010).

The paper presents a hierarchical *Neuro-Fuzzy* method for macroscopic rock texture classification and automated extraction of interpretable fuzzy rules. Although outside the wood domain, it provides a transferable methodological template: *Neuro-Fuzzy* models can combine classification performance with interpretability—an attractive feature for industrial decision-support in wood processing contexts (Gonçalves & Leta, 2010).

The authors demonstrate that moisture conditions (PSF and equilibrium moisture) significantly affect impact strength and static bending of wood. Because thermal modification often targets hygroscopicity reduction, this evidence supports treating moisture-related variables as key predictors/outcomes in any future *Neuro-Fuzzy* modeling of thermally modified wood properties (Vivian et al., 2010a).

The study shows that water presence significantly reduces elasticity and bending strength in *Carya illinoensis* wood. This reinforces the centrality of moisture content as a driver of mechanical performance and, by extension, a critical variable to be modeled when evaluating processing routes that modify hygroscopic behavior (Stangerlin et al., 2010).

By demonstrating that different pretreatments influence drying rate, the work highlights that process history changes kinetics and efficiency. For thermal modification research, pretreatments can be treated as controllable inputs (features) in optimization-oriented *Neuro-Fuzzy* pipelines (Vivian et al., 2010b).

The article provides an integrated evaluation of silvicultural, chemical, and physical aspects of *Eucalyptus urograndis* stands. This supports the need for multidimensional datasets for predictive modeling, since wood behavior in later processing steps can be influenced by both material and site variables (Andrade et al., 2011).

The authors report that mixed plantations (eucalyptus + black acacia) do not reduce growth or productivity versus monocultures. Indirectly, this suggests that management practices can alter resource supply and potentially material properties, which are relevant covariates for property prediction frameworks in engineered wood products (Viera et al., 2011).

The paper proposes a *Neuro-Fuzzy* system to characterize arm movements from myoelectric signals, showing *Neuro-Fuzzy* performance in noisy, nonlinear signal contexts. Methodologically, this supports the suitability of *Neuro-*

*Fuzzy*/ANFIS for complex multivariate relationships— analogous to wood properties influenced by multiple interacting factors (Balbinot & Favieiro, 2013).

This study uses a *Neuro-Fuzzy* network to estimate daily microalgae biomass concentration from initial batch concentrations. Although unrelated to wood, it exemplifies predictive modeling where outputs are estimated from measurable process states—an approach transferable to predicting post-treatment wood properties from process parameters (Furlong et al., 2013).

The authors compare experimental versus calculated embedding strength values for *Pinus taeda* and discuss adequacy of ABNT NBR 7190:1997. This is directly relevant to engineering validation: future modeling (including *Neuro-Fuzzy*) should be benchmarked against experimental data and, where applicable, design-standard constraints (Almeida et al., 2014).

The work demonstrates *Neuro-Fuzzy* inference to predict wheat yield under varying nitrogen fertilization. As methodological evidence, it shows ANFIS capability to model nonlinear input–output relationships and supports its potential for multi-parameter optimization in industrial processes (Silva et al., 2014).

The article provides anatomical and physical-mechanical characterization of Liquidambar wood, supplying baseline descriptors useful for comparative studies before/after treatments. Such baseline property characterization is essential for building training datasets for later predictive modeling (Freitas et al., 2015).

The authors describe proteomic responses of *Eucalyptus urograndis* stems to short-term cold stress. While not thermal modification, it indicates that stressors can trigger measurable molecular changes; in advanced research, such markers may inform explanatory variables associated with physicochemical modifications (Leonardi et al., 2015).

The study advances cellulosic ethanol production from steam-exploded *Eucalyptus urograndis* and sugarcane bagasse, addressing process efficiency under high solids and low enzyme loading. This is adjacent evidence in lignocellulosic processing; it is not direct evidence for wood thermal modification, but illustrates thermal/chemical pretreatment relevance to biomass conversion workflows (Chiarello et al., 2016).

The authors show viability of non-destructive techniques (vibration, stress wave) to estimate stiffness and strength across species. This is directly useful for scaling data collection in future studies on thermally modified wood,

enabling larger datasets for modeling with lower cost and specimen damage (Medeiros Neto et al., 2016).

The paper evaluates how moisture and loading direction affect nailed-joint strength in plantation woods. Because thermal modification changes moisture uptake behavior, this evidence supports investigating downstream structural connection performance as an important outcome in treated wood applications (Xavier et al., 2016).

The NSGA II-ANFIS approach for short-term power demand forecasting illustrates a common optimization architecture: evolutionary multiobjective search coupled with ANFIS predictors. This is transferable for optimizing thermal modification parameters (time/temperature/atmosphere) with multiple property targets (Jadidi et al., 2019).

The article proposes fuzzy clustering followed by Neuro-Fuzzy optimization for complex system modeling. For wood datasets characterized by heterogeneity (species, density, moisture), clustering-then-ANFIS is a plausible approach to improve prediction accuracy and interpretability (Silva & Silva, 2020).

The hybrid ensemble model for insulator contamination forecasting shows how modern ML handles signal variability and prediction robustness. Although outside forestry, it reinforces that industrial prediction tasks require transparent validation strategies—an expectation that should guide future modeling of thermal modification outcomes (Stefenon et al., 2021).

The full-scale glulam beam study using *Eucalyptus urograndis* demonstrates material viability for engineered wood products. This is directly relevant as a downstream application context: if thermal modification is applied to eucalyptus for value-added products, mechanical performance at structural scale must be considered (Nogueira et al., 2023).

The Neuro-Fuzzy modeling in alcoholic fermentation applies fuzzy logic and Neuro-Fuzzy AI to optimize a bioindustrial process. In this review, it must be treated strictly as methodological analog evidence (optimization workflow) and not as direct evidence for wood thermal modification (Godinho et al., 2023).

This is the closest included study combining wood-related properties and Neuro-Fuzzy: ANFIS is applied to predict basic wood density across forest species influenced by multiple factors. It supports feasibility of Neuro-Fuzzy for wood property prediction, reinforcing a logical path to extend ANFIS models to post-thermal-modification properties in future research (Godinho et al., 2024).

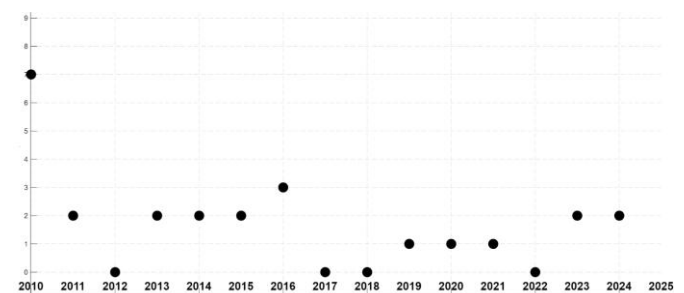
The systematic bibliographic review on Neuro-Fuzzy in elephant grass processes maps opportunities and highlights benefits in predictive/control modeling in bioenergy contexts. In the present manuscript, it should be used to justify Neuro-Fuzzy's broader applicability and review-driven gap identification, without implying direct contribution to wood thermal modification (Godinho et al., 2024).

The integrated kinetic modeling and ANFIS optimization for ethanol production demonstrates coupling mechanistic models with Neuro-Fuzzy to optimize complex processes. Here it is also methodological analog evidence only; it supports the proposed future agenda (hybrid modeling + optimization) for wood thermal modification once dedicated datasets become available (Godinho et al., 2025).

Based on the included evidence, *Neuro-Fuzzy* methods are consistently applied as efficient tools for modeling and optimizing complex industrial processes. However, within the scope of this review, no studies were identified that directly apply Neuro-Fuzzy to wood thermal modification; thus, the evidence supports an application gap rather than confirmed optimization results for ThermoWood processes.

To the best of the authors' knowledge, and within the scope and time window of this review, no studies were found applying *Neuro-Fuzzy*/ANFIS directly to wood thermal modification. This indicates a relevant evidence gap and supports future research focused on data pipelines and reproducible modeling frameworks.

Figure 3 shows the number of publications per year; 26 documents were found. All 26 were published in the last fifteen years (2010 to 2025), demonstrating the progress and importance of the addressed theme.



**Figure 3.** Number of included publications per year (2010–2025), based on the 26 included studies.

The data regarding (Figure 3) the number of publications per year show significant variation over the analyzed period, totaling 26 articles between 2010 and 2025. An initial peak is observed in 2010, with 7 publications, followed by a decrease and stabilization at lower levels in the following years, with small fluctuations between 1 and 3 publications annually.

Some years, such as 2012, 2017, 2018, and 2022, had no publications recorded. From 2019 onward, there is a slight resurgence in production, maintaining around 1 to 2 articles per year. This distribution suggests that the topic has received consistent attention, albeit with variations, reflecting possible shifts in academic community interest or availability of specific research. The accumulated total of 26 articles represents a reasonable body of literature supporting the research, allowing a consistent and updated analysis of the subject.

Figure 4 shows a word cloud developed from keywords extracted from the articles selected in the research. This visualization highlights the most frequent and relevant terms, facilitating the identification of the main topics addressed in the analyzed literature and contributing to a clearer understanding of trends and study focuses within the investigated field.

To produce the word cloud (Figure 4), a quantitative analysis was performed on the keywords extracted from the articles selected in the research.

Each term was counted according to its estimated frequency of occurrence, highlighting the most recurrent terms such as "*Neuro-Fuzzy* System" (12 occurrences), "Thermowood Modification" and "Physical Properties" (9



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