

*Systematic Review*

# Experimental and Analytical Methods in Nanotechnology-Based Wood Surface Treatments: A Systematic Review

Michał Rykaczewski , Izabela Betlej  and Piotr Boruszewski \* 

Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences—SGGW, 159 Nowoursynowska St., 02-776 Warsaw, Poland; [michal\\_rykaczewski@sggw.edu.pl](mailto:michal_rykaczewski@sggw.edu.pl) (M.R.); [izabela\\_betlej@sggw.edu.pl](mailto:izabela_betlej@sggw.edu.pl) (I.B.)

\* Correspondence: [piotr\\_boruszewski@sggw.edu.pl](mailto:piotr_boruszewski@sggw.edu.pl)

## Featured Application

The primary application of this review is to support the planning of future research on new wood protection agents based on nanomaterials. Additionally, it may contribute to the development of standardised assessment criteria for nanomaterial-based wood surface treatments. The findings are also intended to support the commercialisation of nanomaterial-based chemical products in the civil engineering sector.

## Abstract

The growing application of nanotechnology in wood modification has led to significant improvements in the durability, fire resistance, and biological stability of wood-based building materials, such as glued laminated timber (GLT), as well as related chemical products, including fire retardants and anticorrosion preservatives. While numerous review papers have focused on material performance and functionalisation strategies, a comprehensive analysis of the research methodologies employed in this field remains limited. This review addresses this gap by systematically examining the experimental and analytical methods used in studies on nanomaterial-modified wood surface treatments. Scientific articles published and indexed in the Web of Science and Scopus databases within the last ten years were selected using keywords related to wood, nanotechnology, and surface applications simulating industrial timber treatment processes applied in factories and construction sites. Publications were screened according to predefined inclusion and exclusion criteria. The study selection process was conducted according to the PRISMA methodology, and 74 studies meeting the inclusion criteria were selected for the final analysis. Extracted methodological features were coded and analysed using frequency-based descriptive statistics. Considerable methodological heterogeneity was observed among the analysed studies. Softwood species, TiO<sub>2</sub>- and ZnO-based nanomaterials, and brushing or immersion treatments represented the most frequently investigated research configurations. Scanning electron microscopy (SEM), often combined with EDS and XRD analyses, occupied a central role within the analytical framework of nanomodified wood research. In contrast, long-term durability assessments, biological resistance testing, and fire-performance evaluations were comparatively underrepresented. The review also revealed substantial variability in the use of testing standards and statistical methods. By linking research methodologies to normative requirements for construction materials, this work provides a methodological framework supporting future research, standardisation, certification, and commercial implementation of nanomaterial-based wood protection systems.



Academic Editor: Javier Orozco-Messana

Received: 26 May 2026

Revised: 19 June 2026

Accepted: 24 June 2026

Published: 29 June 2026

**Copyright:** © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

**Keywords:** wood; nanotechnology; nanomaterials; nanoparticles; wood modification; surface treatment; research methodologies

## 1. Introduction

Wood remains one of the most widely used renewable materials in construction and engineering due to its favourable strength-to-weight ratio, low environmental impact, and role in bioeconomy and carbon storage strategies [1–4]. However, moisture-induced degradation, biological attack, and weathering limit its long-term performance in outdoor and structural applications. Fungal decay and insect damage are among the most critical degradation mechanisms, contributing to significant economic losses worldwide [5–7]. As a result, numerous strategies have been developed to extend the service life of wood, including chemical modification, thermal treatment, coatings, and preservative systems [8–10].

Building upon these approaches, traditional wood protection methods have increasingly been supplemented by surface engineering strategies aimed at mitigating the most critical environmental impact, particularly ultraviolet radiation and moisture-related weathering processes, including rainfall exposure, water sprinkling, water absorption, humidity fluctuations, and wetting–drying cycles, which are primary drivers of weathering [11]. In this context, research has increasingly shifted toward multifunctional solutions, including nanomaterial-based coating systems.

Nanotechnology has emerged as a promising solution for wood modification due to the unique properties of nanomaterials, such as enhanced reactivity and the ability to penetrate the porous structure of the wood cell wall [12,13]. This penetration enables modification of surface chemistry and improved performance characteristics, including resistance to moisture and biological degradation [12,14]. Nanoparticles have been widely explored as active agents in wood preservatives, offering improved delivery efficiency, controlled release, and enhanced stability of basic compounds [15,16].

Recent research has also focused on developing bio-based, eco-friendly nanostructured systems for wood protection. Examples include chitosan-nanoparticle-encapsulated essential oils, which provide antimicrobial and barrier functions while aligning with green chemistry principles [16]. Similarly, nanocomposite coatings incorporating materials such as graphene, clay minerals, and bio-based polymers have demonstrated improved fire resistance and thermal stability [17,18]. Graphene-based systems, in particular, act as effective thermal and oxygen barriers, thereby reducing ignition risk and enhancing char formation during combustion [18].

Advances in surface engineering are driving the development of multifunctional coatings, such as superhydrophobic sol–gel systems, which dramatically enhance water repellency and durability of wood surfaces [15]. This shift marks a decisive move toward eco-friendly polymer nanocomposites, as bio-based or hybrid flame retardant systems replace traditional toxic options, reducing environmental impact while elevating performance [17].

Despite the growing number of studies on nanomaterial-modified wood systems, there remains a lack of systematic analysis of the experimental and analytical methodologies used in this field. Existing reviews primarily emphasize material performance, functional improvements, or specific modification strategies, while methodological consistency, testing standards, and comparative evaluation of analytical techniques remain underexplored [8]. This gap is particularly relevant given the diversity of characterisation methods applied in the field, including morphological and microstructural analysis (SEM, TEM), chemical characterisation (FTIR, EDS), thermal analysis (TGA, DTG), mechanical testing, durability assessment, and fire performance evaluation [11,18].

Furthermore, concerns regarding long-term environmental impact, health safety, and scalability of nanotechnology-based wood treatments highlight the need for standardised testing approaches [12,15]. Addressing these challenges is essential for translating laboratory-scale innovations into reliable, industrially applicable wood protection technologies.

The aim of this study was to systematically analyse and categorise current research approaches in the field of nanomodified wood coatings. The review focuses on identifying and quantifying the most commonly used nanomaterials, wood substrates, application methods, and experimental techniques reported in the literature. In addition, the study evaluates the frequency and scope of physicochemical, mechanical, biological, and durability-related testing methods, as well as the use of standardised testing procedures. Particular attention was given to the reporting practices and the application of normative standards. Based on this analysis, key research trends, methodological gaps, and areas requiring further development were identified to support the advancement of more robust, reproducible, and standardised approaches in nanotechnology-based wood protection systems.

## 2. Methods

To ensure a transparent and reproducible selection process of the relevant literature, the study followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [19,20]. A systematic search was conducted in major scientific databases, including Scopus and Web of Science, using predefined keywords related to wood and nanomaterial-based surface treatments. The following search queries were used:

The Web of Science query was as follows:

TS = (wood)

AND AK = (nanotechnology OR nanomaterial\* OR nanoparticle\*)

AND TS = (surface\* OR coating\*)

AND PY = (2016–2026)

The Scopus query in material sciences, chemistry, chemical engineering, engineering, and multidisciplinary was as follows:

KEY (wood)

AND TITLE-ABS-KEY (nanotechnology OR nanomaterial\* OR nanoparticle\*)

AND TITLE-ABS-KEY (surface\* OR coating\*)

AND PUBYEAR > 2015 AND PUBYEAR < 2027

The initial search yielded 1505 records. After removing duplicates and applying the selection criteria described in Figure 1, 470 studies remained for title and abstract screening. During this stage, studies unrelated to nanomaterial-modified wood or lacking an experimental focus were excluded. The eligibility criteria applied during title and abstract screening (step 2.2 in the PRISMA diagram) are presented below.

Studies were eligible for inclusion if they were as follows:

- (a) Investigated nanomaterial-based coatings, surface treatments, or impregnation systems intended for wood protection or wood modification;
- (b) Reported experimental evaluation of coating, treatment, material, or functional properties;
- (c) Were published in peer-reviewed journals indexed in the Web of Science or Scopus databases and were accessible in full-text form.

Studies were excluded if they were as follows:

- (a) Focused solely on the synthesis or characterisation of nanomaterials without evaluating their application in wood-surface treatment systems;
- (b) Investigated nanomaterial modification of bulk wood without a surface treatment, coating, or impregnation component;
- (c) Did not include experimental testing of the coating, treatment system, or treated substrate;
- (d) Were review articles, conference abstracts, editorials, or other non-original research publications;
- (e) Were not available in full-text form.

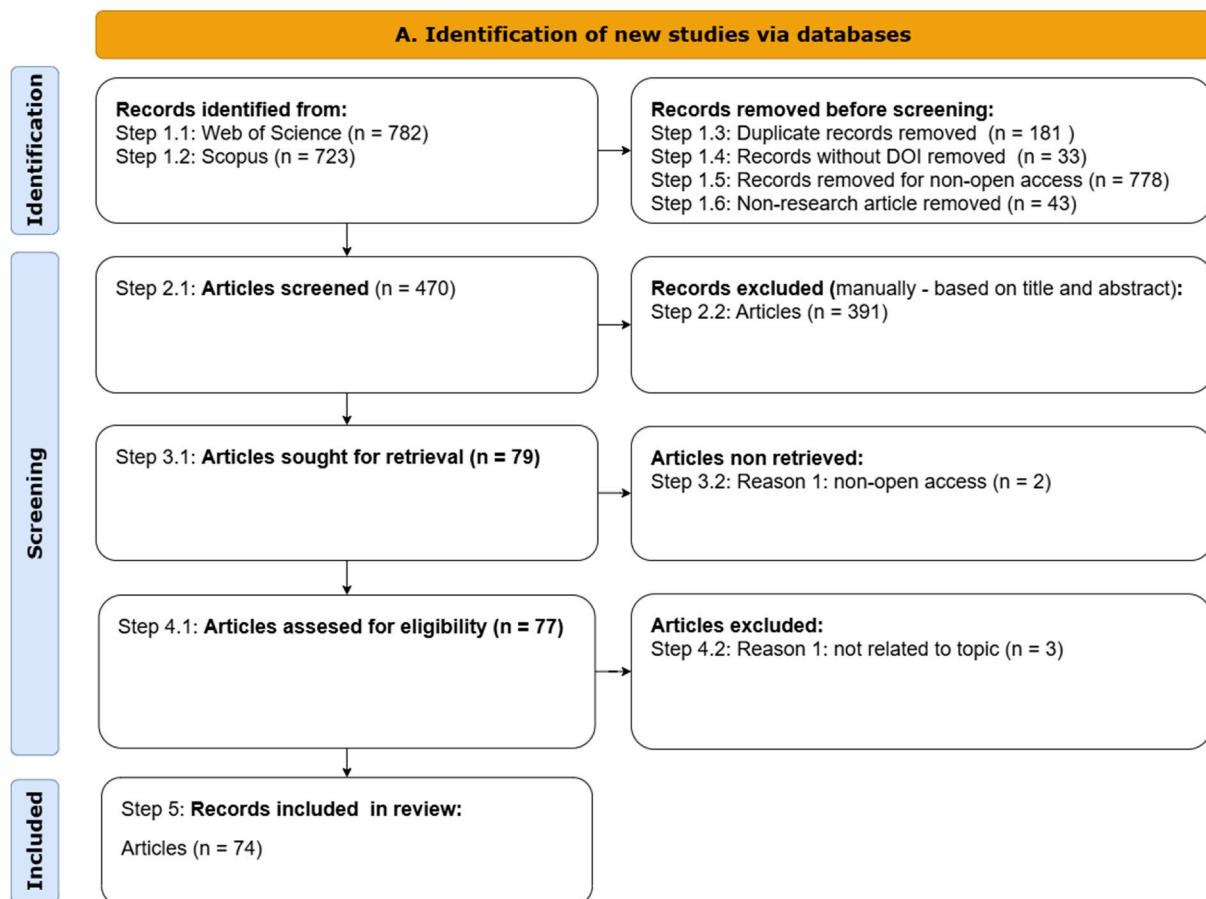
Studies evaluating coatings on model substrates such as glass or steel were retained when the investigated systems were specifically developed for wood protection or wood surface treatment applications.

Ultimately, 74 studies were included in the final analysis. The study selection process is illustrated in the PRISMA flow diagram.

Data extracted from the studies included the occurrence of physicochemical and instrumental analysis methods; mechanical and physical property assessments; durability tests, including biological resistance and artificial ageing methods; human safety tests; statistical methods; and testing standards used in the analysed publications.

Additional variables included the type of base material used for impregnation, treatment technology, applied nanoparticles, and the testing standards reported in the studies.

In cases of incomplete methodological descriptions, only explicitly reported data were included in the analysis. Eligible studies were categorised according to the reported methodologies and could be assigned to more than one category when multiple methods were described.



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

Data extraction and coding were performed manually after reviewing the publications. Each feature was individually assessed and coded as a binary variable, as follows: 1 for presence, 0 for absence.

Descriptive statistical analyses were performed using MS Excel 2013 (Microsoft, Redmond, WA, USA). The extracted data were synthesised using frequency analysis. For each feature, the occurrence count ( $n$ ) and relative frequency (%) among all included articles ( $N = 74$ ) were calculated. The results were presented in tabular form to facilitate comparison of methodological approaches reported in the literature.

Additionally, binary co-occurrence and similarity analyses were conducted in R (R Foundation for Statistical Computing, Vienna, Austria). The binary data matrix was used to assess pairwise associations among categorical variables, including treated materials, nanoparticle type, application methods, and testing methods. Co-occurrence patterns were evaluated using presence–absence data, enabling the identification of frequently co-occurring feature combinations and similarity structures within the dataset. The results were visualised using a heatmap.

Due to the methodological nature of the review and the absence of a quantitative synthesis of the experimental results, formal risk of bias assessment, heterogeneity analyses, sensitivity analyses, and formal evaluation of certainty of evidence were not conducted.

An internal review protocol specifying the search strategy, eligibility criteria, and data extraction procedures was prepared prior to conducting the literature search; however, it was not formally registered or publicly available. No major deviations from the original review protocol occurred during the review process.

The datasets generated and analysed during the current study, including literature screening records and extracted methodological data, are available from the corresponding author upon reasonable request.

### 3. Results

A total of 74 studies met the predefined inclusion criteria and were included in the final analysis. The selected publications investigated nanomaterial-based wood-treatment systems, encompassing treatment materials and application methods, physicochemical and instrumental characterisation techniques, durability assessment procedures, and evaluations of mechanical, physical, biological, and fire-related properties. The review also examined the use of standardised testing methods and statistical approaches. To facilitate a systematic comparison of the reported methodologies, the extracted data were organised into thematic blocks, including wood species, nanomaterial type, application method, characterisation techniques, evaluated properties, testing standards, and statistical methods. Due to the dataset's multi-label binary structure, each thematic block was analysed separately.

Among the studies assessed for eligibility, three articles were excluded after full-text review despite their apparent relevance during title and abstract screening. Two studies focused primarily on nanoparticle synthesis and characterisation without evaluating the performance of the resulting wood-treatment systems [21,22], while one study investigated nanoparticle properties and mechanisms of action without assessing their effect on wood-treatment performance [23].

The reasons for exclusion further define the scope of the present review, which focuses on nanomaterial-based wood-treatment technologies and their performance rather than on nanoparticle development and characterisation alone.

#### 3.1. Materials and Application of Wood Surface Treatments

The most commonly used nanoparticles were TiO<sub>2</sub> (31% of publications) and zinc oxide (ZnO) (28% of publications). Moving to the next group, SiO<sub>2</sub>, silver, and copper-based nanoadditives were reported in 14%, 12%, and 11% of the reviewed articles, respectively.

Nanocellulose- and lignin-based nanomaterials represented smaller but increasingly important groups of bio-based modifiers. The nanocellulose category included nanofibrillated cellulose (NFC) [24,25], cellulose nanocrystals (CNCs) [26], and nitrocellulose nanoparticles [27]. These materials were incorporated into coating formulations and surface-treatment systems as bio-based nanoscale additives in 8% of publications.

The nanolignin category comprised kraft lignin [28,29], acetylated lignin [28], organo-solv lignin [30], and lignin nanoparticles (LNPs) produced from different biomass sources [28,29,31]. The analysed studies demonstrated a diversity of lignin-based materials and preparation methods, ranging from chemically modified lignins to engineered lignin nanoparticles intended for incorporation into wood protection systems.

Finally, other or less frequently used nanoparticles were reported in 16% of the reviewed articles. The results are presented in Table 1.

**Table 1.** Overview and frequency of nanomaterial additives in the reviewed studies.

| No. | Nanoparticles                        | Frequency of Occurrence (n) | Relative Frequency [%] | References                   |
|-----|--------------------------------------|-----------------------------|------------------------|------------------------------|
| 1   | Titanium dioxide (TiO <sub>2</sub> ) | 23                          | 31                     | [26,32–53]                   |
| 2   | Zinc oxide (ZnO)                     | 21                          | 28                     | [36,38–40,45,46,50–52,54–65] |
| 3   | Silicon dioxide (SiO <sub>2</sub> )  | 10                          | 14                     | [50,66–74]                   |
| 4   | Silver (Ag)                          | 9                           | 12                     | [46,75–82]                   |
| 5   | Copper/Copper oxide (Cu, CuO)        | 8                           | 11                     | [41,60,63,83–87]             |
| 6   | Nanolignin                           | 6                           | 8                      | [28–31,35,88]                |
| 7   | Nanocellulose                        | 6                           | 8                      | [24–27,88,89]                |
| 8   | Other nanoparticles                  | 12                          | 16                     | [40,46,65,70,90–96]          |

The most commonly tested wood substrate was softwood (41% of articles), suggesting applications primarily in the building sector. Hardwood was reported in 26% of studies, while exotic wood species accounted for 12% of publications, representing a second major application area potentially related to furniture and high-value products. Poplar wood was excluded from the hardwood category due to its distinct mechanical properties. In European standards, poplar is often classified separately from typical hardwood species and is sometimes grouped with softwood species [97–99]. Other tested materials, such as bamboo and rigid panels (e.g., steel or glass substrates), were each represented in approximately 5% of publications. In several studies, steel and glass were used as model substrates to characterise coating properties, transparency, photocatalytic activity, and nanoparticle distribution in coating systems intended for wood protection applications. Approximately 19% of studies involved other individually reported materials. The distribution is presented in Table 2.

**Table 2.** Overview and frequency of treated substrate types in the reviewed studies.

| No. | Materials                        | Frequency of Occurrence (n) | Relative Frequency [%] | References                                                                |
|-----|----------------------------------|-----------------------------|------------------------|---------------------------------------------------------------------------|
| 1   | Softwood                         | 30                          | 41                     | [24,27–29,32,39,41,42,44,47–51,55,56,59,66,67,70,72,73,81,84,86,90–93,95] |
| 2   | Hardwood                         | 19                          | 26                     | [25,28,31,38–40,44,54,58,64,67,72,74,78,80,86,93–95]                      |
| 3   | Poplar                           | 5                           | 7                      | [43,76,77,87,96]                                                          |
| 4   | Exotic wood                      | 9                           | 12                     | [33,36,37,52,57,71,79,89,100]                                             |
| 5   | Bamboo                           | 4                           | 5                      | [61,62,68,86]                                                             |
| 6   | Steel/glass plates               | 5                           | 5                      | [26,34,45,65,69]                                                          |
| 7   | Other materials/<br>unnamed wood | 14                          | 19                     | [26,30,35,45,46,53,60,63,69,75,82,83,85,88]                               |

In 30 articles (41%), nanoparticle synthesis was performed prior to wood treatment. Subsequently, the application was performed using the methods described in Table 3.

The most common methods were brushing and immersion, reported in 32% and 27% of the articles, respectively. Vacuum-based techniques ranked third, accounting for 15% of publications. Other treatment methods, such as pressure impregnation and layer-by-layer (LbL) assembly, were used less frequently.

**Table 3.** Overview and frequency of treatment application methods in the reviewed studies.

| No. | Methods                      | Frequency of Occurrence (n) | Relative Frequency [%] | References                                                       |
|-----|------------------------------|-----------------------------|------------------------|------------------------------------------------------------------|
| 1   | Brushing                     | 24                          | 32                     | [24,29,35,38,40,41,44–47,52,54,58–60,63,65,70,75,80,81,84,93,94] |
| 2   | Spraying                     | 6                           | 8                      | [37,39,41,53,57,69]                                              |
| 3   | Immersion                    | 20                          | 27                     | [31,32,41,48–50,53,57,58,61,66,73,74,76,77,80,86,87,92,93]       |
| 4   | Vacuum impregnation          | 11                          | 15                     | [28,51,52,66,67,72,86,87,91,92,95]                               |
| 5   | Vacuum-pressure impregnation | 5                           | 7                      | [33,42,48,72,79]                                                 |
| 6   | Pressure impregnation        | 3                           | 4                      | [63,83,84]                                                       |
| 7   | Layer-by-layer (LbL)         | 4                           | 5                      | [36,43,55,100]                                                   |
| 8   | Other methods                | 7                           | 9                      | [26,27,62,64,82,88,96]                                           |

### 3.2. Physicochemical and Instrumental Analysis Methods

Data related to spectroscopic and X-ray characterisation methods are presented in Table 4. The most commonly used spectroscopic methods were FTIR (28% of articles) and UV-Vis (DRS) (22%). The most widely used X-ray-based methods were EDS (EDX) and XRD, reported in 38% and 26% of articles, respectively. These techniques were primarily used for chemical composition analysis and structural characterisation.

**Table 4.** Overview and frequency of spectroscopic and X-ray characterisation methods in the reviewed studies.

| No. | Methods            | Frequency of Occurrence (n) | Relative Frequency [%] | References                                                          |
|-----|--------------------|-----------------------------|------------------------|---------------------------------------------------------------------|
| 1   | FT-IR              | 21                          | 28                     | [29–31,33,42,43,53,54,58,61–63,67,71,72,78,82,87,90,91,94]          |
| 2   | FT-IR-ATR          | 17                          | 23                     | [25,26,29,34,42,47,50,52,55,58,60,62,67,78,91,94,96]                |
| 3   | UV-vis (DRS)       | 16                          | 22                     | [24,26,31,32,34,35,37,39,45,53,55,62,69,73,94,95]                   |
| 4   | Raman spectroscopy | 2                           | 3                      | [90,94]                                                             |
| 5   | XPS                | 3                           | 4                      | [63,86,90]                                                          |
| 6   | XRD                | 19                          | 26                     | [25,33,37,42,43,45,48,53,54,56–58,61,76,83,86,87,94,95]             |
| 7   | XRPD               | 2                           | 3                      | [32,58]                                                             |
| 8   | EDS/EDX            | 28                          | 38                     | [33,35,36,39,40,42–45,48,50–54,57,58,60,61,66,67,72,76,86,90,94–96] |
| 9   | XAFS               | 3                           | 4                      | [60,63,83]                                                          |

Microscopic techniques used in the reviewed studies are presented in Table 5. The most commonly applied method was scanning electron microscopy (SEM), reported in 57% of the articles, including its high-resolution variant FE-SEM. These techniques were primarily used to examine surface morphology, coating distribution, and nanoparticle dispersion on wood substrates. Transmission electron microscopy (TEM) and scanning

transmission electron microscopy (STEM) were reported in approximately 24% of the studies and were mainly used for nanoscale structural characterisation of nanoparticles and coating systems. In the reviewed literature, TEM and STEM were often reported jointly without clear methodological separation.

**Table 5.** Overview and frequency of microscopy techniques in the reviewed studies.

| No. | Techniques              | Frequency of Occurrence ( <i>n</i> ) | Relative Frequency [%] | References                                                                                               |
|-----|-------------------------|--------------------------------------|------------------------|----------------------------------------------------------------------------------------------------------|
| 1   | SEM                     | 42                                   | 57                     | [25,27,29,32,34–36,39,40,42–45,47,48,50,51,53–56,58,61,62,66,67,71–73,75,77,80,83,84,86–88,90,94–96,100] |
| 2   | FE-SEM                  | 15                                   | 20                     | [25,26,35,42,44,49,52,57,58,69,72,76,77,80,83]                                                           |
| 3   | TEM/STEM                | 18                                   | 24                     | [25,37,45,47,56,60,63,66,72,75–77,79,80,83,86,90,95]                                                     |
| 4   | AFM                     | 8                                    | 11                     | [25,32,49,55,61,76,79,88]                                                                                |
| 5   | Optical microscopy (OM) | 5                                    | 7                      | [27,51,58,81,94]                                                                                         |
| 6   | CLSM                    | 4                                    | 5                      | [39,40,64,70]                                                                                            |

In addition, atomic force microscopy (AFM), optical microscopy (OM), and confocal laser scanning microscopy (CLSM) were also used, although less frequently. These techniques were used to analyse surface topography, microstructural features, and three-dimensional surface characteristics of nanomodified wood materials.

According to current nanomaterial characterisation guidelines, SEM- and TEM-based methods provide direct imaging of deposited nanoparticles and enable the determination of particle morphology, agglomeration state, and particle size distributions from micrographs [101]. AFM complements electron microscopy by providing three-dimensional surface topography and height measurements at the nanoscale, while CLSM enables visualisation of coating architecture and spatial distribution of selected components within multilayer systems [101].

The identified microscopy techniques provided complementary information on coating structure and wood surface characteristics. SEM and FE-SEM were primarily used for the observation of surface morphology, coating coverage, and nanoparticle distribution, whereas TEM/STEM enabled the characterisation of nanoparticle size, shape, and internal nanostructure. AFM was applied to assess nanoscale surface topography and roughness through three-dimensional surface mapping. Optical microscopy was mainly used for the evaluation of macroscopic surface features and coating defects, while CLSM provided three-dimensional visualisation of coating layers and the spatial distribution of selected components within the analysed systems.

Thermogravimetric methods are presented in Table 6. The most commonly applied technique was thermogravimetric analysis (TGA), reported in 19% of the articles, which was used to evaluate the thermal stability and decomposition behaviour of nanomodified wood coatings and their components. Derivative thermogravimetry (DTG), reported in 7% of studies, was used to determine the rate of mass loss and to identify characteristic degradation stages of the investigated materials.

**Table 6.** Overview and frequency of thermogravimetric methods in the reviewed studies.

| No. | Methods | Frequency of Occurrence (n) | Relative Frequency [%] | References                                |
|-----|---------|-----------------------------|------------------------|-------------------------------------------|
| 1   | TGA     | 14                          | 19                     | [25,27–29,32,34,36,42,43,53,54,66,87,100] |
| 2   | DTG     | 5                           | 7                      | [28,42,43,53,87]                          |
| 3   | DSC     | 3                           | 4                      | [29,34,54]                                |

The frequencies of particle-size-, dispersion-, and colloidal-stability-related properties are summarised in Table 7. Dynamic light scattering (DLS) was the most frequently used technique, reported in 12% of the articles and was applied to determine particle size distribution and assess the dispersion state of nanoparticles in liquid formulations. Zeta potential and viscosity measurements were each reported in 4% of the studies. Zeta potential was used to evaluate the electrokinetic stability of nanoparticle suspensions, while viscosity measurements characterised the rheological behaviour of coating formulations and their suitability for application processes, such as brushing, spraying, or impregnation. The determination of the zeta potential and the isoelectric point of particles (when stabilised by surface charge) can also provide supporting information on the stability of nanomaterials in dispersion [102].

**Table 7.** Overview and frequency of particle size, dispersion, and colloidal properties in the reviewed studies.

| No. | Methods                           | Frequency of Occurrence (n) | Relative Frequency [%] | References                   |
|-----|-----------------------------------|-----------------------------|------------------------|------------------------------|
| 1   | DLS                               | 9                           | 12                     | [27,34,54,55,63,72,73,88,90] |
| 2   | Zeta potential                    | 3                           | 4                      | [27,29,72]                   |
| 3   | Viscosity/rheological measurement | 3                           | 4                      | [26,27,34]                   |

DLS determines the hydrodynamic diameter of nanoparticles dispersed in liquid systems and is particularly useful for evaluating particle dispersion prior to coating application [101]. However, the method does not distinguish between individual particles and agglomerates and may overestimate particle size due to the influence of hydration layers and particle clustering [101]. Consequently, DLS is frequently complemented by imaging techniques such as SEM or TEM when detailed nanoparticle characterisation is required.

A wide range of guidance documents for nanomaterial characterisation has been developed by the Organisation for Economic Co-operation and Development (OECD), including the OECD Series on the Safety of Manufactured Nanomaterials and Other Advanced Materials and the OECD Guidelines for the Testing of Chemicals [101,102]. Some dedicated OECD documents describe analytical methods, such as AFM, DLS, EM, PTA, SAXS, SEM, and TEM. These documents provide general principles, dosimetry considerations, and sample preparation procedures for physical–chemical, environmental, ecotoxicological, and toxicological testing. They also include annexes listing relevant OECD Test Guidelines and Guidance Documents, as well as recommendations for reporting data on stock dispersions [102].

The application of OECD-recommended procedures can improve the planning, comparability, and reproducibility of nanomaterial testing; however, such approaches were only occasionally reported in the reviewed studies.

### 3.3. Nanotechnology-Based Wood-Surface-Treatment Properties

After the identification of the physicochemical and instrumental analysis methods reported in the reviewed articles, the test methods used to assess the functional properties of the nanomodified wood treatments were analysed. All parameters were classified into the following two main groups: physical and mechanical properties of the coatings and their durability-related properties.

The first group includes water- and moisture-related properties, such as contact angle; surface functional properties, such as gloss and self-cleaning ability; and mechanical and surface properties, including abrasion resistance, surface roughness, and hardness.

The second group comprises biological resistance assessments and ageing and weathering tests used to evaluate the long-term performance and stability of nanomodified wood coatings under environmental exposure.

#### 3.3.1. Mechanical and Physical Properties

The most commonly investigated parameter was the contact angle, reported in 32% of the articles, which was primarily used to evaluate the surface wettability and the hydrophobic or hydrophilic character of the nanomodified wood coatings. Water absorption was assessed in 11% of the reviewed studies and was used to quantify the overall water uptake of the treated wood systems under immersion or exposure conditions. Hygroscopicity, reported in 7% of articles, was used to describe the moisture sorption behaviour under varying relative humidity conditions.

Swelling behaviour after water exposure was less frequently evaluated and was reported in only 3% of the reviewed studies, typically expressed in terms of anti-swelling efficiency (ASE), which describes the effectiveness of treatments in reducing dimensional changes in wood under moisture exposure. All water and moisture-related properties are presented in Table 8.

**Table 8.** Overview and frequencies of the water- and moisture-related properties in the reviewed studies.

| No. | Parameters                  | Frequency of Occurrence (n) | Relative Frequency [%] | References                                                 |
|-----|-----------------------------|-----------------------------|------------------------|------------------------------------------------------------|
| 1   | Contact angle (wettability) | 24                          | 32                     | [28,29,38,40,43,49,52–55,57,62,64,67–71,73,75,82,88,93,96] |
| 2   | Water absorption            | 8                           | 11                     | [33,37,53,66,67,73,87,89]                                  |
| 3   | Hygroscopicity              | 5                           | 7                      | [28,29,55,69,94]                                           |
| 4   | Swelling (ASE)              | 2                           | 3                      | [33,67]                                                    |

The influence of the nanomaterials on the colour parameters according to the CIELAB system was investigated in 38% of the reviewed articles. These measurements were primarily used to quantify the changes in the lightness ( $L^*$ ), chromatic coordinates ( $a^*$ ,  $b^*$ ), and overall colour difference ( $\Delta E$ ), enabling an assessment of the aesthetic stability and potential discolouration effects of the nanomodified coatings over time.

Gloss measurements were reported in 11% of the studies and used to evaluate changes in surface reflectance, which is closely related to the optical appearance of the treated wood. Self-cleaning and photocatalytic activity were reported in 14% of the articles; however, these terms were not consistently distinguished in the analysis.

Hardness was measured in about 15% of the articles and surface roughness in 9% of the studies.

The surface functional properties used in the reviewed studies are presented in Table 9.

**Table 9.** Overview and frequencies of the surface functional properties in the reviewed studies.

| No. | Parameters                                       | Frequency of Occurrence ( <i>n</i> ) | Relative Frequency [%] | References                                                    |
|-----|--------------------------------------------------|--------------------------------------|------------------------|---------------------------------------------------------------|
| 1   | Colour parameters (CIELAB)                       | 28                                   | 38                     | [24,28,29,31,35,37–40,47–51,54,55,57–59,62,65,70,74,81,93–96] |
| 2   | Gloss                                            | 8                                    | 11                     | [25,35,38,40,59,75,81,93]                                     |
| 3   | Photocatalytic activity/self-cleaning properties | 10                                   | 14                     | [29,32,33,44,45,47,53,56,69,73]                               |
| 4   | Surface roughness                                | 7                                    | 9                      | [29,39,50,64,70,74,96]                                        |
| 5   | Hardness                                         | 7                                    | 9                      | [35,42,50,56,65,75,94]                                        |
| 6   | Pencil hardness                                  | 4                                    | 5                      | [25,35,54,64]                                                 |

The surface mechanical properties of the materials were most commonly tested using abrasion resistance (about 15% of articles). Some studies also examined the effect of impregnation on the strength properties of wood, particularly compression parallel to the grain.

In surface film coatings, elongation was reported in 5% of the articles, while coating adhesion was evaluated in 7% of the articles, typically to assess the bonding strength between the coating layer and the wood substrate. All data are presented in Table 10.

**Table 10.** Overview and frequencies of the mechanical and surface properties in the reviewed studies.

| No. | Parameters                  | Frequency of Occurrence ( <i>n</i> ) | Relative Frequency [%] | References                         |
|-----|-----------------------------|--------------------------------------|------------------------|------------------------------------|
| 1   | Abrasion resistance         | 11                                   | 15                     | [25,29,35,53,60,64,68,73,75,83,84] |
| 2   | Strength properties         | 6                                    | 8                      | [24,26,50,66,87,89]                |
| 3   | Tensile strength/elongation | 4                                    | 5                      | [25,26,75,82]                      |
| 4   | Coating adhesion            | 5                                    | 7                      | [24,35,37,75,80]                   |

### 3.3.2. Durability Tests

The most commonly reported test related to the biological durability of nanocoatings was decay fungi resistance, noted in 15% of the reviewed articles. Studies were also conducted on resistance to mould fungi (9% of articles) and the antibacterial properties of wood with nanomodified treatments (8%). A limited number of studies investigated insect resistance, suggesting a research gap in this area (3% of articles). Biological resistance properties used in the reviewed studies are presented in Table 11.

**Table 11.** Overview and frequencies of biological resistance in the reviewed studies.

| No. | Parameters             | Frequency of Occurrence ( <i>n</i> ) | Relative Frequency [%] | References                         |
|-----|------------------------|--------------------------------------|------------------------|------------------------------------|
| 1   | Decay fungi resistance | 11                                   | 15                     | [30,48,50,51,54,56,58,78,79,81,90] |
| 2   | Mould resistance       | 7                                    | 9                      | [44,58,61,76,77,86,93]             |
| 3   | Antibacterial activity | 6                                    | 8                      | [32,45,46,75,82,95]                |
| 4   | Insect resistance      | 2                                    | 3                      | [52,92]                            |

The most common ageing factors in the reviewed articles were UV exposure (36% of articles) and leaching (16%). Some studies also evaluated the durability of nanocoatings under humidity fluctuations, high-temperature exposure, and natural weathering (each reported in approximately 8% of articles). Less frequently, acid and alkaline exposure, as well as water exposure (mostly applied in ageing chamber conditions), were considered

(below 5% of articles). The frequencies of ageing and weathering resistance tests are presented in Table 12.

**Table 12.** Overview and frequencies of ageing and weathering resistance tests in the reviewed studies.

| No. | Tests                     | Frequency of Occurrence ( <i>n</i> ) | Relative Frequency [%] | References                                                                |
|-----|---------------------------|--------------------------------------|------------------------|---------------------------------------------------------------------------|
| 1   | UV exposure               | 27                                   | 36                     | [28,29,31,33–35,38–40,44,46,47,49,54,55,57,59,62,64,65,68–70,74,93,94,96] |
| 2   | IR exposure               | 3                                    | 4                      | [58,65,74]                                                                |
| 3   | Water exposure            | 4                                    | 5                      | [39,40,64,70]                                                             |
| 4   | Humidity fluctuations     | 6                                    | 8                      | [28,29,39,40,74,94]                                                       |
| 5   | High temperature exposure | 6                                    | 8                      | [39,40,70,74,80,87]                                                       |
| 6   | Acid and alkali exposure  | 3                                    | 4                      | [53,68,73]                                                                |
| 7   | Natural weathering        | 5                                    | 7                      | [24,51,53,63,83]                                                          |
| 8   | Leaching                  | 12                                   | 16                     | [28,33,49,57,60,63,76,77,86,90,91,95]                                     |

Nanomaterials can be used as antimicrobial and antifungal coatings and impregnation agents. Wood preservation treatments are essential for increasing the service life of timber by imparting bactericidal, fungicidal, and insecticidal properties [85]. The analysed literature indicates that studies related to biological degradation and ageing of nanomodified materials (excluding UV durability tests) account for less than 15% of the reviewed articles, highlighting a significant research gap in this area.

### 3.4. Human Safety Tests End Environmental Impact

Research on the safety assessment of nano-based wood treatments was reported in only five of the reviewed articles (7%), indicating an important research gap in this area. The methods and findings of these studies are summarised and discussed in relation to key guidelines for the design of safe and sustainable nanomaterial-based products proposed by OECD [103].

Most research on nanomaterial safety has focused on nanoparticles of Cu compounds [41,83,85]. Analysis of the most important human health effects associated with nanoscale copper-based wood preservatives was conducted using the SUNDS methodology [104,105]. The Decision Support System developed within the EU FP7 SUN project was designed to estimate environmental, occupational, and consumer health risks associated with nanomaterials used in industrial products throughout their life cycle [41,85]. Based on simulations and risk assessment methods applied to nano-treated wood products, the main exposure scenarios identified were as follows:

- Inhalation of nanoparticles by workers during the preparation of coating formulations involving the handling and mixing of nanoscale powders;
- Inhalation or accidental ingestion of nanoparticles by workers during mechanical processing operations, such as scraping, sanding, and sawing of nano-treated wood;
- Hand-to-mouth transfer of nanoparticles from impregnated wood surfaces, representing a particularly relevant exposure pathway for children.

Due to these risks, nanoparticles can enter the mouth and digestive system or the lungs via inhalation [85].

Safety studies of potentially hazardous particles released during the abrasion of nanoparticle-treated wood were conducted using micronised copper azole (MCA)-treated wood as an example. Particle size distribution was analysed to estimate potential deposition in the respiratory system. Toxicological evaluation was performed in vitro using human lung cells (A549) and immune system cells (THP-1-derived macrophages). Cellular

responses were assessed using cytotoxicity measurements and oxidative stress indicators, such as reactive oxygen species (ROS) production determined by the DCF assay. The results suggested that the observed cytotoxicity of MCA was more likely associated with released  $\text{Cu}^{2+}$  ions rather than with nanoparticles themselves. Therefore, toxicity assessment of nanoparticle-based wood coatings and preservatives should include not only nanoparticle effects but also all components of impregnation formulations, as well as potentially hazardous particles released during the service life of nanoparticle-treated wood [84].

An important method used for testing dermal transfer of nanomaterials is the CPSC wipe sampling method. In this procedure, a cloth was dragged over a 50 cm distance across treated samples, and the copper retained on the cloth was subsequently extracted with nitric acid. In addition, abrasion-based sampling was performed to simulate board wear, in which weathered samples were sanded, and the amount of copper released immediately after sanding was quantified [83].

Simulated dermal contact tests showed that potential exposure is strongly associated with the degradation of the coated material. Leaching experiments show a decrease in zinc nanoparticle release after lumber ageing, whereas dermal contact studies indicate increased potential exposure when coatings are applied to aged substrates [63]. It is the reason why coatings should be applied soon after drying lumber, as this reduces nanoparticle removal during dermal contact tests [60].

As the marketing and application of nano-enabled products continue to expand in both commercial and residential sectors, there is a growing need to develop reproducible methods for quantifying the release and transformation of nanoparticle-based additives under realistic use conditions. Risk assessment approaches include quantitative methods incorporating risk-control measures across the life cycle of nano-enabled products, which are of practical relevance for industrial applications [85].

A wide range of safety testing and risk-assessment frameworks for nanomaterials has been developed by the Organisation for Economic Co-operation and Development (OECD), which provides methodological guidance for the further development of research in this field [101,103,106,107].

Current regulatory frameworks for furniture and building materials primarily address chemical composition and the emissions of hazardous substances, such as formaldehyde and VOCs [108,109]. However, specific requirements for the release of nanoparticles during the service life of nano-treated wood products remain limited, suggesting a potential gap between emerging nanotechnology applications and existing safety regulations.

### 3.5. Testing Standards and Standardisation of Nanomaterials

Normative testing procedures were reported in more than 54% of the reviewed articles. The most common field in which standardised methods were applied was colour and gloss evaluation (14% of articles). Examples of standards used for these measurements include the UNI EN 15886 protocol [54,58], ASTM D523–14:2008, ASTM D2244-14 [62], and EN ISO 2813 for gloss determination [110–113].

Standardised procedures for fungal durability assessment were reported in 11% of the articles. Examples of standards applied for fungal-resistance testing include EN 113:1996 [78,114], ASTM D2017 [48,56,115], and EN 152–1:1990 [50,116].

Standardised ageing and artificial-weathering procedures were also reported in 11% of the reviewed articles, with EN 927-6 [117] being the most frequently used protocol [38,93]. Standardised abrasion tests were identified in 8% of studies, while hardness-related standards were reported in 7%. Other properties were less frequently evaluated using standardised testing procedures. All data are presented in Table 13.

**Table 13.** Overview and frequency of testing standards used in the reviewed studies.

| No. | Standards                              | Frequency of Occurrence (n) | Relative Frequency [%] | References                                                                                        |
|-----|----------------------------------------|-----------------------------|------------------------|---------------------------------------------------------------------------------------------------|
| 1   | Testing standards—total                | 40                          | 54                     | [24–26,28,29,35–40,42,45,46,48,50,54,56,58,62,64,65,70,72,74,75,77,78,80,81,84,86,87,89,90,92–96] |
| 2   | Colour and gloss measurement standards | 10                          | 14                     | [25,35,37,38,40,54,58,62,74,93]                                                                   |
| 3   | Fungal durability standards            | 8                           | 11                     | [48,50,56,78,79,90,92,93]                                                                         |
| 4   | Ageing and weathering standards        | 8                           | 11                     | [38,40,45,64,65,70,74,93]                                                                         |
| 5   | Abrasion testing standards             | 6                           | 8                      | [25,29,35,42,64,75]                                                                               |
| 6   | Leaching standards                     | 4                           | 5                      | [28,77,86,91]                                                                                     |
| 7   | Hardness testing standards             | 5                           | 7                      | [25,35,64,65,75]                                                                                  |
| 8   | Coating adhesion standards             | 4                           | 5                      | [35,37,75,80]                                                                                     |
| 9   | Antimicrobial activity standards       | 2                           | 3                      | [46,86]                                                                                           |
| 10  | Water-related property standards       | 3                           | 4                      | [54,64,87]                                                                                        |
| 11  | Other testing standards                | 17                          | 23                     | [24–26,36,37,39,56,70,72,74,81,84,87,89,94–96]                                                    |

In 2005, the ISO Technical Committee (TC) 229—Nanotechnologies was established to support standardisation in the field of nanotechnology. Several key working areas of the committee include terminology and nomenclature, measurement and characterisation, health, safety and environmental aspects, and material specifications. The terminology and nomenclature group aims to establish clear and harmonised definitions for nanotechnology-related concepts. Measurement and characterisation activities focus on developing standards for analytical methods, metrology, reference materials, and testing procedures. The health, safety, and environmental group is responsible for developing science-based standards for the safe use and environmental impact of nanomaterials, while material specifications define the relevant properties and characteristics of manufactured nanomaterials [118].

By 2026, ISO/TC 229 has published 117 standards and has another 37 standards under development. The use of these normative references in nanotechnology research is strongly recommended because they improve reproducibility, comparability, and harmonisation of experimental procedures. However, the reviewed studies showed limited implementation of nanotechnology-specific standards developed by ISO. A complete catalogue of ISO/TC 229 standards can be accessed through the ISO database (<https://www.iso.org/committee/381983/x/catalogue/>, accessed on 26 May 2026).

Using local or international standards of testing is important to compare outcomes from different researchers and improve the level of knowledge about the quantitative influence of nanomaterials.

### 3.6. Statistical Methods

The choice of statistical methods in studies on wood coatings modified with nanomaterials depends strongly on the experimental design and the number of investigated factors. In most analysed articles, the results are reported using descriptive statistics, primarily mean values and standard deviations. However, in many studies, detailed methodological descriptions of statistical procedures are limited or absent, as shown in Table 14.

Analysis of variance (ANOVA) was the most frequently reported inferential statistical method in the reviewed literature. In many cases, it was referred to generically as “ANOVA”, without specification of the model structure or experimental design. Only a subset of studies explicitly indicated the use of one-way ANOVA.

**Table 14.** Overview and frequencies of the statistical methods in the reviewed studies.

| No. | Method                                                    | Frequency of Occurrence (n) | Relative Frequency [%] | References                                                                          |
|-----|-----------------------------------------------------------|-----------------------------|------------------------|-------------------------------------------------------------------------------------|
| 1   | Descriptive statistics (mean values, standard deviations) | 24                          | 32                     | [24,25,29,35,38–40,47,48,50,55,58–60,62–64,70,77,81,83,90,93,95]                    |
| 2   | Significance level ( $p < 0.05$ )                         | 13                          | 18                     | [24,30,47,48,50,51,59,66,67,74,80,89,95]                                            |
| 3   | One-way ANOVA                                             | 6                           | 8                      | [37,50,64,74,80,91]                                                                 |
| 4   | ANOVA (not specified)                                     | 16                          | 22                     | [28,30,33,39,48,51,52,59,62,63,67,70,79,87,89,95]                                   |
| 5   | Tukey’s test                                              | 13                          | 18                     | [24,28,37,39,40,48,52,56,59,63,70,79,87]                                            |
| 6   | Duncan’s test                                             | 6                           | 8                      | [33,62,64,80,89,95]                                                                 |
| 7   | Shapiro–Wilk test                                         | 3                           | 4                      | [30,50,78]                                                                          |
| 8   | Bartlett’s test                                           | 2                           | 3                      | [24,78]                                                                             |
| 9   | Kruskal–Wallis test                                       | 2                           | 3                      | [24,30]                                                                             |
| 10  | Other statistical methods <sup>1</sup>                    | 9                           | 12                     | [24,41,50,51,66,78,80,85,91]                                                        |
| 11  | Not described                                             | 31                          | 42                     | [27,31,32,34,36,42–46,49,53,54,57,61,65,68,69,71–73,75,76,82,84,86,88,92,94,96,100] |

<sup>1</sup> Single-occurrence methods included the following: Student’s *t*-test, linear mixed models, bootstrapping techniques, Welch’s test, robust statistical approaches, regression analysis, Wilcoxon rank-sum test, Grubbs’ test, and Fisher’s least significant difference (LSD) test.

One-way ANOVA is used to determine whether statistically significant differences exist between groups defined by a single independent variable (e.g., nanoparticle type or concentration) with respect to a dependent variable (e.g., hardness, abrasion resistance, or durability). While one-way ANOVA enables identification of statistically significant differences among treatment groups, it does not account for interaction effects among multiple factors.

For more complex experimental designs involving multiple independent variables, factorial ANOVA may be used to evaluate both main effects and interactions among factors, such as different additives, wood species, or application methods.

In a broader methodological context, the general linear model (GLM) framework may also represent a useful analytical approach, as it allows simultaneous analysis of multiple predictors and their interactions. Such approaches are particularly relevant for nanomodified coating systems, where combined effects of nanoparticle type, concentration, and substrate properties may influence performance outcomes. Although these more advanced modelling approaches were not explicitly reported in the reviewed literature, their application in related materials science studies suggests potential value for improving the robustness and interpretability of statistical analyses.

Before applying parametric tests, the assumptions of normality and homogeneity of variances should be verified. In the analysed literature, only isolated examples of diagnostic procedures were identified. The Shapiro–Wilk test was used to assess normality, while Bartlett’s test was used to evaluate homogeneity of variances [24,30,50,78].

When assumptions for parametric analyses are violated, alternative statistical approaches may be applied. In the reviewed articles, non-parametric methods such as the Kruskal–Wallis and Wilcoxon rank-sum tests were used, along with bootstrapping, Welch’s test, and robust statistical procedures [24,30,50]. Although these methods may provide more reliable analyses under non-normal or heteroscedastic conditions, their application in the reviewed studies was limited.

Post hoc comparisons were performed when ANOVA revealed significant differences. The most commonly applied post hoc test was Tukey’s HSD test, followed by Duncan’s multiple range test. Fisher’s least significant difference (LSD) test was also occasionally used [51]. Outlier detection was occasionally performed using Grubbs’ test for outliers [24].

Statistical significance was commonly evaluated using a  $p < 0.05$  threshold. In general, a  $p$ -value greater than 0.05 indicates insufficient evidence to reject the null hypothesis and

should not be interpreted as definitive proof of the absence of an effect. However, within nanotechnology studies, non-significant results may also have practical relevance depending on the research objective. In studies evaluating treatment stability, colour difference, or safety-related properties of modified materials, the absence of significant differences between treated and reference samples may represent an acceptable or practically relevant outcome depending on the study objective. In the context of nanomodified coatings, this may be particularly relevant for tests related to human safety or potential adverse effects, where the objective is to demonstrate that nanoparticle incorporation does not negatively affect selected properties.

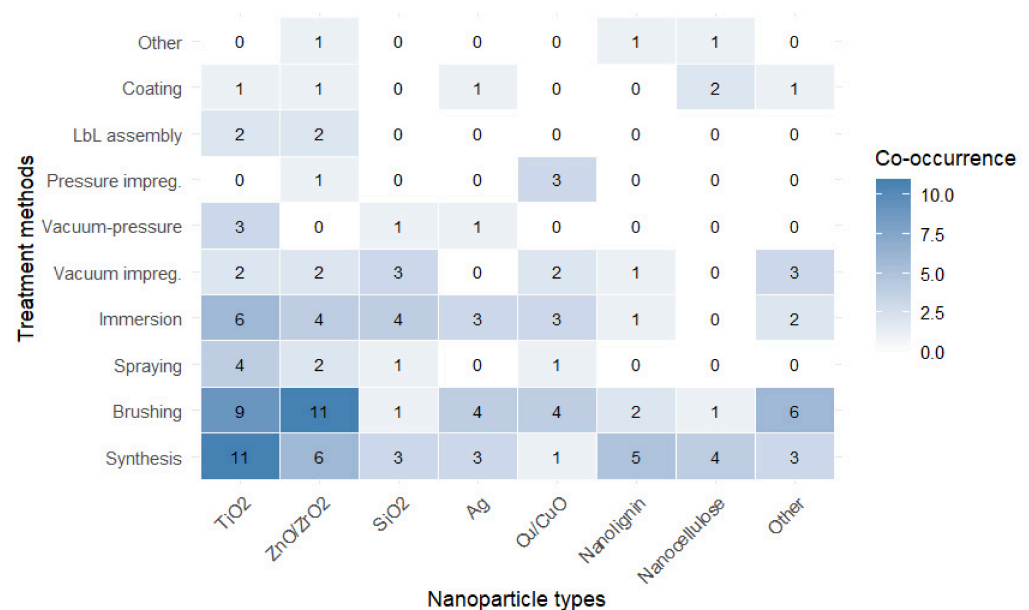
Overall, the reviewed literature indicates that while basic statistical methods are widely used, more advanced experimental designs and multivariate statistical approaches remain underrepresented. Improved reporting of statistical assumptions, clearer specification of ANOVA models, and broader adoption of factorial and mixed-model approaches could significantly enhance the robustness and interpretability of future studies on nanomodified wood coating systems.

#### 4. Co-Occurrence Analyses and Discussion

To identify dominant experimental approaches and relationships among investigated variables, a co-occurrence analysis was performed based on the binary dataset. Heatmaps were used to visualise the frequency with which specific materials, nanomaterials, treatment methods, characterisation techniques, durability tests, and evaluated properties appeared together within individual studies. This approach enabled the identification of prevailing research gaps and underrepresented areas.

##### 4.1. Materials and Application of Wood Surface Treatments

The co-occurrence patterns between treatment methods and nanoparticle types are presented in Figure 2. The results indicate a clear preference for a limited number of treatment–nanoparticle combinations. Titanium dioxide (TiO<sub>2</sub>), the most frequently investigated nanomaterial, was predominantly associated with nanoparticle synthesis, brushing, and immersion treatments. Similarly, ZnO systems were most commonly linked to brushing applications, highlighting the importance of surface coating approaches in wood nanomodification studies.

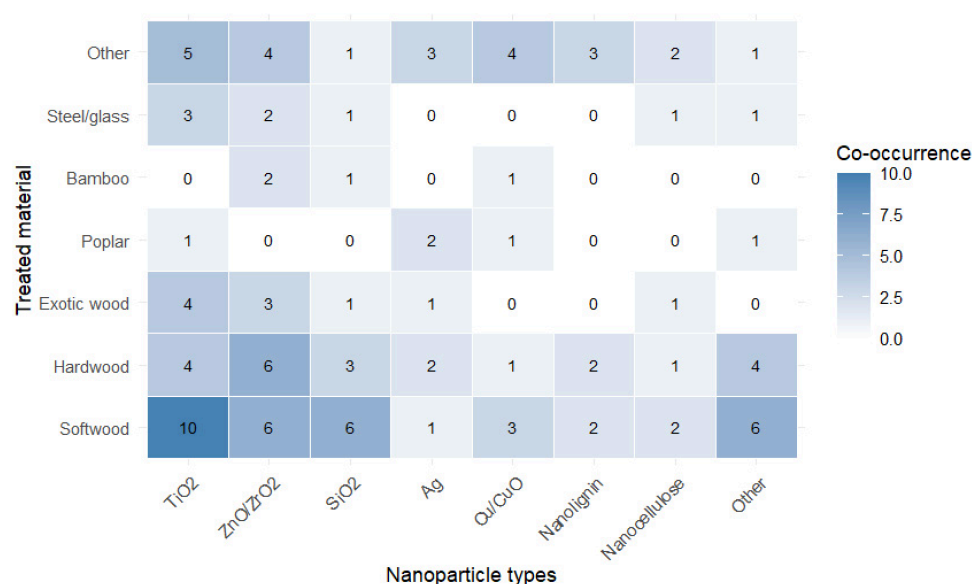


**Figure 2.** Co-occurrence of treatment methods and nanoparticle types used in the analysed studies.

Among all treatment methods, brushing emerged as the most frequently applied technique across different nanoparticle systems, suggesting its widespread acceptance as a simple and effective method for nanomaterial deposition on wood surfaces. Immersion treatments were also commonly associated with TiO<sub>2</sub>-based systems, whereas vacuum-assisted impregnation methods were used less frequently and were limited to selected nanoparticle types.

In contrast, nanolignin and nanocellulose showed a markedly different application profile. These materials were predominantly associated with nanoparticle synthesis rather than conventional wood-treatment methods. This pattern suggests that current research on bio-based nanomaterials remains focused on material development and characterisation, while their practical implementation in wood-treatment systems is comparatively less explored.

The co-occurrence structure presented in Figure 3 further demonstrate that most frequent pairing was softwood–TiO<sub>2</sub>, indicating its role as a primary nanoparticle in wood nanomodification studies.

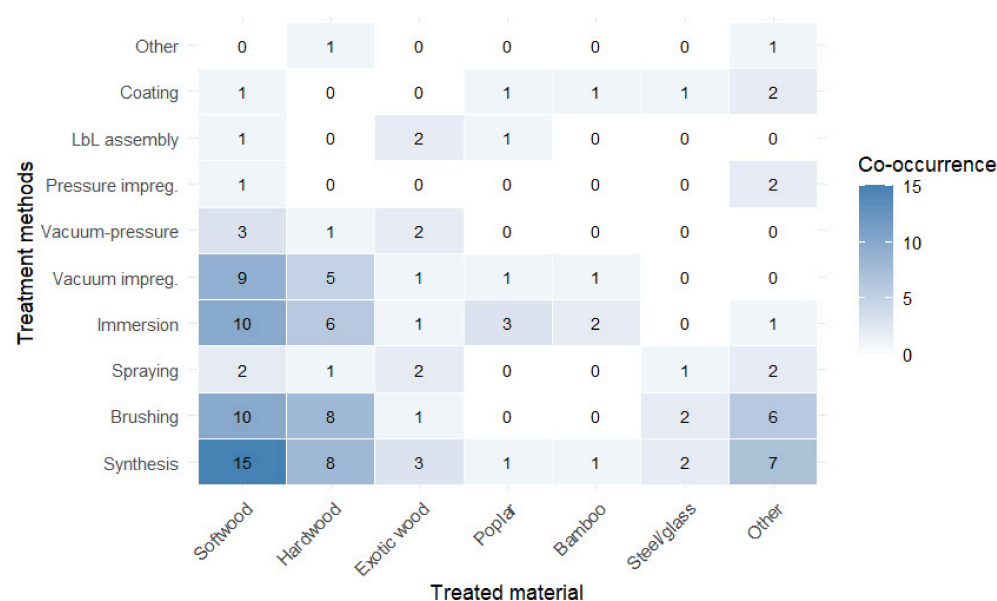


**Figure 3.** Co-occurrence of treated material and nanoparticle types used in the analysed studies.

Zinc oxide (ZnO) exhibit a balanced distribution across softwood and hardwood. Identical occurrence frequencies in both substrate types, suggesting that their application is largely independent of wood type and reflects broader material compatibility rather than substrate-specific selection. Silicon dioxide (SiO<sub>2</sub>) and other nanoparticle systems were less frequent but were predominantly associated with softwood substrates.

The co-occurrence analysis between treatment methods and treated materials are presented in Figure 4.

The results reveal a strong concentration of research efforts on softwood substrates, which were most frequently associated with nanomaterial synthesis, brushing, immersion, and vacuum-impregnation treatments. These combinations represent the dominant experimental configurations identified in the analysed studies, indicating that softwood serves as the principal model material for evaluating nanomaterial-based wood-modification strategies.



**Figure 4.** Co-occurrence of treatment methods and treated material used in the analysed studies.

The predominance of softwood is consistent with its dominant role in the global construction sector. In the United States, softwood species account for more than 80% of total lumber consumption and are primarily used in residential construction and engineered timber products such as glued laminated timber (GLT) and cross-laminated timber (CLT) [2]. The growing mass-timber sector is expected to further increase demand for softwood resources, reinforcing their importance as the principal substrate for the development of advanced wood-protection technologies [119]. Consequently, the strong focus on softwood observed in the analysed literature reflects the practical need to develop nanomodified treatments for the most widely used structural wood products.

A similar pattern was observed for hardwood substrates; however, the frequency of co-occurrence was lower than that recorded for softwood. This finding is consistent with the primary use of hardwoods in furniture production, flooring, joinery, veneers, and decorative products rather than in structural timber applications [3,4]. The relatively frequent occurrence of exotic wood species may also be explained by their use in specialised products requiring unique aesthetic, acoustic, or mechanical properties, including decorative veneers and musical instruments [4]. In contrast, poplar and bamboo, although less frequently represented, reflect the importance of these materials in Asian markets. Poplar constitutes a major raw material for the Chinese plywood industry, while bamboo remains one of the most important rapidly renewable lignocellulosic resources used in construction and furniture production in China [3].

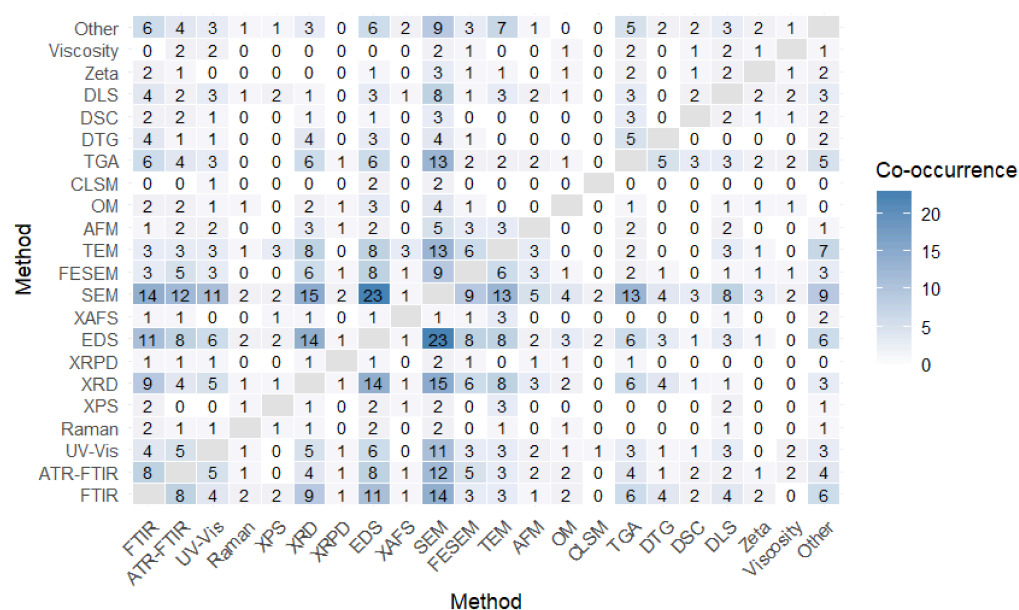
Overall, the co-occurrence structure indicates that contemporary research is strongly focused on modifying softwood using a limited number of well-established treatment techniques, particularly brushing, immersion, and vacuum impregnation with methods of nanomaterial synthesis. This pattern reflects current industrial wood-preservation practices, in which softwood species dominate construction applications and are commonly protected through impregnation-based technologies. Vacuum impregnation and pressure-based treatments are widely employed for preservative applications in softwood products, while surface treatments applied by brushing or coating are gaining importance due to the growing demand for highly processed wood products requiring reduced on-site labour, improved durability, and enhanced resistance to environmental degradation [9].

The co-occurrence analyses presented in Figures 2–4 reveal a highly structured research landscape dominated by a limited number of experimental configurations. Softwood

emerged as the primary substrate, most frequently treated with TiO<sub>2</sub>- and ZnO-based systems using brushing and immersion methods. The results indicate that methodological choices are not randomly distributed but rather follow a well-established wood type–nanomaterial–treatment method, suggesting a relatively narrow experimental approach within the field. In contrast, alternative substrates and emerging bio-based nanomaterials remain comparatively underrepresented and are characterised by greater methodological diversity.

#### 4.2. Testing and Instrumental Methods

The co-occurrence patterns of physicochemical and instrumental characterisation methods are presented in Figure 5. The most frequently observed analytical configuration was the combined use of SEM and EDS, reflecting the complementary nature of morphological and elemental characterisation. Other commonly co-occurring method pairs included SEM–XRD, EDS–XRD, ATR-FTIR–SEM, TGA–SEM, UV-Vis–SEM, and SEM–TEM.



**Figure 5.** Co-occurrence of physicochemical and instrumental characterisation methods used in the analysed studies.

These results indicate that scanning electron microscopy (SEM) occupies a central position within the analytical framework of nanomodified wood research. SEM was frequently combined with elemental (EDS), structural (XRD), chemical (FTIR), thermal (TGA), optical (UV-Vis), and high-resolution imaging (TEM) techniques, demonstrating its role as the primary tool for complementary material characterisation.

The observed co-occurrence patterns are consistent with current recommendations for nanomaterial characterisation, which emphasize the use of complementary analytical techniques based on independent measurement principles [101]. Electron microscopy provides direct visual evidence of nanoparticle morphology, distribution, and agglomeration state, whereas techniques such as EDS, XRD, FTIR, UV-Vis, and TGA supply elemental, structural, chemical, optical, and thermal information, respectively. The frequent combination of these methods reflects the need to characterise nanomodified coatings simultaneously at the morphological, compositional, and functional levels.

The relatively limited use of AFM and CLSM suggests that three-dimensional surface characterisation and coating architecture remain less explored than conventional electron microscopy. Future studies could benefit from a more integrated use of these techniques,

particularly when investigating surface roughness, coating thickness, and nanoparticle distribution within multilayer coating systems.

The co-occurrence between treatment methods and evaluated properties is presented in Figure 6.

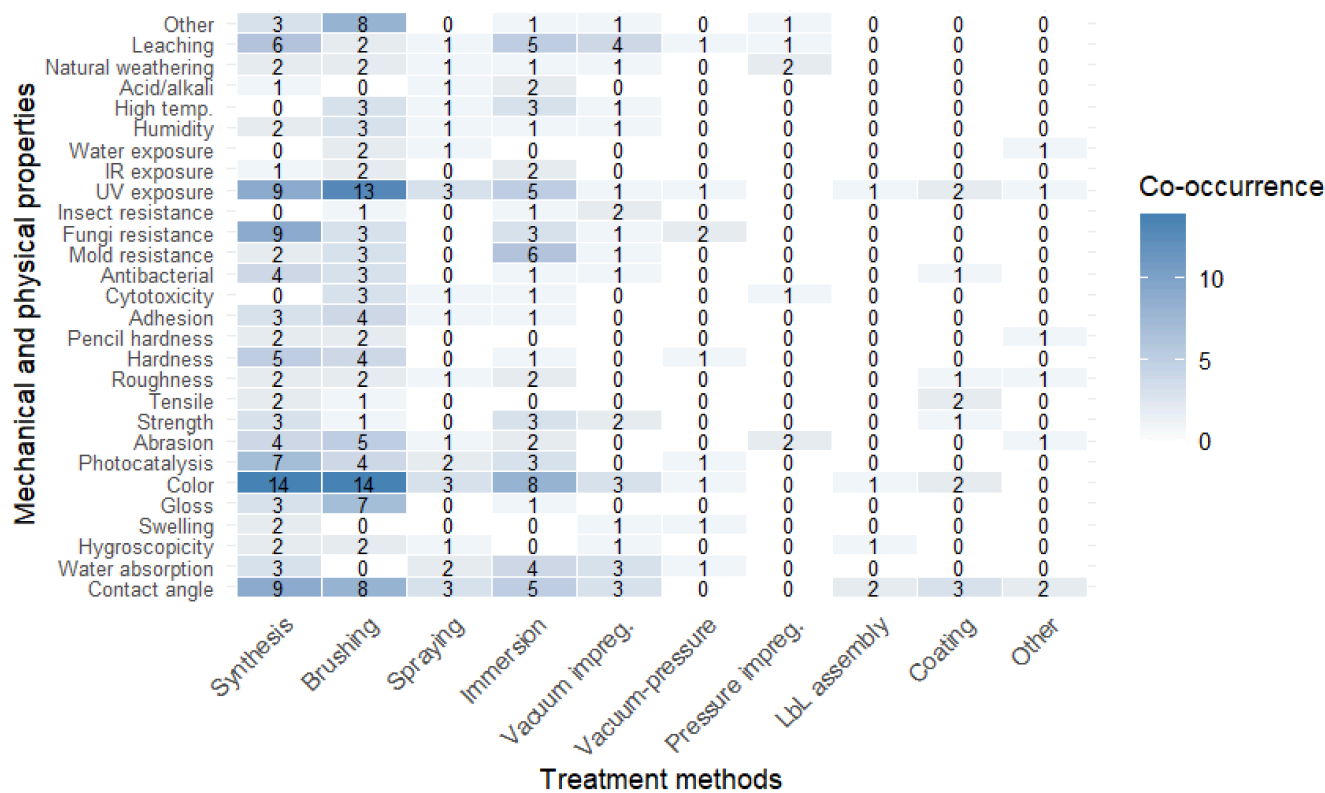


Figure 6. Co-occurrence of testing methods and treatment methods used in the analysed studies.

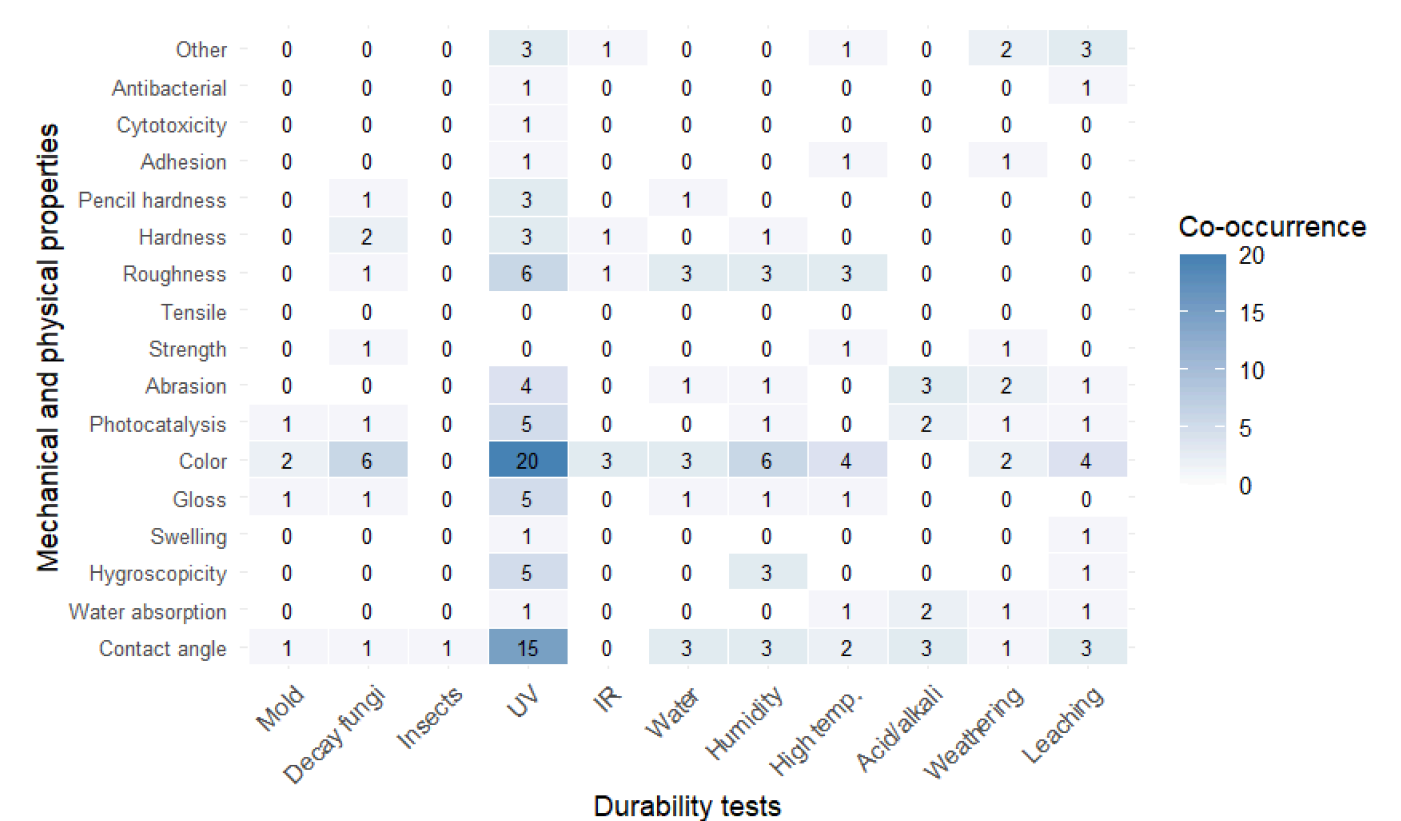
The most frequent associations were observed for brushing treatments combined with UV exposure testing and colour parameter measurements (CIELAB). This indicates that studies primarily focus on assessing the appearance-related properties of nanomodified treatments. Contact-angle measurements, leaching and gloss evaluation also frequently co-occurred with brushing treatments, although at lower frequencies.

A second prominent group of associations was identified for immersion treatments. In these studies, UV exposure, mould resistance, colour parameters, leaching resistance, and contact-angle measurements were commonly evaluated. This pattern suggests that immersion-based treatments are often investigated for both durability performance and surface property modification.

In contrast, most other treatment–property combinations occurred at relatively low frequencies and did not form clearly defined clusters. The absence of strong co-occurrence patterns outside the dominant brushing and immersion-based systems.

Overall, the results suggest that current research is strongly focused on assessing UV resistance and surface-related properties, particularly colour stability and wettability, while many other performance characteristics remain comparatively underexplored.

The co-occurrence between evaluated properties and durability tests is presented in Figure 7.



**Figure 7.** Co-occurrence of the tested mechanical and physical properties and durability tests used in the analysed studies.

The strongest associations were observed between UV exposure tests and the assessment of colour parameters (CIELAB), as well as contact-angle measurements. This finding indicates that artificial weathering studies primarily focus on monitoring changes in the surface appearance and wettability following exposure to ultraviolet radiation.

Apart from the UV exposure–colour and UV exposure–wettability combinations, no clearly defined clusters of durability tests and evaluated properties were identified. Durability-related factors, such as humidity fluctuations, water exposure, high-temperature exposure, acid and alkali resistance, natural weathering, and biological degradation tests, showed relatively weak and scattered associations with the assessed material properties.

The absence of well-defined co-occurrence patterns suggests that ageing and degradation processes are not systematically integrated into the evaluation of nanomodified wood systems. Instead, most studies focus on short-term assessments of surface-related properties, while the long-term effects of environmental exposure on the performance and durability of nanomaterial-based wood treatments remain comparatively underexplored.

The results demonstrate that research on nanomaterial-based wood modification primarily focuses on material characterisation and the evaluation of physical and mechanical properties. In contrast, studies addressing long-term durability, fire performance, and standardised ageing procedures remain relatively limited.

Several limitations of the review process should be acknowledged. The analysis was restricted to publications indexed in the Web of Science and Scopus databases and to studies published within the last ten years, and it is characterised by substantial methodological heterogeneity. Furthermore, variations in terminology used across different research fields may have affected the retrieval of relevant studies. The relatively small number of publications addressing fire performance suggests that some relevant studies may not have been captured by the applied search strategy.

Although the search strategy identified a substantial body of literature on nanomaterial-based wood modification, studies focusing specifically on fire performance and fire testing were underrepresented in the final dataset. This may reflect limitations related to database coverage, keyword selection, or inconsistencies in terminology used across different research fields.

The findings highlight the need for greater standardisation of research methodologies used to evaluate nanomaterial-based wood-treatment systems. Future studies should place greater emphasis on long-term durability, fire performance, and environmentally relevant ageing procedures. The development of harmonised testing protocols may improve comparability between studies and facilitate the practical implementation of nanotechnology-based wood protection systems in industrial applications.

Overall, the co-occurrence analyses revealed a highly concentrated research landscape characterised by a limited number of dominant wood type–nanomaterial–treatment method combinations and analytical workflows. Softwood substrates, TiO<sub>2</sub> and ZnO-based nanomaterials, brushing and immersion treatments, and SEM-centred characterisation strategies represented the most common experimental configurations. At the same time, the results highlighted the limited exploration of alternative substrates, emerging bio-based nanomaterials, and long-term durability assessments, indicating several potential directions for future research.

## 5. From Scientific Research to Commercial Application

The commercial implementation of nanomaterial-based wood protection systems requires not only the development of effective treatment technologies but also compliance with regulatory frameworks governing construction products. For products intended for use in the building sector, technical performance must be evaluated in relation to legal requirements, harmonised standards, and assessment procedures that define the essential characteristics required for market introduction.

From a research and development perspective, these requirements provide an important reference for selecting performance criteria, designing experimental programmes, and identifying the key properties that should be verified before commercialisation. Consequently, the analysis of applicable regulations and assessment documents can be used to define research priorities and establish testing strategies that support both product development and future certification.

### 5.1. Regulatory Requirements and Essential Product Characteristics

To project and implement new nano-based wood treatments to market, a useful tool is the OECD report, which identifies the most important nanoproperty properties, provides hints for planning research according to the Technology Readiness Level, and presents recent digital tools for planning new nanotechnology solutions [103].

New nano-based wood treatments intended for building applications should comply with relevant local legal requirements and standardised testing protocols. In the European Union, the assessment of building materials is regulated through harmonised standards and regulatory frameworks that define the required performance and safety parameters [108,109,120]. Within the European product families defined under applicable regulations, nanomodified wood coatings may fall into several categories, including the following:

1. Code 3: Membranes, including liquid applied and kits (for water and/or water vapour control).
2. Code 21: Internal and external wall and ceiling finishes. Internal partition kits.
3. Code 35: Fire stopping, fire sealing and fire protective products. Fire-retardant products.

The most probable applications of nano-based wood treatments in the building industry include their use in watertight liquid-applied coatings and fire-retardant compositions. Such products must comply with requirements defined in relevant European Assessment Documents [121,122].

Nanotreatments intended for fire-retardant products or kits are typically evaluated using standardised methods. Reaction to fire should be assessed in accordance with EN 13238, including single burning item (SBI) tests [123], while the durability of fire-protective performance after weathering can be evaluated using cone calorimeter methods (ISO 5660-1) [124]. Abrasion resistance for fire-retardant flooring systems should be determined according to EN ISO 7784-2 [125]. Emissions of semi-volatile organic compounds (SVOCs) and volatile organic compounds (VOCs) are assessed in accordance with EN 16516 [126]. Leaching behaviour is evaluated using CEN/TS 16637-2:2014 [127].

The European Assessment Document EAD 350865-00-1106 also defines requirements for biological performance testing and exposure to varying relative humidity conditions. In addition, production and quality-control parameters for fire-retardant formulations include solids content, viscosity, density, sag resistance, ash content, drying time, brightness, pH, and abrasion resistance. The document also provides guidance on thermogravimetric analysis and infrared spectroscopy for material characterisation [122].

The EAD 030352-00-0503 standard [121] defines requirements for liquid-applied watertight covering kits intended for use on wet room floors and walls. Such systems can also be applied to engineered timber elements, including cross-laminated timber (CLT), as protective surface coatings to enhance water resistance and overall durability [121].

The standard includes methods for assessing the content, emission, and/or release of dangerous substances; vapour permeability; water tightness; crack-bridging ability; bond strength; scratching resistance; joint-bridging ability; and watertightness around penetrations. In addition, it covers resistance to temperature, water, alkalinity, and mechanical wear.

Overall, aligning research methodologies with these normative references can facilitate the standardisation, comparability, and potential commercialisation of nanotechnology-based fire-protective and water-proofing wood coatings.

The development of nano-based wood treatments intended for building applications requires not only the optimisation of material performance but also alignment with regulatory frameworks governing construction products. In particular, the successful market introduction of such technologies depends on the early consideration of essential safety, environmental, and functional requirements defined within European regulatory systems. From a research and development perspective, this implies that experimental design should not be limited to performance enhancement alone but should also incorporate evaluation criteria relevant to product certification and compliance.

For nano-based wood treatments, the identification of essential product characteristics is required within the regulatory framework for construction materials [89,90]. These essential requirements can be grouped into the following key categories [121,122]:

1. Fire safety and combustion control: the generation and spread of fire and smoke.
2. Emission of hazardous substances indoors and to the environment: the emissions of hazardous substances, greenhouse gases, toxic gases, and hazardous particles, including microplastics.
3. Water and soil protection: the release of hazardous substances into drinking water, ground water, marine and surface waters, or soil is controlled.
4. Moisture and water transfer: the passage of moisture into the interior of the building, or dampness within construction works.

5. End-of-life and circularity aspects: the reuse or recyclability of treated woods after end-of life.

Consequently, future studies should systematically address the key categories of properties that determine the suitability of nanomodified wood coatings for commercialisation. These include aspects related to fire safety, emissions and indoor air quality, environmental release pathways, moisture and structural integrity, waste management, and end-of-life considerations. Integrating these categories at the material design and testing stage can significantly improve the translational potential of laboratory-scale developments into market-ready construction products.

### 5.2. Framework for Further Research and Development Works

The analysis of testing standards, regulatory requirements, and assessment procedures presented in the previous sections provides a basis for planning future research and development activities related to nanomaterial-based wood protection systems. However, the successful implementation of such technologies requires not only compliance with technical and regulatory requirements but also a structured development pathway leading from fundamental research to commercial application.

Technology Readiness Levels (TRLs) provide a widely recognised framework for managing this process by linking scientific research, proof-of-concept studies, product development, durability assessment, certification activities, and market implementation. In parallel, the OECD Safe and Sustainable by Design (SSbD) framework emphasises the integration of functionality, safety, and sustainability considerations throughout the entire innovation process. The following sections propose a research and development framework for nanomaterial-based wood protection technologies based on the combined application of TRL methodology, SSbD principles, and the research directions identified through the analysis of the reviewed literature.

#### 5.2.1. TRL 1—Basic Principles Observed and Reported

At TRL 1, research focuses on identifying and understanding the fundamental physicochemical properties of nanomaterials and their potential relevance for future wood protection applications. At this stage, potential applications may be identified, but performance requirements, product specifications, and validation procedures are not yet defined [128].

According to the OECD Safe and Sustainable by Design (SSbD) framework, early-stage nanomaterial research should address the following three key aspects: functionality, safety, and sustainability [103]. For nanomaterial-based wood coatings, this includes the selection of promising nanomaterials, mechanism of impregnation or a coating application, identification of design principles, evaluation of physicochemical stability, and assessment of the potential impacts on human health and the environment. Sustainability-related considerations include the use of renewable or critical raw materials, resource efficiency, recyclability, and circularity potential throughout the product life cycle.

Fundamental characterisation is typically performed using microscopic, spectroscopic, thermal, and colloidal characterisation techniques. Electron microscopy (SEM, TEM, STEM) and atomic force microscopy (AFM) are used to determine nanoparticle morphology, particle size, agglomeration state, and surface topography. Spectroscopic and structural techniques, such as FTIR, UV–Vis, EDS, and XRD, provide information on chemical composition, molecular structure, crystallinity, and elemental distribution. Thermogravimetric methods (TGA and DTG) are applied to investigate thermal stability and degradation behaviour, while DLS, zeta potential, and viscosity measurements are used to evaluate particle size distribution, dispersion quality, and colloidal stability of nanomaterial suspensions [102]. Fundamental research at TRL 1 encompasses not only the characterisation

of nanomaterials themselves but also the development of scientific methodologies for investigating durability, ageing mechanisms, environmental interactions, and long-term performance. Such studies establish the scientific basis for the future evaluation of weathering resistance, hydrophobicity, UV protection, fire performance, antimicrobial activity, and other functional properties relevant to wood protection systems.

In parallel, the OECD SSbD framework recommends the early identification of physicochemical properties potentially associated with human and environmental hazards, including particle size, shape, surface characteristics, reactivity, dissolution behaviour, and the potential for release during future use scenarios [103]. Sustainability-related considerations should also be introduced at this stage, including the expected use of critical raw materials, resource efficiency, and the potential recyclability of future products.

Consequently, TRL 1 research establishes the scientific basis required for subsequent formulation development, proof-of-concept studies, and safe-and-sustainable-by-design optimisation at higher technology readiness levels.

#### 5.2.2. TRL 2—Technology Concept or Application Idea

At TRL 2, knowledge generated during fundamental research is translated into preliminary technological concepts and potential application scenarios. For nanomaterial-based wood protection systems, this stage involves the identification of promising nanomaterials, target wood products, intended service conditions, and potential market applications. Potential functionalities, such as weathering resistance, hydrophobicity, UV protection, fire retardancy, antimicrobial performance, self-cleaning ability, or extended service life, are identified according to anticipated user needs and application requirements. Although the expected benefits of the technology are formulated, experimental proof of effectiveness has not yet been demonstrated [128].

According to the OECD Safe and Sustainable by Design (SSbD) framework, functionality, safety, and sustainability considerations should already be integrated into the technology concept [103]. Potential nanomaterials are selected based on physicochemical properties and mechanisms identified during TRL 1 studies, while preliminary assessments are performed regarding raw material cost and availability, environmental and human health impact, recyclability, and end-of-life scenarios.

At this stage, performance requirements remain general and broadly defined but consistent with the proposed application concept [128]. Activities in TRL 2 may include identification of target users, preliminary market analysis, assessment of acceptable production costs, evaluation of potential distribution pathways, and identification of relevant legal, regulatory, and standardisation requirements.

The activities presented in Section 5.1, including the identification of relevant standards, testing methods, performance requirements, and regulatory frameworks, represent part of typical TRL 2 works supporting the formulation of a technology concept and development strategy. The outcome of this stage is a scientifically and commercially justified concept describing the intended application, expected functionality, potential risks, and the key parameters to be verified during proof-of-concept studies at TRL 3.

#### 5.2.3. TRL 3—Analytical and Experimental Proof of Concept Critical Function

At TRL 3, critical functions associated with the proposed technology concept are experimentally verified under controlled laboratory conditions. The objective is not yet to comprehensively assess product performance, durability, or regulatory compliance, but rather to demonstrate that the key functionality underlying the technology concept can be achieved [128].

For nanomaterial-based wood protection systems, proof-of-concept studies focus on the most critical functional properties associated with the intended application. For fire-retardant treatments, this may include preliminary determination of gross heat of combustion according to EN 1716 [129] and preliminary fire-performance assessment, like cone calorimeter tests. Hydrophobic and moisture-protective systems are typically evaluated through contact-angle measurements, water absorption tests, and moisture-related properties. For coating technologies intended for construction applications, critical functions may additionally include water vapour permeability, coating adhesion, dimensional stability, and resistance to moisture-induced swelling and cracking.

According to the OECD Safe and Sustainable by Design (SSbD) framework, TRL 3 should also include preliminary verification of critical safety-related characteristics [103]. For nanomaterial-based systems, this may involve initial assessment of nanoparticle release during abrasion, leaching, weathering, or other degradation processes, together with screening-level evaluation of potential human and environmental hazards.

The outcome of TRL 3 is the experimental demonstration that the proposed technology concept is capable of delivering its intended critical function and that no fundamental technical or safety-related barriers have been identified prior to further technology development.

#### 5.2.4. TRL 4—Component Functional Verification in Laboratory Environment

At TRL 4, the individual functions demonstrated during proof-of-concept studies are integrated into a laboratory-scale prototype of the product to verify that the different components operate together as intended. For nanomaterial-based wood protection technologies, this typically involves the preparation of complete coating or impregnation systems consisting of nanomaterials, binders, additives, and wood substrates according to the proposed treatment technology. Verification of compliance with the functional requirements specified during TRL 2 is performed under controlled laboratory conditions and remains limited to small-scale laboratory testing [128].

The primary objective of TRL 4 is to establish the base performance of the developed material system and to verify that the intended properties can be achieved simultaneously. Therefore, testing focuses on the reference functional properties of the product rather than on long-term durability. Depending on the intended application, the assessed properties may include preliminary fire performance (e.g., cone calorimeter tests), emissions and release of hazardous substances, water vapour permeability, watertightness, wettability (contact angle), water absorption, hygroscopicity, swelling resistance, colour and gloss properties, photocatalytic activity, abrasion resistance, coating adhesion, hardness, surface roughness, mechanical performance, and biological resistance against moulds, decay fungi, insects, or microorganisms. Preliminary assessments of human safety and environmental compatibility should also be conducted at this stage [103].

In parallel with laboratory performance verification, TRL 4 activities should include optimisation of formulation design, manufacturing procedures, and treatment technologies. For nanomaterial-based wood protection systems, this may involve the development of laboratory-scale impregnation or coating processes, optimisation of nanomaterial content, reduction in raw-material consumption, improvement in application efficiency, and adaptation of the technology to existing industrial production reality. The objective is to demonstrate that the proposed technology can be manufactured and applied in a repeatable manner while maintaining the intended functional properties.

At this stage, a preliminary techno-economic assessment should be performed. Estimated production costs, scalability of the manufacturing process, availability of raw materials, compatibility with industrial application methods, and potential market acceptance should be evaluated before progressing to extensive durability and environmental

ageing studies. The objective is to establish a laboratory-scale prototype representing a minimum viable product (MVP) from a technological and commercial perspective.

TRL 4 is also an important decision point within the innovation process. If the developed technology cannot realistically satisfy the requirements identified during TRL 2, including technical feasibility, economic viability, regulatory constraints, or market expectations, further optimisation may be required before advancing to higher technology readiness levels. In some cases, the identified limitations may indicate the need to revisit the technology concept formulated at TRL 2 or even return to TRL 1 research to investigate alternative nanomaterials, physicochemical mechanisms, or design principles capable of overcoming the observed barriers.

The outcome of TRL 4 is a laboratory-verified nanomaterial-based wood protection system with the established base performance characteristics, preliminary manufacturing procedures, and an initial assessment of its technical, economic, safety, and implementation potential. These results provide the basis for progression to durability validation and environmental exposure studies under relevant service conditions at TRL 5.

#### 5.2.5. TRL 5—Component Critical Function Verification in a Relevant Environment

At TRL 5, the critical functions tested during TRL 3 and TRL 4 are assessed under representative service conditions relevant to the intended application. The objective is to demonstrate that the developed nanomaterial-based wood protection system maintains its functionality when exposed to environmental factors expected during its service life. Although the tested specimens may still be laboratory-scale prototypes, they should be representative of the final product in terms of composition, manufacturing process, and treatment technology [128].

For wood protection systems, the relevant environment is typically defined by the principal degradation factors expected during service. Depending on the intended application, these may include ultraviolet radiation, water exposure, humidity fluctuations, biological attack, leaching, abrasion, or combinations of these factors. Consequently, TRL 5 research is primarily focused on artificial ageing procedures and durability assessment methods designed to reproduce relevant environmental exposures under controlled conditions.

The functional properties determined during TRL 4 are re-evaluated following environmental exposure. The objective is not only to determine whether degradation occurs but also to quantify the magnitude of the performance loss and identify the dominant degradation mechanisms.

TRL 5 also enables verification of assumptions adopted during TRL 2 regarding product durability, service life, and suitability for the intended application. Where critical performance losses or unexpected degradation mechanisms are identified, modifications to the formulation, application technology, or product concept may be required. In some cases, the obtained results may justify returning to earlier development stages in order to optimise the technology before further scale-up.

According to the literature review and the OECD Safe and Sustainable by Design (SSbD) framework, TRL 5 represents a critical stage for evaluating the potential impacts of nanomaterial-based wood protection systems on human health and the environment [103]. At this stage, environmental ageing procedures can be combined with the assessment of nanoparticle release and exposure pathways. Particular attention should be given to quantifying nanoparticle emissions and degradation products generated during service-life simulation.

An important method used for assessing potential dermal transfer of nanomaterials from treated ageing surfaces is the standardised surface wipe testing method developed by the Consumer Product Safety Commission (CPSC) to simulate dermal contact with

nanomaterial-based products [60,63]. Combined with ageing procedures, release measurements, and cytotoxicity testing, such approaches provide valuable information regarding the potential risks associated with the long-term use of nanomaterial-based wood protection systems. The generated data support both technology optimisation and the development of safe-by-design solutions before progression to larger-scale validation studies.

The outcome of TRL 5 is the demonstration that the developed nanomaterial-based wood protection system can maintain its critical functions under representative environmental conditions. Small-scale durability studies at TRL 5 provide a means to identify critical degradation mechanisms and technological weaknesses before large-scale validation. Because testing is conducted on small-scale laboratory specimens, unsuccessful solutions can be modified and re-evaluated at significantly lower cost and shorter development time than would be possible at higher technology readiness levels.

#### 5.2.6. TRL 6—Model Demonstrating the Critical Functions of the Element in a Relevant Environment

At TRL 6, the developed nanomaterial-based wood protection technology is evaluated using representative product models that closely resemble the intended final application in terms of materials, dimensions, manufacturing procedures, and treatment technology. The objective is to demonstrate that the critical functions previously verified during TRL 5 remain effective when implemented in realistic product configurations and exposed to relevant service conditions [128].

For wood protection systems, TRL 6 should involve the transition from laboratory-scale specimens to representative building products and structural elements. These may include [123,130] façade claddings, decking boards, windows, doors, structural timber members, or pilot-scale demonstrator constructions. The investigated elements should be manufactured using application methods, process parameters, and material compositions representative of the intended industrial implementation.

Artificial ageing procedures may be supplemented by outdoor exposure tests, semi-natural weathering experiments, pilot-scale demonstrations, or field trials. Representative elements may be exposed to natural weathering conditions, including solar radiation, rainfall, humidity fluctuations, biological attack, and wetting–drying cycles. Such studies enable verification of ageing processes under realistic service conditions and provide valuable information on the expected service life of the developed technology.

For fire-retardant wood protection systems, TRL 6 should involve the transition from small-scale fire testing methods used during TRL 4 and TRL 5, such as cone calorimeter tests, to intermediate-scale fire performance assessment. In the European construction sector, this may include single burning item (SBI) testing according to EN 13823 and classification of reaction-to-fire performance according to EN 13501-1 [123,130]. These tests verify whether the fire performance demonstrated on laboratory specimens can be maintained in representative product configurations and treatment systems.

According to the OECD Safe and Sustainable by Design (SSbD) framework, TRL 6 should include more comprehensive assessment of human health and environmental aspects under realistic use scenarios [103]. This may involve evaluation of nanoparticle release during weathering, abrasion, maintenance operations, cleaning procedures, or end-of-life processing. Exposure pathways identified during earlier development stages should be verified using representative product configurations and service conditions.

TRL 6 also provides the basis for preliminary implementation planning. Manufacturing reproducibility, quality-control procedures, production scalability, and expected service life should be reassessed based on results from representative demonstrators. Remaining technical uncertainties should be sufficiently reduced to support pilot implementation and larger-scale validation activities.

The outcome of TRL 6 is a representative product model demonstrating that the nanomaterial-based wood protection technology can reliably deliver its intended functionality under relevant service conditions. At this stage, the technological feasibility of the solution is largely confirmed, with the remaining uncertainties primarily related to full-scale implementation and long-term performance under operational conditions.

#### 5.2.7. TRL 7–9—Validation, Certification and Commercial Deployment

While the previous technology readiness levels are primarily concerned with testing and verifying performance, TRL 7–9 aim to demonstrate that the developed technology can be successfully manufactured, certified, and distributed to end users [128].

At TRL 7, the performance of the developed technology is demonstrated under operational conditions using full-scale or near full-scale product models. For nanomaterial-based wood protection systems, this may include pilot-scale production and demonstrator structures, such as façade systems, decking elements, parts of timber buildings, or other representative applications exposed to real environmental conditions.

At this stage, demonstration projects may be implemented in real construction works. According to European construction-product regulations, individually manufactured or custom-made products intended for a single identified construction work may be placed on the market using specific technical documentation demonstrating compliance with the applicable requirements and equivalence of the procedures used to those specified in harmonised standards [108]. Such simplified procedures may facilitate the practical verification of innovative technologies before full certification is obtained.

At TRL 8, the technology is considered technically complete and ready for market introduction. Manufacturing procedures, quality control systems, and supply chains are established as the product undergoes final qualification and certification. For construction products, this stage may involve obtaining European technical assessments (ETAs), CE marking, national approvals, or other certification pathways required for commercialisation. Product documentation, application guidelines, and safety information should also be completed at this stage.

For nanomaterial-based products, compliance with chemical regulations becomes particularly important. Depending on the composition and intended use of the product, registration and safety assessment requirements under REACH should be fulfilled, including nanoform-specific data, where applicable [120]. Information generated during earlier development stages regarding exposure, release, toxicity, and environmental behaviour may support the preparation of regulatory dossiers and safe-use recommendations.

TRL 9 is reached when the technology is successfully implemented and operated under real service conditions. For nanomaterial-based wood protection systems, this includes commercial production, market deployment, and long-term use in buildings and infrastructure. The technology is no longer evaluated as a prototype or demonstrator but functions as a commercial product within its intended operational environment.

Activities at TRL 9 should include post-market monitoring, long-term durability observations, collection of user feedback, and verification of environmental and health performance throughout the product life cycle. Information gathered during operational use can support future product improvements and refinement of the achieved properties.

According to the OECD Safe and Sustainable by Design (SSbD) framework, TRL 9 should also include continuous assessment of occupational, consumer, and environmental safety associated with large-scale production and use of nanomaterial-based products [103]. Depending on the application and exposure scenarios, activities may include periodic occupational exposure measurements, health surveillance of exposed workers or consumers.

From a sustainability perspective, industrial-scale production enables comprehensive life-cycle evaluation of the developed technology. At this stage, environmental impacts may be quantified using life-cycle assessment (LCA) methods, taking into account actual manufacturing processes, transport, service life, and end-of-life scenarios. The resulting data can support the preparation of Environmental Product Declarations (EPD Type III) in accordance with EN 15804 and related standards, providing transparent and verified environmental information for building-sector users [131].

The outcomes of TRL 7–9 are the successful transformation of a laboratory-developed technology into a commercially implemented product with demonstrated performance, established manufacturing procedures, regulatory acceptance, verified environmental and safety impacts, and documented essential characteristics.

## 6. Conclusions

This study analysed the current state of research on nanomodified wood coatings and related testing approaches. The following conclusions can be drawn:

1. Approximately half of the reviewed studies used normative references for testing the physical, mechanical, and durability properties of nanomodified coatings and preservatives, particularly for colour and gloss evaluation, fungal durability, and ageing and weathering resistance. However, standardised testing procedures were less frequently applied in other areas, such as abrasion resistance and leaching tests. In general, many of the methods used to assess the physical, mechanical, and durability properties of the nanomodified coatings and preservatives do not fully comply with harmonised European standards for nanomaterials intended for civil engineering applications.
2. Standardisation of testing methods for nanomaterials is still under development. A wide range of techniques and guidance documents is provided within OECD frameworks and ISO/TC 229 standards. The use of standardised procedures for nanomaterial sample preparation and testing represents a clear direction for future research; however, further development and harmonisation of these standards are still required.
3. Only a small number of studies addressed the safety and biological durability of nanomaterial-based wood treatments, indicating a significant research gap in this area.
4. Safety assessments and nanoparticle emission scenarios suggest that the most appropriate application of nanotechnology-based wood treatments may be industrial pre-fabrication processes, particularly surface modification of engineered timber products such as CLT and GLT, rather than on-site application. This approach may reduce occupational exposure risks and ensure higher quality and more controlled coating conditions, thereby minimising nanoparticle release and improving coating performance.
5. The co-occurrence analyses revealed a limited number of dominant wood type–nanomaterial–treatment combinations and identified the most frequently applied analytical approaches in nanomaterial-based wood-modification studies. Softwood was the most commonly treated substrate and was predominantly associated with TiO<sub>2</sub>- and ZnO-based nanomaterials applied by brushing and immersion. SEM-centred characterisation strategies represented the most frequently used analytical framework. The results further demonstrated a strong research focus on colour stability and wettability, while comprehensive long-term durability assessments remain relatively scarce, highlighting important opportunities for future research.

**Author Contributions:** Conceptualisation, M.R., P.B., and I.B.; methodology, M.R.; validation, M.R.; formal analysis, M.R.; identification and screening, M.R.; resources, M.R.; data curation, M.R.;

writing—original draft preparation, M.R.; writing—review and editing, P.B. and I.B.; visualisation, M.R.; supervision, P.B. and I.B.; funding acquisition, P.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The original data presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

Spectroscopy Techniques:

ATR Attenuated Total Reflectance (mode to FTIR)

DRS Diffuse Reflectance Spectroscopy

FTIR Fourier Transform Infrared Spectroscopy

UV-Vis Ultraviolet–Visible spectroscopy

Microscopy Techniques:

ATM Atomic Force Microscopy

CLSM Confocal Laser Scanning Microscopy

FE-SEM Field Emission Scanning Electron Microscopy

SEM Scanning Electron Microscopy

STEM Scanning Transmission Electron Microscopy

TEM Transmission Electron Microscopy

X-ray Techniques:

EDS Energy-Dispersive Spectroscopy

EDX Energy-Dispersive X-Ray Spectroscopy

XRD X-Ray Diffraction

XRPD X-Ray Powder Diffraction

Thermal Analysis Methods:

DSC Differential Scanning Calorimetry

DTA Differential Thermal Analysis

TA Thermal Analysis (including TGA, DSC, and DTA)

TGA Thermogravimetric Analysis

Other:

DLS Dynamic Light Scattering

## References

1. Švajlenka, J.; Pošiváková, T. Innovation potential of wood constructions in the context of sustainability and efficiency of the construction industry. *J. Clean. Prod.* **2023**, *411*, 137209. [\[CrossRef\]](#)
2. Ling, K.; Won, S.; Li, W. Investigating Production Cycles in the U.S. Softwood Lumber Industry: 1965–2017. *J. For. Econ.* **2025**, *40*, 383–404. [\[CrossRef\]](#)
3. Barbu, M.C.; Tudor, E.M. State of the art of the Chinese forestry, wood industry and its markets. *Wood Mater. Sci. Eng.* **2022**, *17*, 1030–1039. [\[CrossRef\]](#)
4. Mračková, A.; Šimek, M.; Haviarová, E.; Pásztor, Z. Hardwood trade in selected countries of Eastern Europe. *Wood Res.* **2021**, *66*, 1064–1075. [\[CrossRef\]](#)
5. Keržič, E.; Vek, V.; Oven, P.; Humar, M. Changes in wood durability due to leaching of biologically active substances (extractives) resulting from weathering. *Case Stud. Constr. Mater.* **2024**, *21*, e03921. [\[CrossRef\]](#)
6. Laleicke, P.F.; Hubbe, M.A. Outdoor wood finishing: A review on making wood resistant to moisture, ultraviolet light, and degradation. *BioResources* **2025**, *20*, 7903–7982. [\[CrossRef\]](#)

7. Wang, Y.; Xue, J.; Peng, Y.; Cao, J. Effect of photodegradation on fungal colonization on wood during initial stage of brown-rot decay. *Holzforschung* **2022**, *76*, 356–367. [[CrossRef](#)]
8. Spear, M.J.; Curling, S.F.; Dimitriou, A.; Ormondroyd, G.A. Review of Functional Treatments for Modified Wood. *Coatings* **2021**, *11*, 327. [[CrossRef](#)]
9. Järvinen, J.; Ilgin, H.E.; Karjalainen, M. Wood Preservation Practices and Future Outlook: Perspectives of Experts from Finland. *Forests* **2022**, *13*, 1044. [[CrossRef](#)]
10. Altaner, C. Preservative treated timber products in New Zealand. *Cellul. Chem. Technol.* **2022**, *56*, 705–716. [[CrossRef](#)]
11. Jirouš-Rajković, V.; Miklečić, J. Enhancing Weathering Resistance of Wood—A Review. *Polymers* **2021**, *13*, 1980. [[CrossRef](#)] [[PubMed](#)]
12. Alsalamah, S.A.; Alghonaim, M.I.; Al Abboud, M.A. Role of nanoparticles for wood protection from decaying microorganisms and their enzymes: A review study. *BioResources* **2025**, *20*, 8119–8134. [[CrossRef](#)]
13. Papadopoulos, A.N.; Taghiyari, H.R. Innovative Wood Surface Treatments Based on Nanotechnology. *Coatings* **2019**, *9*, 866. [[CrossRef](#)]
14. Wang, Y.; Ge-Zhang, S.; Mu, P.; Wang, X.; Li, S.; Qiao, L.; Mu, H. Advances in Sol-Gel-Based Superhydrophobic Coatings for Wood: A Review. *Int. J. Mol. Sci.* **2023**, *24*, 9675. [[CrossRef](#)] [[PubMed](#)]
15. Ong, Z.; Mat Arip, M.N.; Lipeh, S.; Besserer, A.; Brosse, N.; Fredon, E.; Singham, G.V.; Yuen, K.H.; Lee, H.L. Advances in wood preservation technology: A review of conventional and nanotechnology preservation approaches. *BioResources* **2025**, *20*, 8209–8255. [[CrossRef](#)]
16. Ahmed, N.; Boyd-Shields, G.D.; Stokes, C.E.; Hassan, E.B. Nano-Chitosan Formulations and Essential Oil Encapsulation for Sustainable Wood Protection: A Comprehensive Review. *Appl. Sci.* **2026**, *16*, 2207. [[CrossRef](#)]
17. Kolya, H.; Kang, C.-W. Eco-Friendly Polymer Nanocomposite Coatings for Next-Generation Fire Retardants for Building Materials. *Polymers* **2024**, *16*, 2045. [[CrossRef](#)] [[PubMed](#)]
18. Albert, C.M.; Liew, K.C. Recent development and challenges in enhancing fire performance on wood and wood-based composites: A 10-year review from 2012 to 2021. *J. Bioresour. Bioprod.* **2024**, *9*, 27–42. [[CrossRef](#)]
19. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [[CrossRef](#)] [[PubMed](#)]
20. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ* **2021**, *372*, n160. [[CrossRef](#)] [[PubMed](#)]
21. Yao, X.; Zhao, W.; Zhang, H.; Zhang, Y.; Zhong, L.; Wu, Y. Performance study of a superhydrophobic nanocellulose membrane on the surface of a wood-based panel prepared via the sol-gel method. *Colloid Interface Sci. Commun.* **2023**, *57*, 100758. [[CrossRef](#)]
22. Majeed, H.; Iftikhar, T.; Ashir Nadeem, M.; Altaf Nazir, M. Green synthesis of Eucalyptus globulus zinc nanoparticles and its use in antimicrobial insect repellent paint formulation in bulk industrial production. *Heliyon* **2024**, *10*, e24467. [[CrossRef](#)] [[PubMed](#)]
23. Henry, P.; Halbus, A.F.; Athab, Z.H.; Paunov, V.N. Enhanced Antimould Action of Surface Modified Copper Oxide Nanoparticles with Phenylboronic Acid Surface Functionality. *Biomimetics* **2021**, *6*, 19. [[CrossRef](#)] [[PubMed](#)]
24. Fonte, A.P.N.D.; Cabral, B.M.; Lins, T.R.D.S.; Carneiro, M.E.; Lengowski, E.C.; Bonfatti Júnior, E.A.; Klock, U.; Andrade, A.S.D.; Silva, D.A.D. Performance of Spray-Dried Nanofibrillated Cellulose as Wood Varnish Reinforcement in Outdoor Environment. *Braz. Arch. Biol. Technol.* **2024**, *67*, e24231048. [[CrossRef](#)]
25. Kong, L.; Xu, D.; He, Z.; Wang, F.; Gui, S.; Fan, J.; Pan, X.; Dai, X.; Dong, X.; Liu, B.; et al. Nanocellulose-Reinforced Polyurethane for Waterborne Wood Coating. *Molecules* **2019**, *24*, 3151. [[CrossRef](#)] [[PubMed](#)]
26. Jorbandian, A.; Jonoobi, M.; Ashori, A.; Ranjbar, Z. Transparent flexible waterborne acrylic nanocomposite coatings for UV-resistant outdoor wood protection. *Mater. Today Commun.* **2026**, *50*, 114450. [[CrossRef](#)]
27. Höfer, T.; Szabo, G.; Rössler, A.; Strube, O.I. Application of cellulose nitrate nanoparticles as binder in waterborne wood coatings and their additional use in debonding on demand. *J. Coat. Technol. Res.* **2025**, *22*, 1269–1279. [[CrossRef](#)]
28. Herrera, R.; Poohphajai, F.; Sandak, A.; Gordobil, O. Simultaneous Improvement of Surface Wettability and UV Resistance of Wood with Lignin-Based Treatments. *Polymers* **2023**, *15*, 3409. [[CrossRef](#)] [[PubMed](#)]
29. Henn, K.A.; Forsman, N.; Zou, T.; Österberg, M. Colloidal Lignin Particles and Epoxies for Bio-Based, Durable, and Multiresistant Nanostructured Coatings. *ACS Appl. Mater. Interfaces* **2021**, *13*, 34793–34806. [[CrossRef](#)] [[PubMed](#)]
30. Zikeli, F.; Vettraino, A.M.; Biscontri, M.; Bergamasco, S.; Palocci, C.; Humar, M.; Romagnoli, M. Lignin Nanoparticles with Entrapped Thymus spp. Essential Oils for the Control of Wood-Rot Fungi. *Polymers* **2023**, *15*, 2713. [[CrossRef](#)] [[PubMed](#)]
31. Zikeli, F.; Vinciguerra, V.; D'Annibale, A.; Capitani, D.; Romagnoli, M.; Scarascia Mugnozza, G. Preparation of Lignin Nanoparticles from Wood Waste for Wood Surface Treatment. *Nanomaterials* **2019**, *9*, 281. [[CrossRef](#)] [[PubMed](#)]
32. Jafarpisheh, F.; Kolvir, H.R.; Ghorbanpour, M. Photocatalytic self-cleaning and antibacterial activity of modified wood by Ag doped TiO<sub>2</sub> nanoparticles. *Next Mater.* **2024**, *4*, 100207. [[CrossRef](#)]

33. Rahayu, I.; Darmawan, W.; Nawawi, D.S.; Prihatini, E.; Ismail, R.; Laksono, G.D. Physical Properties of Fast-Growing Wood-Polymer Nano Composite Synthesized through TiO<sub>2</sub> Nanoparticle Impregnation. *Polymers* **2022**, *14*, 4463. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Zeljko, M.; Ocelić Bulatović, V.; Špada, V.; Blagojević, S.L. Environmentally Friendly UV-Protective Polyacrylate/TiO<sub>2</sub> Nanocoatings. *Polymers* **2021**, *13*, 2609. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Song, X.; Guo, W.; Zhu, Z.; Han, G.; Cheng, W. Preparation of uniform lignin/titanium dioxide nanoparticles by confined assembly: A multifunctional nanofiller for a waterborne polyurethane wood coating. *Int. J. Biol. Macromol.* **2024**, *258*, 128827. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Zhou, L.; Fu, Y. Flame-Retardant Wood Composites Based on Immobilizing with Chitosan/Sodium Phytate/Nano-TiO<sub>2</sub>-ZnO Coatings via Layer-by-Layer Self-Assembly. *Coatings* **2020**, *10*, 296. [\[CrossRef\]](#)
37. Moya, R.; Rodríguez-Zúñiga, A.; Vega-Baudrit, J.; Puente-Urbina, A. Effects of adding TiO<sub>2</sub> nanoparticles to a water-based varnish for wood applied to nine tropical woods of Costa Rica exposed to natural and accelerated weathering. *J. Coat. Technol. Res.* **2017**, *14*, 141–152. [\[CrossRef\]](#)
38. Pánek, M.; Oberhofnerová, E.; Zeidler, A.; Šedivka, P. Efficacy of Hydrophobic Coatings in Protecting Oak Wood Surfaces during Accelerated Weathering. *Coatings* **2017**, *7*, 172. [\[CrossRef\]](#)
39. Pánek, M.; Oberhofnerová, E.; Hýsek, Š.; Šedivka, P.; Zeidler, A. Colour Stabilization of Oak, Spruce, Larch and Douglas Fir Heartwood Treated with Mixtures of Nanoparticle Dispersions and UV-Stabilizers after Exposure to UV and VIS-Radiation. *Materials* **2018**, *11*, 1653. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Pánek, M.; Hýsek, Š.; Dvořák, O.; Zeidler, A.; Oberhofnerová, E.; Šimůnková, K.; Šedivka, P. Durability of the Exterior Transparent Coatings on Nano-Photostabilized English Oak Wood and Possibility of Its Prediction before Artificial Accelerated Weathering. *Nanomaterials* **2019**, *9*, 1568. [\[CrossRef\]](#) [\[PubMed\]](#)
41. Hristozov, D.; Pizzol, L.; Basei, G.; Zabeo, A.; Mackevica, A.; Hansen, S.F.; Gosens, I.; Cassee, F.R.; De Jong, W.; Koivisto, A.J.; et al. Quantitative human health risk assessment along the lifecycle of nano-scale copper-based wood preservatives. *Nanotoxicology* **2018**, *12*, 747–765. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Garskaite, E.; Karlsson, O.; Stankeviciute, Z.; Kareiva, A.; Jones, D.; Sandberg, D. Surface hardness and flammability of Na<sub>2</sub>SiO<sub>3</sub> and nano-TiO<sub>2</sub> reinforced wood composites. *RSC Adv.* **2019**, *9*, 27973–27986. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Lu, X.; Hu, Y. Layer-by-layer Deposition of TiO<sub>2</sub> Nanoparticles in the Wood Surface and its Superhydrophobic Performance. *BioResources* **2016**, *11*, 4605–4620. [\[CrossRef\]](#)
44. Goffredo, G.B.; Citterio, B.; Biavasco, F.; Stazi, F.; Barcelli, S.; Munafò, P. Nanotechnology on wood: The effect of photocatalytic nanocoatings against *Aspergillus niger*. *J. Cult. Herit.* **2017**, *27*, 125–136. [\[CrossRef\]](#)
45. Solano, R.; Patiño-Ruiz, D.; Herrera, A. Preparation of modified paints with nano-structured additives and its potential applications. *Nanomater. Nanotechnol.* **2020**, *10*, 184798042090918. [\[CrossRef\]](#)
46. Jia, C.; Zhang, Y.; Cui, J.; Gan, L. The Antibacterial Properties and Safety of a Nanoparticle-Coated Parquet Floor. *Coatings* **2019**, *9*, 403. [\[CrossRef\]](#)
47. Hernandez, V.; Morales, C.; Sagredo, N.; Perez-Gonzalez, G.; Romero, R.; Contreras, D. Radical Species Production and Color Change Behavior of Wood Surfaces Treated with Suppressed Photoactivity and Photoactive TiO<sub>2</sub> Nanoparticles. *Coatings* **2020**, *10*, 1033. [\[CrossRef\]](#)
48. Zanatta, P.; Lazarotto, M.; Gonzalez De Cademartori, P.H.; Cava, S.D.S.; Moreira, M.L.; Gatto, D.A. The effect of titanium dioxide nanoparticles obtained by microwave-assisted hydrothermal method on the color and decay resistance of pinewood. *Maderas Cienc. Tecnol.* **2017**, *19*, 495–506. [\[CrossRef\]](#)
49. Pereira Acosta, A.; Zanatta, P.; Gallio, E.; Freire, N.; Lazarotto, M.; Gomes Jardim, P.L.; Gatto, D.A.; Moreira, M.L. TiO<sub>2</sub>-modified *Pinus elliottii*: A pine wood presenting increased resistance to water and ultraviolet radiation. *Maderas Cienc. Tecnol.* **2021**, *23*, 38. [\[CrossRef\]](#)
50. Paul, D.; Humar, M.; Tesařová, D.; Petrič, M.; Gaff, M. Nanoparticle-based impregnation coatings for wood: Improving hydrophobicity, mechanical properties, and blue stain fungi resistance through structure–property relationship. *J. Mater. Sci.* **2025**, *60*, 13381–13397. [\[CrossRef\]](#)
51. Hernandez, V.A.; Sagredo, N.; Riquelme, J.; Romero, R.; Evans, P.D. Fungal Colonization of Weathered Radiata Pine Surfaces Protected with Inorganic Nanoparticles and Coatings. *Forests* **2023**, *14*, 1338. [\[CrossRef\]](#)
52. Urriza, L.M.C.; Acda, M.N.; Grande-Flores, J.O. Polymethylmethacrylate and polydimethylsiloxane coatings with nano TiO<sub>2</sub> and ZnO: Surface property and resistance against drywood termite. *Results Surf. Interfaces* **2025**, *21*, 100684. [\[CrossRef\]](#)
53. Srivastava, A.A.; Bondarev, V.P.; Kostyleva, E.I.; Novikov, A.N.; Fukina, D.G.; Markov, A.N.; Markin, Z.A.; Kazarina, O.V. Doped TiO<sub>2</sub> and oligoalkylhydrosiloxane-based surface modifiers with self-cleaning and hydrophobic properties. *Next Mater.* **2026**, *10*, 101414. [\[CrossRef\]](#)
54. Weththimuni, M.L.; Milanese, C.; Licchelli, M.; Malagodi, M. Improving the Protective Properties of Shellac-Based Varnishes by Functionalized Nanoparticles. *Coatings* **2021**, *11*, 419. [\[CrossRef\]](#)

55. Lozhechnikova, A.; Bellanger, H.; Michen, B.; Burgert, I.; Österberg, M. Surfactant-free carnauba wax dispersion and its use for layer-by-layer assembled protective surface coatings on wood. *Appl. Surf. Sci.* **2017**, *396*, 1273–1281. [\[CrossRef\]](#)
56. De Peres, M.L.; Delucis, R.D.A.; Amico, S.C.; Gatto, D.A. Zinc oxide nanoparticles from microwave-assisted solvothermal process: Photocatalytic performance and use for wood protection against xylophagous fungus. *Nanomater. Nanotechnol.* **2019**, *9*, 184798041987620. [\[CrossRef\]](#)
57. Tuong, V.M.; Huyen, N.V.; Kien, N.T.; Dien, N.V. Durable Epoxy ZnO Coating for Improvement of Hydrophobicity and Color Stability of Wood. *Polymers* **2019**, *11*, 1388. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Weththimuni, M.L.; Capsoni, D.; Malagodi, M.; Licchelli, M. Improving Wood Resistance to Decay by Nanostructured ZnO-Based Treatments. *J. Nanomater.* **2019**, *2019*, 6715756. [\[CrossRef\]](#)
59. Oberhofnerová, E.; Pánek, M.; Podlena, M.; Pavelek, M.; Štěrbová, I. Color Stabilization of Siberian and European Larch Wood Using UVA, HALS, and Nanoparticle Pretreatments. *Forests* **2019**, *10*, 23. [\[CrossRef\]](#)
60. Clar, J.G.; Platten, W.E.; Baumann, E.; Remsen, A.; Harmon, S.; Rodgers, K.; Thomas, T.; Matheson, J.; Luxton, T.P. Transformation and release of nanoparticle additives & byproducts from commercially available surface coatings on pressure treated lumber via dermal contact. *Sci. Total Environ.* **2019**, *694*, 133669. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Li, J.; Wu, Z.; Bao, Y.; Chen, Y.; Huang, C.; Li, N.; He, S.; Chen, Z. Wet chemical synthesis of ZnO nanocoating on the surface of bamboo timber with improved mould-resistance. *J. Saudi Chem. Soc.* **2017**, *21*, 920–928. [\[CrossRef\]](#)
62. Rao, F.; Zhang, Y.; Bao, M.; Zhang, Z.; Bao, Y.; Li, N.; Chen, Y.; Yu, W. Photostabilizing Efficiency of Acrylic-based Bamboo Exterior Coatings Combining Benzotriazole and Zinc Oxide Nanoparticles. *Coatings* **2019**, *9*, 533. [\[CrossRef\]](#)
63. Thornton, S.B.; Boggins, S.J.; Peloquin, D.M.; Luxton, T.P.; Clar, J.G. Release and transformation of nanoparticle additives from surface coatings on pristine & weathered pressure treated lumber. *Sci. Total Environ.* **2020**, *737*, 139451. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Gholamiyan, H.; Gholampoor, B.; Mastouri, A.; Hosseinpourpia, R. Surface properties of oak wood (*Quercus castaneifolia*) coated with polyester reinforced with ceramic nanoparticles using a plasma deposition technique. *J. Coat. Technol. Res.* **2025**, *22*, 2143–2151. [\[CrossRef\]](#)
65. Vitosytė, J.; Krystofiak, T.; Lis, B.; Ukvalbergienė, K. Nanocomposite wood coating film parameter stability after short term intensive UV+IR irradiation. *Drewno* **2018**, *61*, 107–118. [\[CrossRef\]](#)
66. Lemaire-Paul, M.; Beuthe, C.A.; Riahinezhad, M.; Reza Foruzanmehr, M. The impact of vacuum pressure on the effectiveness of SiO<sub>2</sub> impregnation of spruce wood. *Wood Sci. Technol.* **2023**, *57*, 147–171. [\[CrossRef\]](#)
67. Bak, M.; Takács, D.; Rákosa, R.; Németh, Z.I.; Németh, R. One-Step Process for the Fabrication of Hydrophobic and Dimensional Stable Wood Using Functionalized Silica Nanoparticles. *Forests* **2023**, *14*, 651. [\[CrossRef\]](#)
68. Jian, Y.; Xu, T.; Hess, D.W.; Tang, W.; Chai, X.; Zhang, L.; Xu, K.; Guo, Z.; Wan, H.; Xie, L. Efficient synthesis of durable superhydrophobic SiO<sub>2</sub>@PFDMs coatings on bamboo by liquid deposition. *Ind. Crops Prod.* **2024**, *219*, 119078. [\[CrossRef\]](#)
69. Nguyen, N.B.; Ly, N.H.; Tran, H.N.; Son, S.J.; Joo, S.; Vasseghian, Y.; Osman, S.M.; Luque, R. Transparent Oil–Water Separating Spiky SiO<sub>2</sub> Nanoparticle Supramolecular Polymer Superhydrophobic Coatings. *Small Methods* **2023**, *7*, 2201257. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Oberhofnerová, E.; Pánek, M.; Böhm, M. Effect of surface pretreatment with natural essential oils on the weathering performance of spruce wood. *BioResources* **2018**, *13*, 7053–7070. [\[CrossRef\]](#)
71. Yue, D.; Feng, Q.; Huang, X.; Zhang, X.; Chen, H. In Situ Fabrication of a Superhydrophobic ORMOSIL Coating on Wood by an Ammonia–HMDS Vapor Treatment. *Coatings* **2019**, *9*, 556. [\[CrossRef\]](#)
72. Bossert, D.; Geers, C.; Placencia Peña, M.I.; Volkmer, T.; Rothen-Rutishauser, B.; Petri-Fink, A. Size and Surface Charge Dependent Impregnation of Nanoparticles in Soft- and Hardwood. *Chemistry* **2020**, *2*, 361–373. [\[CrossRef\]](#)
73. Su, J.; Zhang, H.; Zhu, M.; Cai, J.; Xu, B. Green and Abrasion-Resistant Superhydrophobic Coatings Constructed with Tung Oil/Carnauba Wax/Silica for Wood Surface. *Materials* **2024**, *17*, 3000. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Mitani, A.; Kamperidou, V.; Terzopoulou, P. Surface Treatment of Oak Wood with Silica Dioxide Nanoparticles and Paraloid B72. *Forests* **2024**, *15*, 1842. [\[CrossRef\]](#)
75. Feng, B.; Zhang, S.; Wang, D.; Li, Y.; Zheng, P.; Gao, L.; Huo, D.; Cheng, L.; Wei, S. Study on antibacterial wood coatings with soybean protein isolate nano-silver hydrosol. *Prog. Org. Coat.* **2022**, *165*, 106766. [\[CrossRef\]](#) [\[PubMed\]](#)
76. Qi, Y.; Dai, X.; Wei, L.; Luo, H.; Liu, Y.; Dong, X.; Yang, D.; Li, Y. Nano-AgCu Alloy on Wood Surface for Mold Resistance. *Nanomaterials* **2022**, *12*, 1192. [\[CrossRef\]](#) [\[PubMed\]](#)
77. Dai, X.; Qi, Y.; Luo, H.; He, Z.; Wei, L.; Dong, X.; Ma, X.; Yang, D.-Q.; Li, Y. Leachability and Anti-Mold Efficiency of Nanosilver on Poplar Wood Surface. *Polymers* **2022**, *14*, 884. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Silva-Castro, I.; Casados-Sanz, M.; Alonso-Cortés, A.L.; Martín-Ramos, P.; Martín-Gil, J.; Acuña-Rello, L. Chitosan-Based Coatings to Prevent the Decay of Populus spp. Wood Caused by Trametes Versicolor. *Coatings* **2018**, *8*, 415. [\[CrossRef\]](#)
79. Moya, R.; Rodriguez-Zuñiga, A.; Berrocal, A.; Vega-Baudrit, J. Effect of Silver Nanoparticles Synthesized with NPs Ag-Ethylene Glycol (C<sub>2</sub>H<sub>6</sub>O<sub>2</sub>) on Brown Decay and White Decay Fungi of Nine Tropical Woods. *J. Nanosci. Nanotechnol.* **2017**, *17*, 5233–5240. [\[CrossRef\]](#)

80. Taghiyari, H.; Esmailpour, A.; Papadopoulos, A. Paint Pull-Off Strength and Permeability in Nanosilver-Impregnated and Heat-Treated Beech Wood. *Coatings* **2019**, *9*, 723. [\[CrossRef\]](#)
81. Boivin, G.; Ritcey, A.M.; Landry, V. The effect of silver nanoparticles on the black-stain resistance of acrylic resin for translucent wood coating application. *BioResources* **2019**, *14*, 6353–6369. [\[CrossRef\]](#)
82. Xu, J.; Liu, Y.; Wen, M.; Park, H.-J.; Zhu, J.; Liu, Y. Preparation of Flame Retardant and Antibacterial Wood with Composite Membrane Coating. *J. Korean Wood Sci. Technol.* **2021**, *49*, 658–666. [\[CrossRef\]](#)
83. Platten, W.E.; Sylvest, N.; Warren, C.; Arambewela, M.; Harmon, S.; Bradham, K.; Rogers, K.; Thomas, T.; Luxton, T.P. Estimating dermal transfer of copper particles from the surfaces of pressure-treated lumber and implications for exposure. *Sci. Total Environ.* **2016**, *548–549*, 441–449. [\[CrossRef\]](#) [\[PubMed\]](#)
84. Civardi, C.; Schlagenhauf, L.; Kaiser, J.-P.; Hirsch, C.; Mucchino, C.; Wichser, A.; Wick, P.; Schwarze, F.W.M.R. Release of copper-amended particles from micronized copper-pressure-treated wood during mechanical abrasion. *J. Nanobiotechnol.* **2016**, *14*, 77. [\[CrossRef\]](#) [\[PubMed\]](#)
85. Semenzin, E.; Subramanian, V.; Pizzol, L.; Zabeo, A.; Fransman, W.; Oksel, C.; Hristozov, D.; Marcomini, A. Controlling the risks of nano-enabled products through the life cycle: The case of nano copper oxide paint for wood protection and nano-pigments used in the automotive industry. *Environ. Int.* **2019**, *131*, 104901. [\[CrossRef\]](#) [\[PubMed\]](#)
86. Zhou, D.; Zhang, F.; Chen, M. In Situ Growth of Cu<sub>2</sub>O-Coated Cu Aggregates on Wood and Bamboo for Efficient Mold Resistance. *Surfaces* **2025**, *8*, 66. [\[CrossRef\]](#)
87. Zhao, P.; Yang, H.; Xu, G.; Huang, C.; Zhong, Y. Combination of nano-CuO/silica sol preservative with various post-treatments to improve the compressive strength, water resistance, and thermal stability of wood. *BioResources* **2021**, *16*, 7444–7460. [\[CrossRef\]](#)
88. Shimanouchi, T.; Hirota, D.; Yoshida, M.; Yasuhara, K.; Kimura, Y. Preparation of Nano- and Microparticles Obtained from Polymerization Reaction and Their Application to Surface Coating of Woody Materials. *Appl. Sci.* **2024**, *14*, 11326. [\[CrossRef\]](#)
89. Babahan Bircan, I.; Altay, Ç.; Baysal, E.; Kırım, B.; Emirdağ, S.; Toker, H.; Çelik, M.; Kocaman, E. The utilisation of turpentine and moss oil as epoxy hardeners for bio-based epoxy nanocomposite coatings. *Maderas-Cienc. Tecnol.* **2026**, *28*, e0526. [\[CrossRef\]](#)
90. Wang, L.; Zhao, X.; Ren, S.; Hu, Z.; Wang, Y. Application of pH-responsive functionalized hollow mesoporous organosilica nanoparticles for wood preservation. *Mater. Des.* **2023**, *225*, 111538. [\[CrossRef\]](#)
91. Khademibami, L.; Jeremic, D.; Shmulsky, R.; Barnes, H.M. Chitosan oligomers and related nanoparticles as environmentally friendly wood preservatives. *BioResources* **2020**, *15*, 2800–2817. [\[CrossRef\]](#)
92. Usmani, S.M.; Plarre, R.; Hübert, T.; Kemnitz, E. Termite resistance of pine wood treated with nano metal fluorides. *Eur. J. Wood Prod.* **2020**, *78*, 493–499. [\[CrossRef\]](#)
93. Pánek, M.; Šimůnková, K.; Novák, D.; Dvořák, O.; Schönfelder, O.; Šedivka, P.; Kobetičová, K. Caffeine and TiO<sub>2</sub> Nanoparticles Treatment of Spruce and Beech Wood for Increasing Transparent Coating Resistance against UV-Radiation and Mould Attacks. *Coatings* **2020**, *10*, 1141. [\[CrossRef\]](#)
94. Ion, R.-M.; Nyokong, T.; Nwahara, N.; Suica-Bunghez, I.-R.; Iancu, L.; Teodorescu, S.; Dulama, I.D.; Stirbescu, R.M.; Gheboianu, A.; Grigorescu, R.M. Wood preservation with gold hydroxyapatite system. *Herit. Sci.* **2018**, *6*, 37. [\[CrossRef\]](#)
95. Elmaaty, T.A.; Swidan, A.; Sayed-Ahmed, K.; Zaghloul, N. A novel approach for enhancing the color and antimicrobial properties of pine and beech wood using Se-NPs. *Sci. Rep.* **2023**, *13*, 12972. [\[CrossRef\]](#) [\[PubMed\]](#)
96. Gholamiyan, H.; Tarmian, A. Weathering Resistance of Poplar Wood Coated by Organosilane Water Soluble Nanomaterials. *Drv. Ind.* **2018**, *69*, 371–378. [\[CrossRef\]](#)
97. EN 14080:2013; Timber Structures—Glued Laminated Timber and Glued Solid Timber—Requirements. iTeh Standards: Newark, DE, USA, 2013.
98. EN 15497:2014; Structural Finger Jointed Solid Timber—Performance Requirements and Minimum Production Requirements. iTeh Standards: Newark, DE, USA, 2014.
99. EN 338:2016; Structural Timber—Strength Classes. iTeh Standards: Newark, DE, USA, 2016.
100. Zhao, F.; Tang, T.; Hou, S.; Fu, Y. Preparation and Synergistic Effect of Chitosan/Sodium Phytate/MgO Nanoparticle Fire-Retardant Coatings on Wood Substrate through Layer-By-Layer Self-Assembly. *Coatings* **2020**, *10*, 848. [\[CrossRef\]](#)
101. OECD. Test No. 125: Nanomaterial Particle Size and Size Distribution of Nanomaterials; OECD Guidelines for the Testing of Chemicals, Section 1; OECD Publishing: Paris, France, 2023. [\[CrossRef\]](#)
102. OECD. Guidance on Sample Preparation and Dosimetry for Manufactured Nanomaterials, 2025 Edition. In *OECD Series on the Safety of Manufactured Nanomaterials and Other Advanced Materials*; OECD Publishing: Paris, France, 2025. [\[CrossRef\]](#)
103. OECD. Safe and sustainable by design tools, integrative systems and platforms for nanomaterials and nano-enabled products. In *OECD Series on the Safety of Manufactured Nanomaterials and Other Advanced Materials*; OECD Publishing: Paris, France, 2025. [\[CrossRef\]](#)
104. Pizzol, L.; Hristozov, D.; Zabeo, A.; Basei, G.; Wohlleben, W.; Koivisto, A.J.; Jensen, K.A.; Fransman, W.; Stone, V.; Marcomini, A. SUNDS probabilistic human health risk assessment methodology and its application to organic pigment used in the automotive industry. *NanoImpact* **2019**, *13*, 26–36. [\[CrossRef\]](#)

105. Subramanian, V.; Semenzin, E.; Hristozov, D.; Zabeo, A.; Malsch, I.; McAlea, E.; Murphy, F.; Mullins, M.; Van Harmelen, T.; Ligthart, T.; et al. Sustainable nanotechnology decision support system: Bridging risk management, sustainable innovation and risk governance. *J. Nanopart Res.* **2016**, *18*, 89. [\[CrossRef\]](#)
106. OECD. *Test No. 124: Determination of the Volume Specific Surface Area of Manufactured Nanomaterials; OECD Guidelines for the Testing of Chemicals, Section 1*; OECD Publishing: Paris, France, 2022. [\[CrossRef\]](#)
107. OECD. The Identification of Exposure Metrics for Use in Evaluation of Inhalation Exposure to Nano-Objects and their Aggregates and Agglomerates (NOAA) in the Workplace. In *OECD Series on the Safety of Manufactured Nanomaterials and other Advanced Materials*; OECD Publishing: Paris, France, 2025. [\[CrossRef\]](#)
108. Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 Laying Down Harmonised Conditions for the Marketing of Construction Products and Repealing Council Directive 89/106/EEC. 2024. Available online: <https://www.legislation.gov.uk/eur/2011/305/contents> (accessed on 26 May 2026).
109. Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011. 2024. Available online: <https://eur-lex.europa.eu/eli/reg/2024/3110/oj/eng> (accessed on 26 May 2026).
110. *EN 15886:2010*; Conservation of Cultural Property—Test Methods—Colour Measurement Of Surfaces. iTeh Standards: Newark, DE, USA, 2010.
111. *ASTM D523-25*; Test Method for Specular Gloss. ASTM International: West Conshohocken, PA, USA, 2025.
112. *ASTM D2244-14*; Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates. ASTM International: West Conshohocken, PA, USA, 2014.
113. *ISO 2813:2014*; Paints and Varnishes—Determination of Gloss Value at 20°, 60° and 85°. International Organization for Standardization: Geneva, Switzerland, 2014.
114. *EN 113-1:2020*; Durability of Wood and Wood-Based Products—Test Method Against Wood Destroying Basidiomycetes—Part 1: Assessment of Biocidal Efficacy of Wood Preservatives. iTeh Standards: Newark, DE, USA, 2020.
115. *ASTM D2017-05*; Test Method of Accelerated Laboratory Test of Natural Decay Resistance of Woods. ASTM International: West Conshohocken, PA, USA, 2005.
116. *EN 152:2011*; Wood Preservatives—Determination of the Protective Effectiveness of a Preservative Treatment Against Blue Stain in Wood in Service—Laboratory Method. iTeh Standards: Newark, DE, USA, 2011.
117. *EN 927-6:2018*; Paints and Varnishes—Coating Materials and Coating Systems for Exterior Wood—Part 6: Exposure of Wood Coatings to Artificial Weathering Using Fluorescent UV Lamps and Water. iTeh Standards: Newark, DE, USA, 2018.
118. Benko, H. ISO Technical Committee 229 Nanotechnologies. In *Metrology and Standardization of Nanotechnology*; Mansfield, E., Kaiser, D.L., Fujita, D., Van De Voorde, M., Eds.; Wiley: Hoboken, NJ, USA, 2017; pp. 259–268. ISBN 978-3-527-34039-2.
119. Nepal, P.; Johnston, C.M.T.; Ganguly, I. Effects on Global Forests and Wood Product Markets of Increased Demand for Mass Timber. *Sustainability* **2021**, *13*, 13943. [\[CrossRef\]](#)
120. Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), Establishing a European Chemicals Agency, Amending Directive 1999/45/EC and Repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as Well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. 2006. Available online: <https://www.legislation.gov.uk/eur/2006/1907/contents> (accessed on 26 May 2026).
121. *EAD 030352-00-0503*; Liquid Applied Watertight Covering Kits for Wet Room Floors and/or Walls. European Organisation for Technical Assessment: Brussels, Belgium, 2019.
122. *EAD 350865-00-1106*; Fire Retardant Products. European Organisation for Technical Assessment: Brussels, Belgium, 2018.
123. *EN 13823:2010*; Reaction to Fire Tests for Building Products—Building Products Excluding Floorings Exposed to the Thermal Attack by a Single Burning Item. iTeh Standards: Newark, DE, USA, 2010.
124. *ISO 5660-1:2015*; Reaction-to-Fire Tests. Heat Release, Smoke Production and Mass Loss Rate—Part 1: Heat Release Rate (Cone Calorimeter Method) and Smoke Production Rate (Dynamic measurement). International Organization for Standardization: Geneva, Switzerland, 2015.
125. *ISO 7784-2:2016*; Paints and Varnishes—Determination of Resistance to Abrasion—Part 2: Method with Abrasive Rubber Wheels and Rotating Test Specimen. International Organization for Standardization: Geneva, Switzerland, 2016.
126. *EN 16516:2017+A1:2020*; Construction Products: Assessment of Release of Dangerous Substances—Determination of Emissions into Indoor air. iTeh Standards: Newark, DE, USA, 2020.
127. *EN 16637-2:2023*; Construction Products: Assessment of Release of Dangerous Substances—Part 2: Horizontal Dynamic Surface Leaching Test. iTeh Standards: Newark, DE, USA, 2023.
128. *ISO 16290:2013*; Space Systems—Definition of the Technology Readiness Levels (TRLs) and Their Criteria of Assessment. International Organization for Standardization: Geneva, Switzerland, 2013.

129. *EN ISO 1716:2018*; Reaction to Fire Tests for Products—Determination of the Gross Heat of Combustion (Calorific Value). iTeh Standards: Newark, DE, USA, 2018.
130. *EN 13501-1:2018*; Fire Classification of Construction Products and Building Elements—Part 1: Classification Using Data from Reaction to Fire Tests. iTeh Standards: Newark, DE, USA, 2018.
131. *EN 15804:2012+A2:2019*; Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. iTeh Standards: Newark, DE, USA, 2019.

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.