Ε Λ Λ Η Ν Ι Κ Η Δ Η Μ Ο Κ Ρ Α Τ Ι Α
ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ
ΤΜΗΜΑ ΔΑΣΟΛΟΓΙΑΣ, ΕΠΙΣΤΗΜΩΝ ΞΥΛΟΥ & ΣΧΕΔΙΑΣΜΟΥ

ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ

ΠΡΟΗΓΜΕΝΕΣ ΜΕΘΟΔΟΙ ΣΧΕΔΙΑΣΜΟΥ, ΤΕΧΝΟΛΟΓΙΑΣ & ΜΑΝΑΤΖΜΕΝΤ ΠΡΟΙΟΝΤΩΝ ΑΠΌ ΞΥΛΟ

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

«Επίδραση νανοσωματιδίων πυριτίου στις ιδιότητες ξύλου iroko, meranti, ελάτης και πεύκου»

Μανδραβέλη Ελένη του Ιωάννη

ΤΡΙΜΕΛΗΣ ΣΥΜΒΟΥΛΕΥΤΙΚΗ ΕΠΙΤΡΟΠΗ

Δρ. Μητάνη Ανδρομάχη, Ακαδημαϊκή Υπότροφος, Επιβλέπουσα
Δρ. Νταλός Γεώργιος, Καθηγητής, Μέλος
Δρ. Δημήτριος Κουτσιανίτης, Επίκουρος καθηγητής, Μέλος

Καρδίτσα 2025

Περίληψη

Η παρούσα μελέτη διερευνά την επίδραση των νανοσωματιδίων διοξειδίου του πυριτίου (SiO_2) στις φυσικές και χρωματικές ιδιότητες τεσσάρων ειδών ξύλου: Iroko (Milicia excelsa), Meranti (Shorea spp.), Ελάτη (Abies spp.) και Πεύκο (Pinus spp.). Εξετάστηκαν η υγροσκοπικότητα, η τραχύτητα της επιφάνειας, η ανθεκτικότητα στην υπεριώδη (UV) ακτινοβολία και η σταθερότητα χρώματος πριν και μετά από τεχνητή γήρανση.

Τα αποτελέσματα έδειξαν ότι η παρουσία νανοσωματιδίων SiO_2 επηρέασε διαφορετικά κάθε είδος ξύλου. Ειδικότερα, η υγροσκοπικότητα μειώθηκε, με σημαντικότερη επίδραση στο Iroko και μικρότερη στο Meranti, γεγονός που αποδίδεται στη διαφοροποιημένη πορώδη δομή των ειδών. Όσον αφορά τη τραχύτητα, οι νανοσωματιδιακές επικαλύψεις δεν προκάλεσαν σημαντική μεταβολή, εκτός από το Meranti και την Ελάτη, όπου καταγράφηκαν διαφοροποιήσεις σε συγκεκριμένους δείκτες (Rz).

Στη χρωματική σταθερότητα, παρατηρήθηκε ότι τα νανοσωματίδια επηρέασαν κυρίως τη διατήρηση της απόχρωσης (hue) στο Iroko και το Πεύκο, ενώ δεν είχαν σημαντική επίδραση στο Meranti. Η ανθεκτικότητα στην υπεριώδη ακτινοβολία βελτιώθηκε οριακά, ωστόσο η κατανομή και συγκέντρωση των νανοσωματιδίων έπαιξαν καθοριστικό ρόλο στην αποτελεσματικότητα της προστασίας.

Τα ευρήματα αυτά συμβάλλουν στην κατανόηση της αλληλεπίδρασης νανοσωματιδίων με το ξύλο, αναδεικνύοντας τη σημασία της επιλογής του ξύλου και της συγκέντρωσης νανοσωματιδίων για την επίτευξη της βέλτιστης προστασίας.

HELLENIC REPUBLIC
UNIVERSITY OF THESSALY
DEPARTMENT OF FORESTRY, WOOD SCIENCE & DESIGN
POSTGRADUATE PROGRAMME
ADVANCED METHODS OF DESIGN, TECHNOLOGY & MANAGEMENT OF WOODEN PRODUCTS

MASTER THESIS

«Impact of Silica Nanoparticles on the Properties of Iroko, Meranti, Fir, and Pine Wood»

Mandraveli Eleni

SUPERVISORY COMMITTEE

Dr Mitani Andromachi, Academic Scholar, Supervisor
Dr Ntalos Georgios, Professor, Member
Dr Koutsianitis Dimitrios, Assistant Professor, Member

Karditsa 2025

Abstract

This study investigates the effect of silicon dioxide (SiO_2) nanoparticles on the physical and colorimetric properties of four wood species: Iroko (Milicia excelsa), Meranti (Shorea spp.), Fir (Abies spp.), and Pine (Pinus spp.). The research examined hygroscopicity, surface roughness, UV resistance, and color stability before and after artificial aging.

The results showed that SiO_2 nanoparticles influenced each wood species differently. Specifically, hygroscopicity was reduced, with the most significant effect observed in Iroko and the least in Meranti, likely due to differences in porosity. Regarding surface roughness, nanoparticle coatings did not cause substantial changes, except in Meranti and Fir, where specific roughness parameters (Rz) exhibited variations.

In terms of color stability, nanoparticles primarily affected hue retention in Iroko and Pine, while they had no significant impact on Meranti. UV resistance showed only marginal improvement, but the effectiveness of protection depended on nanoparticle distribution and concentration.

These findings contribute to a better understanding of the interaction between nanomaterials and wood, emphasizing the importance of wood selection and nanoparticle concentration in achieving optimal protection.

Acknowledgements

I would like to thank my supervisor, Dr Andromachi Mitani, for her guidance and support throughout this research. I also appreciate the Department of Forestry, Wood Science & Design at the University of Thessaly for providing the necessary academic resources.

A special thanks to Hellas Wood Theocharis and Tsigas for providing the wood samples used in this study.

Finally, I am grateful to my colleagues, family, and friends for their support during this process.

Table of Contents

Lists of Tables, Photos and Figures

1. Introduction

1.1. Objective and Scope of the Study

This study investigates the effects of silica nanoparticle impregnation on the dimensional stability, hygroscopic behavior, surface roughness, and color stability of four different wood species: Fir (*Abies alba*), Pine (*Pinus sylvestris*), Iroko (*Milicia excelsa*), and Meranti (*Shorea spp.*). The primary objective is to assess how varying concentrations of silica nanoparticles influence water absorption, swelling, weight changes, surface roughness, and color alterations over time, particularly after artificial weathering.

The research aims to:

- Evaluate the impact of silica nanoparticle treatment on wood's moisture uptake, dimensional changes, and swelling behavior.
- Analyze the effect of nanoparticle concentration on surface roughness and color stability after artificial weathering.
- Compare the performance of different wood species in terms of stability, resistance to moisture variations, and surface degradation.

By understanding these effects, the study contributes to the development of more durable and moisture-resistant wood materials, with improved surface properties and color retention, which can be beneficial for construction, furniture, and wood-based industries.

1.2. Hygroscopicity, UV Aging, and Surface Degradation of Wood

Wood is inherently hygroscopic due to the presence of free hydroxyl (OH) groups within its main structural components—cellulose, hemicellulose, and lignin. This characteristic significantly impacts its physical, mechanical, and biological properties, making it highly susceptible to environmental fluctuations. As temperature and humidity levels vary, wood absorbs and releases moisture, leading to expansion and contraction. These continuous dimensional changes result in instability, which can cause deformation and structural weaknesses over time (Rowell, 2006).

Beyond moisture-related issues, wood is also prone to degradation when exposed to outdoor conditions. Among the various environmental stressors, ultraviolet (UV) radiation is particularly destructive. Prolonged UV exposure leads to substantial color alterations and the breakdown of surface layers, making the wood more vulnerable to biological agents such as fungi. Additionally, this degradation increases the hydrophilicity of the material, further exacerbating moisture-related problems (FEIST & HON, 1984).

The weathering process is complex and influenced by multiple factors beyond UV radiation. Elements such as precipitation, temperature shifts, air pollution, and mechanical abrasion from airborne particles all contribute to the deterioration of wood surfaces. Moreover, oxidation reactions and human activities can accelerate this degradation, leading to further structural and aesthetic changes (Živković et al., 2014).

One of the earliest visible signs of UV-induced degradation is a shift in wood color. This discoloration occurs due to the breakdown of lignin and cellulosic polymers in the wood's cell walls. Over time, the photodegradation of these components alters the wood's surface, diminishing its natural appearance and potentially affecting its functional properties (Rosu et al., 2010).

In addition to color changes, repeated cycles of wetting and drying can lead to the formation of surface checks and cracks. These micro-fissures not only affect the wood's aesthetic appeal but also compromise its durability and performance, particularly in applications where weather resistance is crucial. While the effects of weathering are generally confined to the surface, they can significantly impact the longevity and usability of wood products, necessitating protective treatments and coatings (Jirouš-Rajković & Miklečić, 2021).

1.3. Advancing Wood Protection: Challenges and Innovations

Ensuring the longevity and durability of wood-based materials is crucial in both industrial and research contexts. Traditional approaches to wood preservation have largely relied on surface coatings or treatments that penetrate the material to provide protection against decay, UV degradation, and biological deterioration (Bansal et al., 2024). These methods help mitigate environmental wear and structural weaknesses, making wood more suitable for various applications.

Despite their effectiveness, conventional wood preservation techniques present several challenges. One major issue is the leaching of preservatives, which can reduce long-term protection and introduce environmental contaminants. Additionally, many wood treatment formulations contain harmful chemicals, raising concerns about their impact on human health and ecosystems. Proper disposal of treated wood also remains a significant challenge, as residues of these chemicals can persist beyond the wood's functional life (Venmalar, 2017).

Industrial wood coatings often incorporate solvent-based formulations, which release volatile organic compounds (VOCs) into the atmosphere. These emissions contribute to air pollution and pose risks to both workers and end-users. As a result, there is a growing need for environmentally friendly, non-biocidal alternatives that provide long-term protection without harmful side effects (Baysal et al., 2004).

Nanotechnology has emerged as a promising solution to address these limitations. In recent years, the application of nanomaterials in wood science has provided innovative ways to enhance the structural and protective properties of wood and wood-based composites (Hill & Papadopoulos, 2001). Nanoparticles offer significant advantages over traditional preservation methods, including superior resistance to UV degradation, microbial attacks, and fire hazards. Additionally, nanocoatings can improve scratch resistance and create self-cleaning, superhydrophobic surfaces, enhancing both durability and aesthetic appeal (Dufresne, 2013).

The push for sustainable materials has further fueled interest in nanotechnology-based wood treatments. The demand for eco-friendly products has led to increased research into non-toxic and biodegradable nanomaterials. Cellulose, for example, is a naturally occurring polymer that can be processed into nanoparticles (NPs) using mechanical or chemical methods, offering a renewable and environmentally safe option for wood modification (Dufresne, 2013).

One of the key advantages of nanotechnology is its ability to modify wood at a microscopic level. Due to their small size, nanoparticles can penetrate deep into the wood structure, ensuring more uniform dispersion and long-lasting effectiveness. When properly engineered, these nanomaterials can pass through the wood's natural pores, leading to enhanced mechanical strength and greater resistance to external stressors (Hill & Papadopoulos, 2001).

1.4. SiO_2 Nanoparticles as Modifiers for Wood

Silicon dioxide (SiO_2) nanoparticles have emerged as a promising material for enhancing wood properties, particularly in improving moisture resistance, UV protection, and fire retardancy. One of their key advantages is their ability to reduce water absorption and enhance hydrophobicity, making wood more resistant to dimensional instability caused by moisture fluctuations (Bauer & Mehnert, 2005). Their nanoscale size allows them to penetrate wood structures effectively, forming a protective barrier that limits swelling, shrinking, and water uptake.

In addition to moisture resistance, SiO_2 nanoparticles contribute to UV protection by absorbing and scattering ultraviolet radiation, thereby slowing the degradation of lignin and other wood components. This protection extends the service life of wood by preventing discoloration, surface roughness, and structural weakening (Aloui et al., 2007; Forsthuber et al., 2013). Their role in coatings is particularly beneficial, as they enhance durability while maintaining the natural appearance of wood, unlike traditional UV-protective additives that often alter the wood's aesthetics.

Furthermore, SiO_2 nanoparticles have been shown to improve the fire resistance of treated wood. When combined with flame-retardant agents, they reduce smoke emissions and inhibit the spread of flames, making them a valuable addition to fire-resistant wood treatments (Zhu et al., 2014). Their ability to enhance thermal stability has also been demonstrated, offering an additional layer of protection in environments where fire safety is a concern.

Given these benefits, SiO_2 nanoparticles have become an essential component in modern wood modification strategies. Their multifunctional properties make them highly attractive for both industrial applications and research developments aimed at increasing the longevity and sustainability of wood-based materials. As interest in nanotechnology-driven wood protection grows, further advancements in SiO_2 applications are expected to enhance wood durability and performance across various environmental conditions.

1.5. Research Questions

This study aims to address the following research questions:

- Effect on Dimensional Stability: How do SiO_2 nanoparticles influence the weight and dimensional stability of wood over time, particularly in response to moisture variations?
- Impact on Surface Characteristics: To what extent do these nanoparticles alter the surface roughness of wood before and after UV exposure?
- UV Protection and Aesthetic Durability: Can SiO_2 nanoparticles improve color retention and reduce discoloration caused by prolonged exposure to ultraviolet radiation?
- Wood Species Variability: Is there a significant difference in the effectiveness of SiO_2 nanoparticle treatments across different wood species, and how does wood structure influence their performance?
- Optimization of Treatment: What is the optimal concentration of SiO_2 nanoparticles required to achieve the best balance between durability, UV resistance, and dimensional stability?

By addressing these questions, this research seeks to contribute to a deeper understanding of SiO_2 nanoparticle applications in wood science, providing insights that can guide industrial and environmental applications of nanotechnology in wood preservation.

2. Literature Review

2.1 Introduction to Nanotechnology in Wood Science

The integration of nanotechnology into wood science has garnered substantial interest in recent years due to its potential to enhance the durability, stability, and protective properties of wood and wood-based composites (Bansal et al., 2024). Wood, being an organic and hygroscopic material, is highly susceptible to degradation caused by environmental factors such as moisture, ultraviolet (UV) radiation, and biological deterioration (Rowell, 2006). Traditional wood preservation methods have certain limitations, including the leaching of preservatives, environmental toxicity, and disposal concerns (Venmalar, 2017). Therefore, novel approaches that are both effective and environmentally friendly are increasingly being explored.

Nanomaterials offer a promising solution to many of these challenges. Their small particle size allows for deep penetration into wood, leading to enhanced protection without significantly altering the material's natural properties (Bak & Németh, 2018). Furthermore, nanoparticles can impart photostability, improve water repellency, and enhance mechanical properties, all while demonstrating low toxicity compared to traditional wood preservatives (Kong et al., 2017). This review focuses on the application of nanotechnology, particularly silicon dioxide (SiO_2) nanoparticles, in addressing key challenges associated with wood protection, including UV aging, surface roughness, and hygroscopicity.

2.2 UV Aging and Weathering of Wood

2.2.1 Mechanisms of UV-Induced Wood Degradation

Wood is vulnerable to photodegradation, primarily driven by UV radiation, which causes chemical and structural changes at the surface level (Nikolic et al., 2015). UV rays can be categorized into three types: UV A, UV B, and UV C, with only UV A penetrating through window glass and affecting indoor-exposed wood surfaces. Among the various components of wood, lignin absorbs the most UV light due to the presence of chromophoric groups, which leads to oxidative reactions and discoloration over time (Bansal et al., 2022).

Exposure to sunlight initiates the breakdown of lignin and cellulosic polymers, causing surface discoloration, loss of gloss, and increased roughness (Derbyshire & Miller, 1981). Additionally, photodegradation results in the loosening and erosion of surface fibers, ultimately compromising the structural integrity of wood (Bansal et al., 2022). The oxidation of natural and synthetic polymers also plays a significant role in wood yellowing, with studies indicating that oxidation rates directly correlate with color changes.

2.2.2 Role of Nanoparticles in UV Protection

Nanoparticles, particularly inorganic metal oxides such as titanium dioxide (TiO_2) and zinc oxide (ZnO), have been extensively studied for their UV-absorbing properties (Forsthuber et al., 2013). These materials act as semiconductors, absorbing UV radiation and dissipating the energy as heat, thereby preventing damage to the underlying wood structure (Nikolic et al., 2015). Several studies have demonstrated that ZnO and CeO_2 nanoparticles exhibit superior UV-blocking capabilities compared to conventional UV stabilizers like Tinuvin 477 DW and Tinuvin 5151 (Blanchard & Blanchet, 2011).

Nanoparticle-infused coatings have shown promise in extending the longevity of wood coatings by reducing photodegradation. For instance, coatings containing nano-TiO_2 have demonstrated enhanced UV resistance while maintaining the transparency of the wood surface, a crucial factor for aesthetic and functional applications (Aloui et al., 2007).

2.3 Surface Roughness and Hygroscopicity of Wood

2.3.1 Impact of Environmental Factors on Surface Roughness

Environmental factors such as moisture fluctuations, UV exposure, and mechanical abrasion significantly impact the surface roughness of wood (Jirouš-Rajković & Miklečić, 2021). Repeated wetting and drying cycles cause surface checks, which can expand into cracks over time (Rosu et al., 2010). Additionally, exposure to pollutants, airborne particles, and biological agents further accelerates surface degradation, resulting in decreased durability (Živković et al., 2014).

Nanocoatings play a crucial role in mitigating these effects. The addition of nanoparticles to protective coatings has been found to reduce surface roughness and enhance hydrophobic properties, leading to improved durability (Bauer & Mehnert, 2005).

3.3.2 Addressing Hygroscopicity through Nanotechnology

Wood's hygroscopic nature stems from the presence of free hydroxyl (-OH) groups in cellulose, hemicellulose, and lignin, making it susceptible to moisture absorption and subsequent dimensional instability (Rowell, 2006). Fluctuations in humidity cause wood to expand and contract, which can lead to warping and structural weaknesses (Bansal et al., 2024).

Nanoparticles such as nano-silica have been employed to mitigate this issue by modifying the surface properties of wood. Studies have shown that nano-silica coatings can enhance water repellency and develop superhydrophobic surfaces, thereby reducing moisture absorption and improving dimensional stability (Bauer & Mehnert, 2005; Jia et al., 2016). Moreover, the synergistic effect of polyethylene glycol (PEG) and silica sol has been found to further enhance moisture resistance due to their bulking and filling properties (Jiang et al., 2021).

2.4 SiO_2 Nanoparticles as Wood Modifiers

2.4.1 Benefits of SiO_2 Nanoparticles in Wood Protection

Silicon dioxide (SiO_2) nanoparticles have emerged as effective wood modifiers, providing significant improvements in moisture resistance, UV protection, and surface durability. Their ability to reduce water absorption and create superhydrophobic surfaces makes them particularly beneficial in outdoor applications (Bak et al., 2023).

The effectiveness of SiO_2 nanoparticles is largely attributed to their nanoscale dimensions, which enable deep penetration into the wood matrix, altering its physicochemical properties without compromising its natural appearance (Hill & Papadopoulos, 2001). Additionally, the dispersion of nano-SiO_2 in polymer coatings has been shown to enhance the stability and adhesion of protective layers, leading to increased resistance against environmental stressors (Nikolic et al., 2015).

2.4.2 Applications of SiO_2 Nanoparticles in Wood Coatings

Research has demonstrated that the incorporation of SiO_2 nanoparticles in coatings significantly improves the durability of treated wood. A study utilizing a sol-gel method incorporating silica nanoparticles and PFOTS reagent successfully created superhydrophobic wood surfaces with a high contact angle of 159° (Wang et al., 2010). Furthermore, coatings incorporating polydimethylsiloxane (PDMS) and hydrophobic silica nanoparticles (HSNP) achieved even greater water repellency, with contact angles reaching 172° (Soytürk et al., 2023).

In addition to moisture resistance, nano-SiO_2 has been found to enhance fire-retardancy properties when combined with phosphorus-based flame retardants, reducing smoke emissions and improving the overall fire performance of treated wood (Zhu et al., 2014). These multifunctional attributes underscore the potential of SiO_2 nanoparticles as a sustainable alternative for wood preservation.

Wood, as a natural and versatile material, has traditionally been used for construction and decorative purposes due to its desirable physical and aesthetic qualities. Despite its advantages, wood is susceptible to challenges such as biological degradation, UV-induced discoloration, and dimensional instability under fluctuating moisture conditions. Over the past two decades, chemical modifications (e.g., acetylation, furfurylation) and coating systems (often containing UV absorbers and hindered amine light stabilizers) have been widely adopted to enhance wood's performance in these respects. With the surge of nanotechnology in materials science, researchers have increasingly focused on nanoparticles, such as silica (SiO_2), zinc oxide (ZnO), titanium dioxide (TiO_2), and silver (Ag), for wood preservation and modification (Bi et al., 2021; Papadopoulos & Taghiyari, 2019). This chapter reviews the state of knowledge regarding nanoparticle applications in wood science—particularly the role of silica nanoparticles in mitigating hygroscopicity, UV aging, and surface roughness concerns.

2.4 Comparative Studies on Nanoparticle-Treated Wood

The application of nanoparticles in wood science has gained significant attention due to their potential to enhance durability, water resistance, and UV stability. Various nanoparticles, including silicon dioxide (SiO_2), zinc oxide (ZnO), and cerium dioxide (CeO_2), have been explored for their protective properties. This section compares different nanoparticle treatments applied to wood, their methods of application, and the results of comparative studies.

2.4.1 Methods for Nanoparticle Application and Testing

The selection and preparation of wood samples are crucial in nanoparticle treatment studies. For instance, Blanchard & Blanchet (2011) used sugar maple (Acer saccharum) conditioned at 20°C and 50% relative humidity, and sanded to 150-grit before treatment to ensure uniformity. Similar approaches have been adopted in other studies, adjusting for wood species and treatment specifications.

Different methods have been employed to apply nanoparticle coatings. Blanchard & Blanchet (2011) applied a waterborne UV-curable polyurethane/polyacrylate resin using a roller coater to ensure a uniform layer with a thickness of 3×10^{-5} m. Other studies, such as Yi & Morrell (2023), used 0.50% or 1.00% wt/wt water-dispersed Fe_2O_3 and ZnO nanoparticles to treat radiata pine sapwood panels. To ensure the proper bonding of coatings, drying and curing steps are employed. Blanchard & Blanchet (2011)used a two-step drying process, initially flashing samples at 60°C for 10 minutes to allow water evaporation, followed by UV radiation exposure to cross-link the polyurethane.

Artificial aging tests simulate real-world weathering effects. In Blanchard & Blanchet's (2011) study, specimens underwent 400 hours of continuous UV radiation using a xenon-arc Weather-OMeter CI 3000+, following ASTM G155 standards. Other studies, such as Yi & Morrell (2023), subjected wood samples to outdoor exposure for eight weeks to evaluate real-world performance.

2.4.2 Analysis on Nanoparticles as UV Absorbers

ZnO and CeO_2 nanoparticles have been found to absorb UV light effectively, similarly to organic UV stabilizers. Blanchard & Blanchet (2011) reported that these nanoparticles were more efficient at medium durations of UV exposure. Furthermore, the combination of multiple absorbers created a synergistic effect that enhanced wood protection against UV-induced degradation. Yi & Morrell (2023) compared alpha Fe_2O_3 and ZnO nanoparticles in protecting wood from photodegradation, finding that alpha Fe_2O_3 provided superior color retention at higher concentrations. These findings highlight the varying effectiveness of different nanoparticles in preventing discoloration and surface deterioration.

2.4.3 Hydrophobicity and Water Resistance

Hydrophobic coatings significantly reduce water absorption, thereby improving the dimensional stability of treated wood. Liu et al. (2013) achieved a water contact angle of 159° by applying a polyvinyl (PVA)/SiO_2 composite polymer coating. Similarly, Hsieh et al. (2011) reported that a fluoro-containing silica coating led to contact angles as high as 168.3° for water and 153.6° for sunflower oil droplets, demonstrating excellent water repellency.

Studies have also confirmed that combining silica nanoparticles with polymers enhances their performance. Jiang et al. (2021) found that polyethylene glycol (PEG) and silica sol improved both dimensional stability and hydrophobicity due to their bulking and filling effects.

2.4.4 Surface Roughness and Abrasion Resistance

Surface roughness is a critical factor in evaluating the effectiveness of nanoparticle coatings. Bansal et al. (2024) noted that nano-silica and nano-alumina coatings improved scratch resistance, surface hardness, and overall durability of polyurethane coatings. Similarly, Pánek et al. (2018) found that ZnO and TiO_2 nanoparticles reduced micro-cracking and lignin degradation, which are common issues in untreated wood exposed to UV radiation

2.4.5 Fire Resistance and Safety Considerations

Apart from UV and moisture protection, some nanoparticles provide additional benefits such as fire retardancy. (Zhu et al., 2014) observed that SiO_2 nanoparticles, when combined with phosphorus-based flame retardants, significantly reduced smoke emissions and toxic gas release. Additionally, Bueno et al. (2014) reported that pine veneers treated with an aqueous dispersion of 3 wt% SiO_2 exhibited enhanced thermal properties and fire resistance.

2.5 Conclusion

Comparative studies on nanoparticle-treated wood highlight the advantages of SiO_2, ZnO, and CeO_2 nanoparticles in enhancing wood properties. While ZnO and CeO_2 nanoparticles excel in UV protection, SiO_2 nanoparticles outperform in hydrophobicity and surface stability. The combination of nanoparticles with polymer matrices further improves their performance, providing a multifunctional approach to wood protection. Future research should explore the long-term durability of these treatments and optimize nanoparticle concentrations for maximum efficiency.

3. Materials and Methods

3.1 Materials

Four wood species were selected for this study: Fir (*Abies alba*), Pine (*Pinus sylvestris*), Iroko (*Milicia excelsa*), and Meranti (*Shorea spp.*). Each wood species was cut into specimens measuring 2 × 2 × 3 cm. A total of 90 specimens per wood species were prepared, distributed among different silica nanoparticle concentrations and control groups.

Photo 1: Prepared wood specimens: cut, sanded, and labeled with unique identification codes

Silica nanoparticles (SiO_2) were used as the treatment agent, dispersed in ethanol (EtOH) solutions at five concentrations by weight/volume (w/v): 1%, 2%, 3%, 4%, and 5%. The nanoparticles were accurately weighed and dispersed in ethanol through magnetic stirring to ensure homogeneity.

Photo 2: Silica nanoparticle solution in ethanol stirred on a magnetic stirrer for homogeneous dispersion

3.2 Sample Preparation

Each specimen was air-dried under controlled conditions (20 ± 2 °C, 65% relative humidity) for two weeks before testing. The initial dimensions and weight of each specimen were recorded before treatment. The samples were devoid of knots and noticeable resin accumulations, with no apparent signs of mold, staining, or deterioration caused by wood-decaying fungi.

Photo 3: Weighing a wood sample on an electronic precision analytical balance A&D ER-180A

3.3 Experimental Setup

The experiment was divided into two parts:

1. Hygroscopicity Test Group – 60 specimens per wood species (10 per nanoparticle concentration + 10 untreated controls).
2. Weathering Test Group – 30 specimens per wood species (5 per nanoparticle concentration + 5 untreated controls).

The hygroscopicity test group was subjected to water immersion at different time intervals, while the weathering test group was exposed to artificial weathering in a Xenon chamber.

3.4 Moisture Content Measurement

The initial moisture content (MC) of each wood specimen was determined using the oven-dry method (ASTM D4442-16). Each specimen was weighed before and after drying in an oven at 103 ± 2 °C until a constant weight (m_1) was achieved.

Photo 4: Memmert Universal Oven used for moisture content determination. Left: Oven with closed door. Right: Oven with open door showing wood specimens inside.

The MC was calculated as:

$MC\ (\%) = ((m_0 - m_1)/m_1) \times 100\ (\%)$

where m_0 is the initial weight, and m_1 is the oven-dry weight.

3.5 Dimensional Measurement

Before treatment, longitudinal, radial, and tangential dimensions of each specimen were measured using a digital caliper (±0.01 mm accuracy) to assess any potential swelling or shrinkage during water absorption.

Photo 5: Specimen measured using a digital caliper.

3.6 Impregnation Procedure

Each specimen was immersed individually in the ethanol-based silica nanoparticle solutions for 1 minute, ensuring uniform absorption. Separate solutions were prepared for each concentration, and the total solution volume was calculated to fully submerge all specimens.

Photo 6: Specimen immersed in the ethanol-based silica nanoparticle solution for 1 minute

After impregnation, the specimens were air-dried at 20 ± 2 °C, 65% RH for 48 hours, allowing ethanol to evaporate and nanoparticles to deposit on the wood surface.

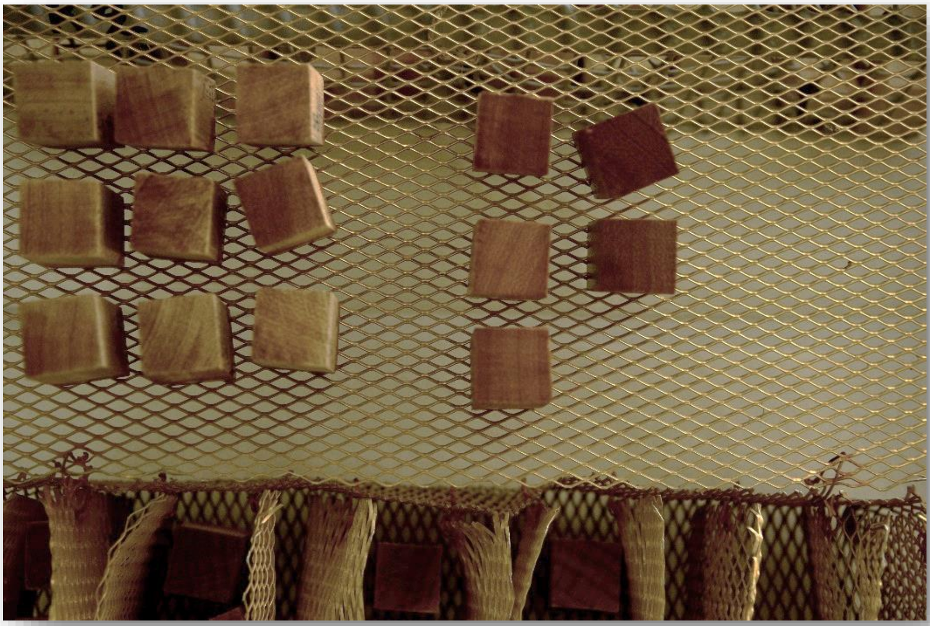

Photo 7: Wood samples after immersion in ethanol, air-dried at 20 ± 2 °C, 65% RH for 48 hours

3.7 Hygroscopicity Test

To evaluate hygroscopicity, specimens were fully submerged in water for 2, 4, 8, 12, and 24 hours. After each time interval, each specimen was removed, surface-dried with filter paper, and weighed. Dimensional changes in the longitudinal, radial, and tangential directions were measured.

Photo 8: Specimen removed from waterbath, surface-dried with filter paper before being weighed

3.8 Surface Roughness Measurement

Surface roughness was measured using the Mitutoyo SJ-210 roughness tester. Measurements were taken on both radial and tangential surfaces, and the following parameters were recorded:

- Ra – Arithmetic mean roughness
- Rq – Root mean square roughness
- Rz – Maximum height of the roughness profile

Photo 9: Surface roughness measured using the Mitutoyo SJ-210 roughness tester

3.9 Color Measurement

Color was analyzed using the PCE-CSM 1 colorimeter before and after weathering. The following color parameters were recorded:

- L* – Lightness
- a* – Red-Green coordinate
- b* – Yellow-Blue coordinate
- C* – Chroma
- h° – Hue angle

Photo 10: Color analyzed using the PCE-CSM 1 colorimeter before and after weathering

3.10 Artificial Weathering Test

The artificial aging of the wood samples was performed using a Xenon-arc weathering chamber, following the BS EN ISO 4892-2:2013 standard for laboratory exposure to light sources. This method simulates the effects of natural weathering, including exposure to UV radiation, temperature fluctuations, and moisture.

The exposure conditions were as follows:

- Light Source: Xenon-arc lamp equipped with daylight filters to replicate solar spectral irradiance.
- Irradiance Level: 60 ± 2 W/m² in the narrowband of 340 nm (or 300-400 nm broadband at 60 ± 2 W/m²).
- Temperature Control: Black-standard temperature maintained at 65 ± 3°C.
- Humidity Control: Chamber relative humidity maintained at 50 ± 10%.
- Wetting Cycle: Specimens subjected to a 102 min dry exposure, followed by an 18 min water spray cycle with deionized water.
- Total Exposure Duration: The specimens were aged for 1,000 hours in continuous light exposure conditions.

The test chamber was equipped with a black-standard thermometer to monitor specimen surface temperature. The radiant exposure was measured at 340 nm and recorded throughout the experiment to ensure compliance with the BS EN ISO 4892-2:2013 protocol. Specimen repositioning was conducted periodically to ensure uniform exposure.

Photo 11: wood samples being placed in the xenon chamber

Following exposure, the samples were evaluated for color change and surface roughness alterations according to the methods described in the subsequent sections.

Photo 12: Wood samples after the weathering process, removed from the xenon chamber

3.11 Statistical Analysis

All statistical analyses were conducted using SPSS. Initially, descriptive statistics (mean, standard deviation, variance, minimum, and maximum were calculated for each measured parameter. Normality tests were performed using the Kolmogorov-Smirnov and Shapiro-Wilk tests to determine whether data followed a normal distribution.

Since several datasets did not meet the assumptions of normality, non-parametric tests were employed. The Kruskal-Wallis test was used to analyze differences in water absorption, dimensional changes, surface roughness, and color across different wood types and nanoparticle concentrations. For pairwise comparisons, the Mann-Whitney U test was applied.

To evaluate the combined effects of wood type and nanoparticle concentration, the Scheirer-Ray-Hare test was performed as a non-parametric alternative to two-way ANOVA. This allowed for assessing interactions between factors in datasets that did not follow a normal distribution.

The Friedman's Two-Way Analysis of Variance by Ranks was conducted to assess whether significant differences exist among the measured parameters (weight differences and dimensional changes) over time.

4. Results

4.1 Descriptive Statistics

4.1.1 Initial Dimensions and Weight

The descriptive statistics for the initial longitudinal, radial, and tangential dimensions, as well as the initial weight, are presented in Table 1. The mean initial longitudinal length was 30.49 mm, radial length 20.01 mm, and tangential length 20.16 mm. The skewness values indicate that the initial longitudinal and tangential lengths were approximately symmetrical, while the initial radial length was highly skewed (-13.84). The kurtosis of the radial length was 206.27, indicating extreme outliers in the dataset.

Table 1: The descriptive statistics for the initial longitudinal, radial, and tangential dimensions, as well as the initial weight

		INITIAL LONGITUDINAL LENGTH	INITIAL RADIAL LENGTH	INITIAL TANGENTIAL LENGTH	INITIAL WEIGHT
N	Valid	240	240	240	240
	Missing	0	0	0	0
Mean		30,4894	20,0062	20,1562	6,0505
Median		30,46	20,04	20,14	5,50815
Std. Deviation		0,4693	1,21228	0,35375	1,1197328
Variance		0,22	1,47	0,125	1,254
Skewness		-0,797	-13,837	-0,088	0,652
Std. Error of Skewness		0,157	0,157	0,157	0,157
Kurtosis		2,263	206,27	-0,371	-0,981
Std. Error of Kurtosis		0,313	0,313	0,313	0,313

The initial weight of the specimens varied across wood types, with Iroko showing the highest mean weight (7.65 g) and Meranti the lowest (5.02 g) (Figure 1). The weight distribution was skewed, particularly for Fir (skewness: 3.44) with a high kurtosis value (15.66), suggesting a non-normal distribution.

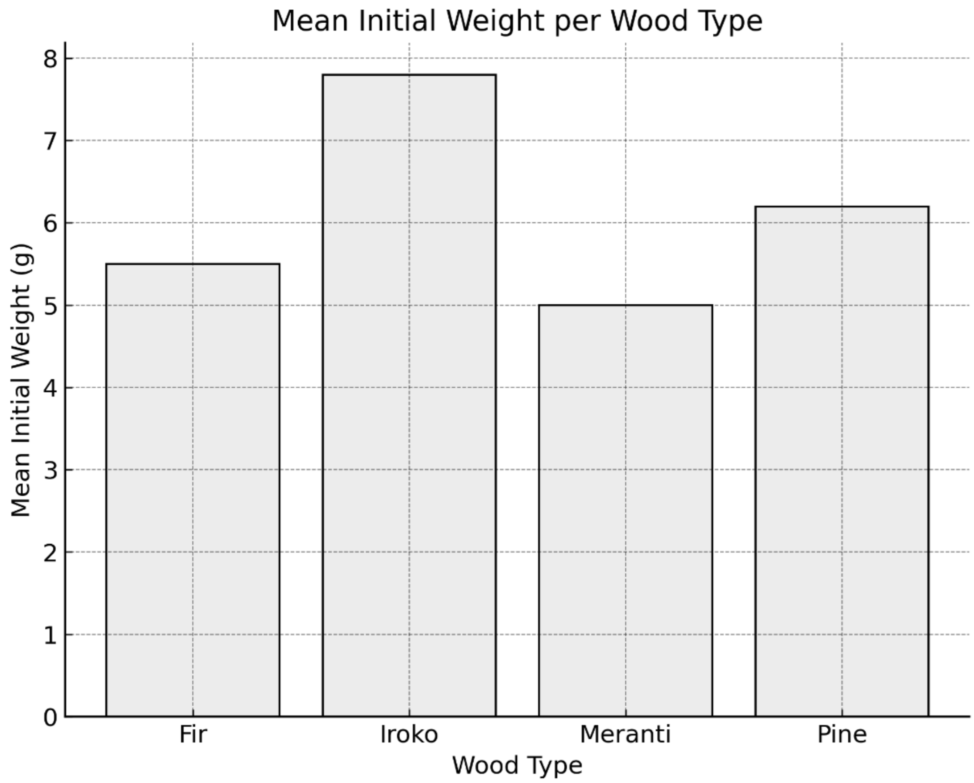

Figure 1: Mean Initial Weight of Different Wood Types (g)

4.1.2 Changes in Surface Roughness (Ra, Rq, Rz)

The initial Ra values were higher for Iroko, indicating a rougher surface, while Pine exhibited the lowest initial roughness. After artificial aging, Ra decreased in most cases, suggesting a surface smoothing effect due to the aging process. The most significant reduction was observed in Iroko, whereas Meranti exhibited the least variation.

The Rq values followed a similar trend to Ra, with an overall decline post-aging and slightly higher standard deviation values.

Rz showed the highest initial variation among the roughness parameters. A significant reduction in Rz was observed in Iroko and Pine, suggesting that the surface peaks and valleys became less pronounced after aging.

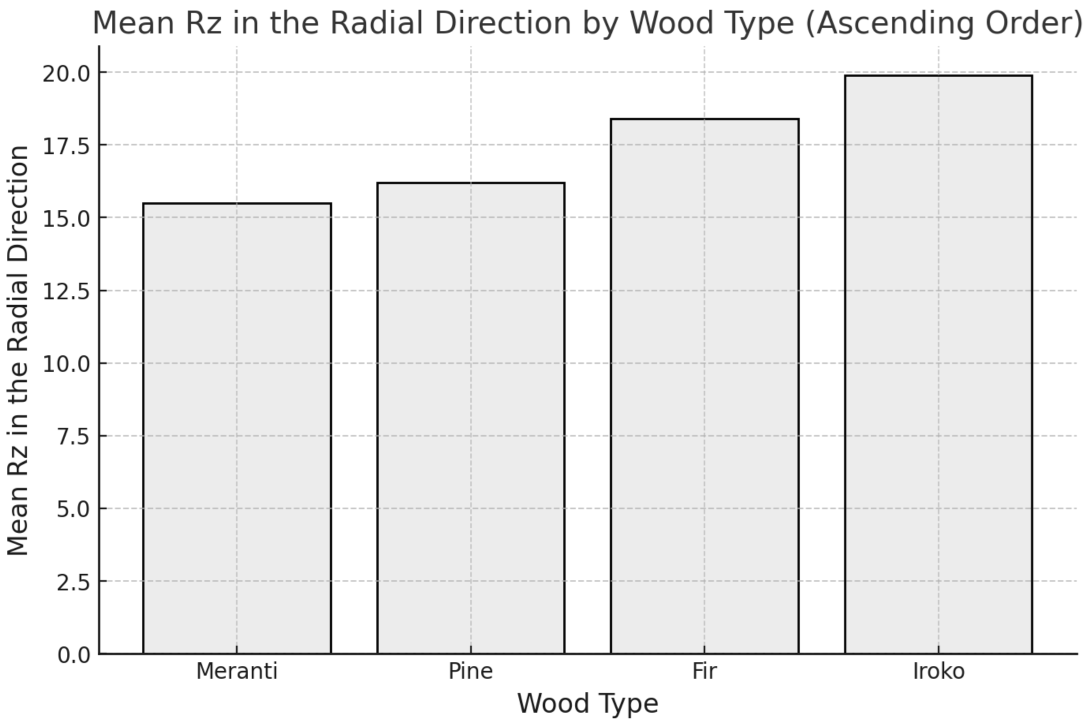

Figure 2: Mean Rz in the Radial Direction per Wood Type (Ascending Order)

4.1.3 Changes in Colorimetric Properties (L, a, b, c, h)

A general decrease in L values was observed after artificial aging across all wood species, indicating darkening of the wood surfaces (Figure 3). The most significant reduction was found in Iroko, suggesting that this species is particularly susceptible to color changes due to aging.

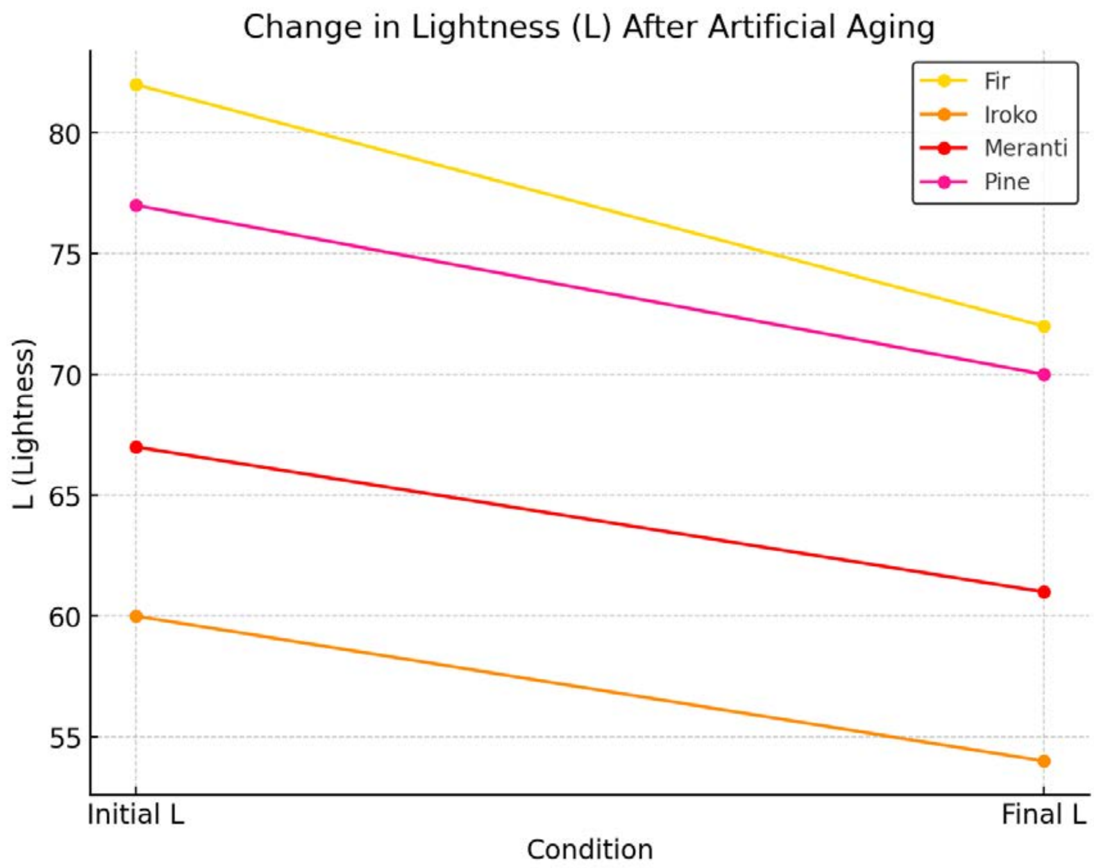

Figure 3: Change in Lightness (L) After Artificial Aging for Different Wood Types

The a values increased in all species, indicating a shift towards redder tones post-aging.

Similarly, b values also increased, meaning the wood surfaces became more yellowish after aging.

Chroma (c) increased, demonstrating a general intensification of color saturation in aged samples.

The hue angle (h) showed minimal changes, implying that the overall direction of color change remained consistent, but the colors became more vivid.

These results confirm that artificial aging not only darkens wood surfaces but also enhances red and yellow tones, intensifying the overall color appearance. These changes are likely caused by chemical transformations in wood components such as lignin, which degrade under thermal and oxidative conditions.

4.1.4 Statistical Analysis of Distribution (Skewness & Kurtosis)

Most roughness parameters showed positive skewness, especially Ra and Rz, indicating the presence of higher roughness values that increase the mean. Pine exhibited the highest skewness, suggesting that its roughness values varied more widely than the other species.

Some parameters, particularly in Pine, displayed high kurtosis values, suggesting the presence of outliers or extreme values in the data. Fir and Meranti, on the other hand, showed more uniform distributions. Since the data do not follow a perfectly normal distribution, non-parametric statistical tests may be more appropriate for further analysis.

Artificial aging reduces surface roughness, particularly in initially rougher woods such as Iroko. Color changes include darkening, increased redness and yellowness, and enhanced color saturation.

4.1.5 Tests of Normality

Kolmogorov-Smirnov and Shapiro-Wilk tests confirmed that the initial dimensions and weights, as well as most roughness and colorimetric parameters were not normally distributed ($p < 0.001$ for most variables). Only the initial tangential length had a non-significant Shapiro-Wilk result ($p = 0.156$), indicating approximate normality.

Influence of Wood Type on Weight and Dimensional Changes

Kruskal-Wallis Test

The Kruskal-Wallis test revealed significant differences in weight and dimensional changes across wood types ($p < 0.001$ for all time intervals). These results indicate that wood type has a significant impact on swelling and water absorption behavior.

Mann-Whitney U Tests

To identify which wood types differed significantly, pairwise comparisons using the Mann-Whitney U test were conducted:

Iroko vs. Meranti, Fir, and Pine: Significant differences were found in initial weight and all weight differences ($p < 0.001$).

Meranti vs. Fir and Pine: Significant differences were observed in all weight measurements ($p < 0.001$).

Fir vs. Pine: No significant differences were found in later weight measurements ($p > 0.05$).

4.2 Dimensional and Weight Changes Over Time

4.2.1 Friedman's Test for Repeated Measures

The Friedman test was conducted to determine whether there were significant differences in weight and dimensional changes across time intervals. The test statistic was 3299.303 with 17 degrees of freedom, and the result was highly significant ($p < 0.001$), rejecting the null hypothesis that distributions remain constant.

4.2.2. Kendall's Coefficient of Concordance

Kendall's W value was 0.809, indicating a strong agreement in ranking among the measured variables over time. This suggests a consistent pattern in dimensional and weight changes across all wood types (Figure 4).

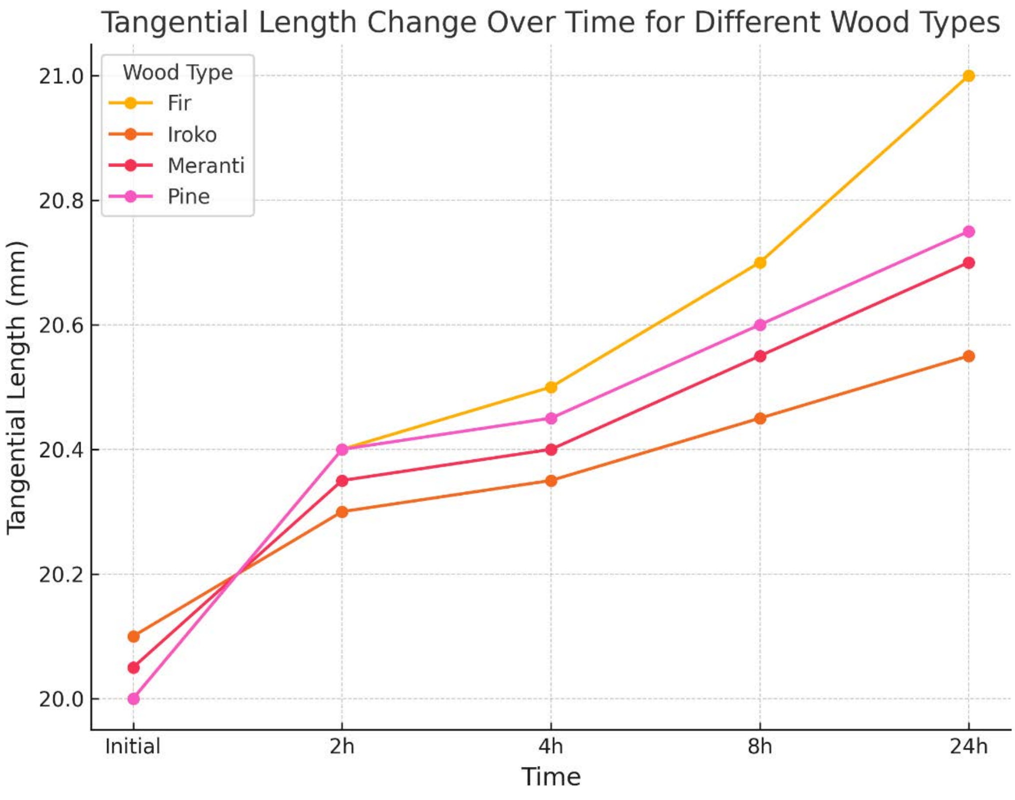

Figure 4:Tangential Length Change Over Time for Different Wood Types

4.2.3 Pairwise Comparisons

Pairwise comparisons identified specific significant differences between time intervals. For example:

- Longitudinal Length Difference at 2h vs. 8h: A significant increase was observed ($p < 0.001$), indicating swelling over time.

- Weight Difference at 2h vs. 24h: A significant increase was recorded ($p < 0.001$), confirming ongoing water absorption.
- Effect of Nanoparticle Concentration: Higher nanoparticle concentrations significantly influenced radial and tangential swelling as well as water absorption ($p < 0.001$).

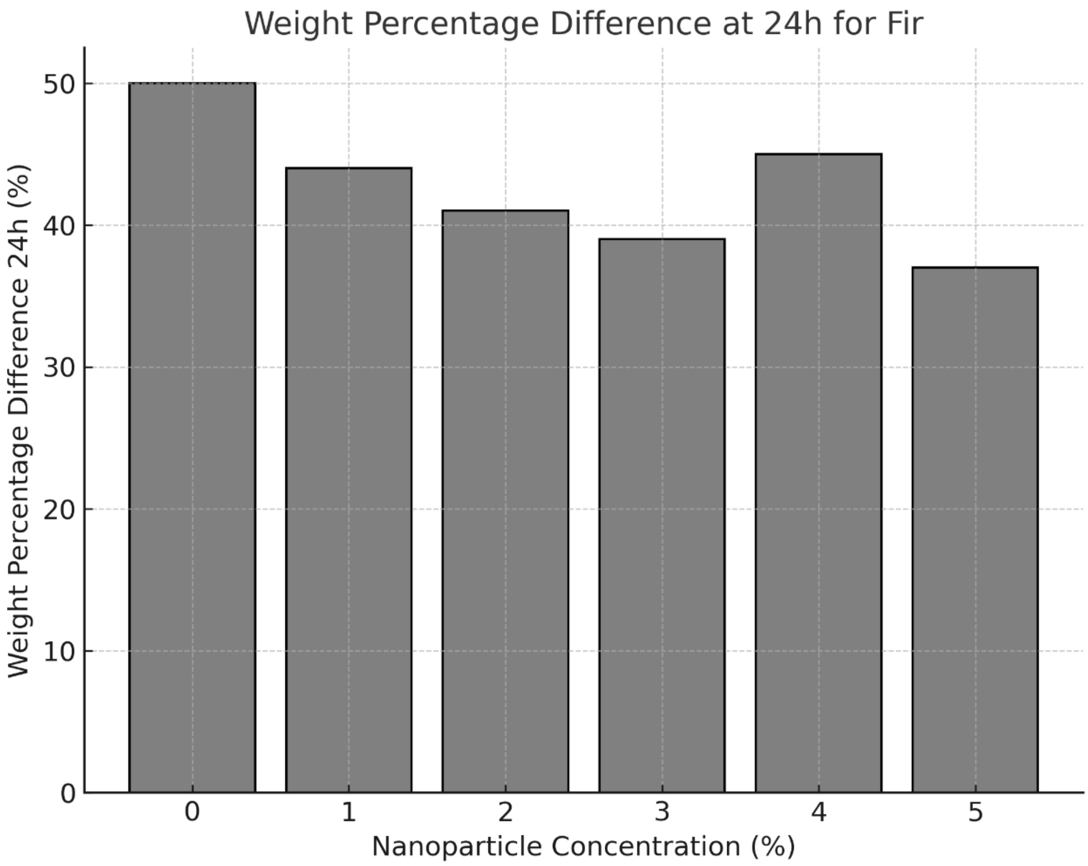

Figure 5: Weight Percentage Difference Over 24h for Fir Wood at Different Nanoparticle Concentrations

4.3 Results After the Weathering Process

The relationship between wood species and surface roughness after artificial aging was examined to determine whether certain wood types exhibit more pronounced roughness changes than others. The Kruskal-Wallis test revealed that wood species significantly influenced roughness, with Iroko showing the highest roughness values, followed by Fir, Meranti, and Pine, which exhibited lower roughness levels. These differences suggest that the natural characteristics of each wood species—such as density, grain structure, and extractive content—play a significant role in how the surface deteriorates over time.

Regarding nanoparticle concentration, statistical analysis showed that the addition of silica nanoparticles did not significantly influence surface roughness across the different wood species. However, there was a notable effect on hue stability (h color difference), particularly in Iroko and Pine, where higher concentrations (3-5%) led to significant color shifts.

4.3.1 Effect of Nanoparticle Concentration on Surface Roughness

To evaluate whether different silica nanoparticle concentrations (0%, 1%, 2%, 3%, 4%, 5%) affected the surface roughness of the wood samples after weathering, Kruskal-Wallis tests were performed separately for each wood type.

Iroko

For Iroko, the Kruskal-Wallis test for Ra, Rq, and Rz in the tangential direction did not yield statistically significant results ($p > 0.05$ in all cases), indicating that nanoparticles did not significantly influence roughness after weathering. While there were variations in mean ranks, with 5% concentration showing slightly higher roughness values, these differences were not strong enough to be considered significant. This suggests that the natural degradation of Iroko dominates over any protective effects of nanoparticles on roughness.

Meranti

In Meranti, the roughness parameter RzRadial showed a statistically significant effect of nanoparticle concentration suggesting that nanoparticles may have influenced the deeper irregularities on the radial surface. However, other roughness parameters (Ra, Rq in radial and tangential directions) did not show significant changes, indicating that any effects were localized rather than uniform across the surface.

Pairwise Mann-Whitney U tests further confirmed this effect, showing that higher concentrations (2%, 3%, and 4%) significantly altered RzRadial compared to the untreated (0%) samples, whereas lower concentrations (1% and 5%) did not have a significant effect. This suggests that the interaction between nanoparticles and the wood surface may be nonlinear, with moderate concentrations having a greater impact.

Fir

For Fir wood, FinalRzRadial was significantly affected by nanoparticle concentration ($p=0.032$), while FinalRaRadial and FinalRqRadial showed marginal significance ($0.05 < p < 0.1$). These results suggest that nanoparticles influenced roughness in Fir more than in Iroko, possibly due to differences in surface porosity and fiber structure.

Pairwise comparisons confirmed significant differences between the 0% and 2%, 3%, and 5% concentrations, indicating that the effect of nanoparticles was more pronounced at these levels. This suggests that nanoparticles might help stabilize or modify roughness in Fir under specific conditions, though further investigation is required.

Pine

For Pine, FinalRzTangential showed a statistically significant difference (p=0.043), meaning that tangential roughness was influenced by nanoparticle treatment. However, other roughness parameters did not show significant changes. This suggests that, for Pine, the impact of nanoparticles on roughness is less consistent than for Fir or Meranti.

The Mann-Whitney U test revealed that only the 3% concentration resulted in a significant roughness difference compared to 0%, whereas other concentrations (1%, 2%, 4%, and 5%) did not have a statistically significant effect. This again suggests a threshold effect, where nanoparticles only influence roughness at certain concentrations.

4.3.2 Effect of Nanoparticle Concentration on Color Stability

To assess whether nanoparticle concentration influenced color stability after weathering, Kruskal-Wallis tests were conducted for L (lightness), a (red-green shift), b (yellow-blue shift), c (chroma), and h (hue shift).

Iroko

For Iroko, hue (h) showed a significant effect of nanoparticle concentration (p=0.040), while other color parameters (L, a, b, c) did not show significant changes. This indicates that hue stability is affected by nanoparticles, whereas overall lightness and chromatic properties remain unchanged.

Pairwise Mann-Whitney U tests confirmed that hue differences became significant at 3% and 5% concentrations, suggesting that higher nanoparticle concentrations might interact with the wood’s extractives, leading to visible hue changes.

Meranti

For Meranti, none of the color parameters showed statistically significant differences across nanoparticle concentrations (p>0.1 in all cases), indicating that Meranti’s color stability is not affected by nanoparticle treatment. This suggests that the extractive composition of Meranti may not react with silica nanoparticles in a way that alters color over time.

Fir

In Fir, hue (h) and aDifference% (red-green axis shift) showed significant differences across nanoparticle concentrations (p=0.030 and p=0.005, respectively). This suggests that nanoparticle concentration affects color stability in Fir more than in Meranti or Pine.

Pairwise comparisons showed that hue (h) was significantly different between 0% and 2%, while aDifference% was significantly different between 0% and 3%. This suggests that nanoparticles may influence Fir's extractives differently than in other wood species, leading to color shifts at lower concentrations.

Pine

For Pine, hue (h) was significantly affected (p=0.004), while other color parameters remained unchanged. Similar to Iroko, higher concentrations (3-5%) led to noticeable hue shifts, whereas lower concentrations did not cause significant changes (Figure 6).

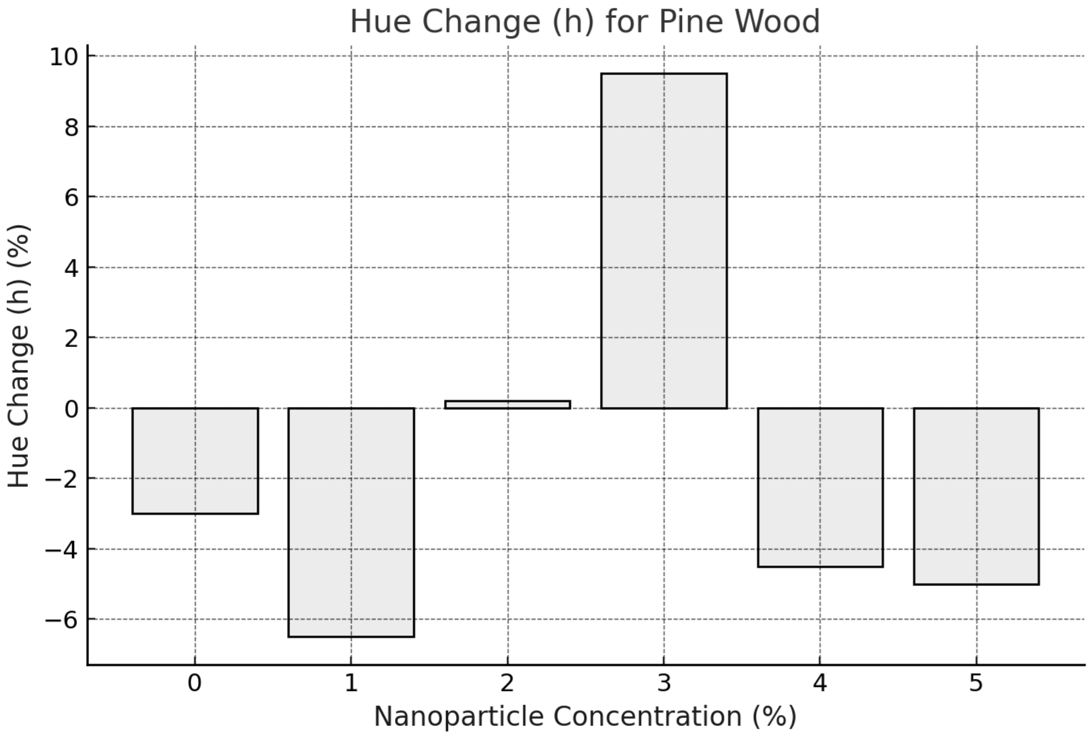

Figure 6: Hue Variation (h) for Pine Wood at Different Nanoparticle Concentrations

4.4 Summary of Findings

Hygroscopicity:

Wood type significantly affects dimensional stability and water absorption, with Iroko being the most stable and Meranti the least.

Weight and dimensional changes increase significantly over time, confirming progressive swelling and water uptake.

Nanoparticle concentration influences swelling behavior, particularly in the radial and tangential directions.

Surface Roughness:

Wood type significantly influences roughness after artificial aging, with Iroko showing the highest roughness and Pine the lowest.

Nanoparticle concentration generally does not affect roughness, except for some cases in Meranti (RzRadial), Fir (RzRadial), and Pine (RzTangential).

Threshold effects were observed, where only certain concentrations (e.g., 2-4%) showed significant roughness changes.

Color Stability:

Hue (h) is significantly influenced by nanoparticle concentration in Iroko, Fir, and Pine but not in Meranti.

Higher concentrations (3-5%) result in noticeable color shifts, while lower concentrations do not have a significant effect.

Other color parameters (L, a, b, c) generally remain unchanged, suggesting that nanoparticles primarily influence hue rather than overall brightness or chromatic intensity.

These results indicate that while nanoparticles do not significantly modify surface roughness, they do have an effect on color stability, particularly in Iroko, Fir, and Pine. This suggests that nanoparticles may alter the chemical properties of certain wood extractives, leading to perceptible changes in hue. However, further investigation is required to determine the mechanisms behind these changes and optimize nanoparticle treatments for wood preservation.

5. Discussion

5.1. Hygroscopicity: Comparison with Literature and Mechanisms

The results demonstrate that wood type significantly influences dimensional stability and water absorption, with Iroko exhibiting the highest stability and Meranti the least. This is consistent with previous studies (Blanchard & Blanchet, 2011; Yi & Morrell, 2023), which have reported that high-density woods generally display lower hygroscopicity due to their compact cell structure and extractive content that may reduce moisture uptake. The significant increases in weight and dimensional changes over time confirm the progressive swelling and water absorption of wood, which aligns with findings from Rao et al. (2019) regarding moisture-induced expansion in natural materials.

The observed effect of silica nanoparticles on radial and tangential swelling suggests that nanoparticle interaction with the wood matrix may influence water penetration and retention. Prior studies have shown that nanoparticles can reduce hygroscopicity by forming hydrophobic coatings or by filling microvoids in the wood structure, thereby limiting water access (Bansal et al., 2024). However, the effectiveness of this modification appears to vary by wood species, potentially due to differences in porosity, extractives, and nanoparticle dispersion. Future research should investigate whether alternative nanoparticle formulations or application methods could further enhance moisture resistance.

5.2. SiO_2 Nanoparticles and Surface Roughness

The findings indicate that silica nanoparticles generally do not significantly influence surface roughness, except in certain cases for Meranti (RzRadial), Fir (RzRadial), and Pine (RzTangential). This suggests that the impact of nanoparticles on roughness is dependent on the wood species and may involve complex interactions between nanoparticles and wood fibers.

One possible explanation is that silica nanoparticles interact with the surface by forming a thin, protective layer that smooths the microstructure of the wood. However, as observed in Iroko, where roughness remained largely unaffected, this effect may be counteracted by natural degradation processes, such as lignin oxidation and cellulose breakdown (Pandey & Pitman, 2003). The threshold effect observed, where only certain concentrations (2–4%) had significant impacts, is consistent with previous studies (Svora et al., 2022), which suggest that nanoparticle distribution plays a critical role in their effectiveness. Too low a concentration may be insufficient to alter the surface, while too high a concentration may lead to nanoparticle aggregation, reducing their ability to modify the roughness.

5.3. Color Stability and UV Resistance

The results confirm that artificial aging leads to significant darkening, increased redness, and yellowing of the wood surfaces, which is consistent with previous research attributing these changes to lignin degradation and oxidation of extractives under UV exposure (Bansal et al., 2022; Rao et al., 2019). The fact that hue stability (h) was significantly influenced by nanoparticle concentration in Iroko, Fir, and Pine suggests that silica nanoparticles interact with wood components to alter UV absorption and photochemical reactions.

Silica nanoparticles have been reported to act as UV absorbers when combined with other protective agents, such as TiO_2 or ZnO (Nguyen et al., 2020). Their potential role in stabilizing hue changes in certain wood species may be attributed to their ability to scatter and partially absorb UV radiation, thereby slowing the degradation of chromophoric groups in lignin. However, the lack of significant impact on overall lightness (L) and chroma (c) suggests that silica nanoparticles alone may not be as effective as other nanoparticle types in preventing UV-induced discoloration.

5.4. Wood Species Comparison: Impregnation and Structure

The variation in results across wood species highlights the importance of structural differences in nanoparticle effectiveness. Iroko, for example, displayed high stability in weight and dimensional changes but also showed minimal response to nanoparticles in terms of roughness and color stability. This suggests that its dense and extractive-rich structure may hinder nanoparticle penetration and interaction with lignin and cellulose. In contrast, Fir and Pine exhibited more pronounced changes in hue and roughness, indicating that their more porous structures allowed better nanoparticle distribution.

These findings align with prior research indicating that nanoparticle treatments are most effective in wood species with moderate porosity, where sufficient penetration occurs without excessive leaching (Clausen et al., 2010). The observed nonlinear effects of nanoparticle concentration further suggest that optimized formulations tailored to specific wood species are necessary to maximize protective benefits.

5.5. Economic and Environmental Impact

The application of silica nanoparticles in wood protection raises important economic and environmental considerations. While silica nanoparticles are generally regarded as safe and chemically inert, concerns remain regarding their potential release into the environment during wood processing or weathering. Studies on nanoparticle-treated coatings suggest that controlled application methods, such as sol-gel deposition or polymer embedding, may mitigate risks by ensuring stronger adhesion to the wood surface (Bansal et al., 2024).

From an economic perspective, the cost-effectiveness of silica nanoparticle treatments depends on their long-term performance relative to conventional UV stabilizers and moisture barriers. If silica nanoparticles provide moderate protection but require frequent reapplication, their use may be less viable compared to more robust alternatives, such as TiO_2 or ZnO-based coatings (Bak & Nemeth, 2012). Future studies should assess the durability of silica nanoparticle treatments under prolonged outdoor exposure to determine their practical feasibility in commercial applications.

6. Conclusions

6.1 Summary of Key Findings

This study examined the effects of SiO_2 nanoparticles on wood properties, specifically hygroscopicity, surface roughness, UV resistance, and color stability. The results showed that while SiO_2 nanoparticles influenced swelling behavior, their impact varied across wood species and concentration levels. Their effect on surface roughness was minimal, except for specific cases in Meranti, Fir, and Pine at moderate concentrations (2-4%).

The nanoparticles had a significant effect on color stability, particularly on hue (h) in Iroko, Fir, and Pine, suggesting interactions with wood extractives. However, they did not uniformly improve UV resistance, as changes in lightness (L) and chromaticity (a, b, c) were limited.

A comparative analysis of wood species revealed that Iroko exhibited the highest initial roughness and color changes, while Meranti was the most susceptible to swelling. Fir and Pine showed better nanoparticle interaction, suggesting higher permeability.

Economic and environmental considerations suggest that SiO_2 nanoparticles could be viable for wood coatings, particularly for color stabilization rather than surface protection. However, further studies on their long-term environmental impact and application optimization are needed.

6.2 Answers to the Initial Research Questions and Objectives

- How do SiO_2 nanoparticles influence weight and dimensional stability in wood over time?

SiO_2 nanoparticles had a limited effect on weight changes but influenced radial and tangential swelling, particularly at concentrations of 3-5%. Their potential mechanism involves modifying moisture interactions rather than fully blocking absorption.

- To what extent do they affect surface roughness before and after UV exposure?

No significant impact on roughness was observed overall, except in Meranti (RzRadial), Fir (RzRadial), and Pine (RzTangential). The effect was concentration-dependent, with moderate concentrations (2-4%) showing slight roughness changes.

- Can SiO_2 nanoparticles improve color retention and reduce UV-induced discoloration?

SiO_2 nanoparticles significantly affected hue (h) stability in Iroko, Fir, and Pine, particularly at higher concentrations (3-5%). However, they did not significantly alter brightness (L) or overall chromaticity (a, b, c), indicating a selective interaction rather than broad UV protection.

- Is there a significant difference in treatment effectiveness among different wood species?

Yes, treatment effectiveness varied by species. Iroko had the highest roughness and color shifts, while Meranti showed the most pronounced swelling. Fir and Pine demonstrated better nanoparticle penetration, influencing both roughness and color stability.

- What is the optimal nanoparticle concentration for achieving the best protective effect?

3-5% SiO_2 nanoparticles had the most noticeable effects on swelling and color stability, while lower concentrations (1-2%) showed minimal influence. Excessive concentrations (≥5%) did not necessarily enhance protection and may lead to non-uniform distribution. Further studies are required to optimize concentration levels based on wood type and intended application.

6.4 Recommendations for Future Research

Overall, the study highlights the complex interactions between silica nanoparticles, wood species, and environmental factors. While nanoparticles did not significantly alter surface roughness in most cases, they did affect hue stability, particularly in Iroko, Fir, and Pine. The hygroscopicity results suggest that nanoparticle treatments may influence swelling and water absorption, though their effects vary by wood type and concentration.

Future research should explore:

- Optimization of nanoparticle formulations to improve UV resistance and moisture stability.
- Long-term weathering studies to evaluate durability under real-world conditions.
- Environmental safety assessments to examine potential nanoparticle leaching and ecological impact.
- Comparative analysis with alternative nanoparticles, such as ZnO and TiO_2, to determine the most effective wood protection strategies.
- By addressing these areas, further advancements can be made in developing sustainable and efficient nanoparticle treatments for wood preservation.

6.5 Final Remarks

While SiO_2 nanoparticles influenced specific wood properties, their effects were not uniformly beneficial across all parameters. Their primary advantage appears to be color stability rather than roughness modification or complete moisture protection. Future research should focus on application techniques, long-term performance, and environmental safety to determine their practical viability for wood preservation.

7. References

Aloui, F., Ahajji, A., Irmouli, Y., George, B., Charrier, B., & Merlin, A. (2007). Inorganic UV absorbers for the photostabilisation of wood-clearcoating systems: Comparison with organic UV absorbers. In *Applied Surface Science* (Vol. 253, Issue 8). https://doi.org/10.1016/j.apsusc.2006.08.029

Bak, M., & Nemeth, R. (2012). Modification of wood by oil heat treatment. *International Scientific Conference on Sustainable Development & Ecological Footprint*.

Bak, M., & Németh, R. (2018). Effect of Different Nanoparticle Treatments on the Decay Resistance of Wood. *BioResources*, *13*(4). https://doi.org/10.15376/biores.13.4.7886-7899

Bak, M., Takács, D., Rákosa, R., Németh, Z. I., & Németh, R. (2023). One-Step Process for the Fabrication of Hydrophobic and Dimensional Stable Wood Using Functionalized Silica Nanoparticles. *Forests*, *14*(3). https://doi.org/10.3390/f14030651

Bansal, R., Barshilia, H. C., & Pandey, K. K. (2024). Nanotechnology in wood science: Innovations and applications. In *International Journal of Biological Macromolecules* (Vol. 262). https://doi.org/10.1016/j.ijbiomac.2024.130025

Bansal, R., Nair, S., & Pandey, K. K. (2022). UV resistant wood coating based on zinc oxide and cerium oxide dispersed linseed oil nano-emulsion. *Materials Today Communications*, *30*. https://doi.org/10.1016/j.mtcomm.2022.103177

Bauer, F., & Mehnert, R. (2005). UV curable acrylate nanocomposites: Properties and applications. *Journal of Polymer Research*, *12*(6). https://doi.org/10.1007/s10965-005-4339-z

Baysal, E., Ozaki, S. K., & Yalinkilic, M. K. (2004). Dimensional stabilization of wood treated with furfuryl alcohol catalysed by borates. *Wood Science and Technology*, *38*(6). https://doi.org/10.1007/s00226-004-0248-2

Bi, W., Li, H., Hui, D., Gaff, M., Lorenzo, R., Corbi, I., Corbi, O., & Ashraf, M. (2021). Effects of chemical modification and nanotechnology on wood properties. In *Nanotechnology Reviews* (Vol. 10, Issue 1). https://doi.org/10.1515/ntrev-2021-0065

Blanchard, V., & Blanchet, P. (2011). Color stability for wood products during use: Effects of inorganic nanoparticles. *BioResources*, *6*(2). https://doi.org/10.15376/biores.6.2.1219-1229

Bueno, A. B. F., Bañón, M. V. N., De Morentín, L. M., & García, J. M. (2014). Treatment of natural wood veneers with nano-oxides to improve their fire behaviour. *IOP Conference Series: Materials Science and Engineering*, *64*(1). https://doi.org/10.1088/1757-899X/64/1/012021

Clausen, C. A., Green, F., & Kartal, S. N. (2010). Weatherability and leach resistance of wood impregnated with nano-zinc oxide. *Nanoscale Research Letters*, *5*(9). https://doi.org/10.1007/s11671-010-9662-6

Derbyshire, H., & Miller, E. R. (1981). The photodegradation of wood during solar irradiation. Part I: effects on the structural integrity of thin wood strips. *Holz Als Roh- Und Werkstoff*, *39*(8).

Dufresne, A. (2013). Nanocellulose: A new ageless bionanomaterial. In *Materials Today* (Vol. 16, Issue 6). https://doi.org/10.1016/j.mattod.2013.06.004

FEIST, W. C., & HON, D. N.-S. (1984). *Chemistry of Weathering and Protection*. https://doi.org/10.1021/ba-1984-0207.ch011

Forsthuber, B., Schaller, C., & Grüll, G. (2013). Evaluation of the photo stabilising efficiency of clear coatings comprising organic UV absorbers and mineral UV screeners on wood surfaces. *Wood Science and Technology*, *47*(2). https://doi.org/10.1007/s00226-012-0487-6

Hill, C. A. S., & Papadopoulos, A. N. (2001). A review of methods used to determine the size of the cell wall microvoids of wood. *Journal of the Institute of Wood Science*, *15*(6).

Hsieh, C. Te, Chang, B. S., & Lin, J. Y. (2011). Improvement of water and oil repellency on wood substrates by using fluorinated silica nanocoating. *Applied Surface Science*, *257*(18). https://doi.org/10.1016/j.apsusc.2011.04.071

Jia, S., Liu, M., Wu, Y., Luo, S., Qing, Y., & Chen, H. (2016). Facile and scalable preparation of highly wear-resistance superhydrophobic surface on wood substrates using silica nanoparticles modified by VTES. *Applied Surface Science*, *386*. https://doi.org/10.1016/j.apsusc.2016.06.004

Jiang, J., Zhou, Y., Mei, C., & Cao, J. (2021). Polyethylene glycol and silica sol penetration improves hydrophobicity and dimensional stability of wood after a short-time treatment. *European Journal of Wood and Wood Products*, *79*(6). https://doi.org/10.1007/s00107-021-01710-5

Jirouš-Rajković, V., & Miklečić, J. (2021). Enhancing weathering resistance of wood—a review. In *Polymers* (Vol. 13, Issue 12). https://doi.org/10.3390/polym13121980

Kong, L., Tu, K., Guan, H., & Wang, X. (2017). Growth of high-density ZnO nanorods on wood with enhanced photostability, flame retardancy and water repellency. *Applied Surface Science*, *407*. https://doi.org/10.1016/j.apsusc.2017.02.252

Liu, F., Wang, S., Zhang, M., Ma, M., Wang, C., & Li, J. (2013). Improvement of mechanical robustness of the superhydrophobic wood surface by coating PVA/SiO 2 composite polymer. *Applied Surface Science*, *280*. https://doi.org/10.1016/j.apsusc.2013.05.043

Nguyen, T. V., Nguyen, T. A., & Nguyen, T. H. (2020). The synergistic effects of SiO2 nanoparticles and organic photostabilizers for enhanced weathering resistance of acrylic polyurethane coating. *Journal of Composites Science*, *4*(1). https://doi.org/10.3390/jcs4010023

Nikolic, M., Lawther, J. M., & Sanadi, A. R. (2015). Use of nanofillers in wood coatings: a scientific review. *Journal of Coatings Technology and Research*, *12*(3). https://doi.org/10.1007/s11998-015-9659-2

Pandey, K. K., & Pitman, A. J. (2003). FTIR studies of the changes in wood chemistry following decay by brown-rot and white-rot fungi. *International Biodeterioration and Biodegradation*, *52*(3). https://doi.org/10.1016/S0964-8305(03)00052-0

Papadopoulos, A. N., & Taghiyari, H. R. (2019). Innovative wood surface treatments based on nanotechnology. In *Coatings* (Vol. 9, Issue 12). https://doi.org/10.3390/coatings9120866

Rao, F., Zhang, Y., Bao, M., Zhang, Z., Bao, Y., Li, N., Chen, Y., & Yu, W. (2019). Photostabilizing efficiency of acrylic-based bamboo exterior coatings combining benzotriazole and zinc oxide nanoparticles. *Coatings*, *9*(9). https://doi.org/10.3390/coatings9090533

Rosu, D., Teaca, C. A., Bodirlau, R., & Rosu, L. (2010). FTIR and color change of the modified wood as a result of artificial light irradiation. *Journal of Photochemistry and Photobiology B: Biology*, *99*(3). https://doi.org/10.1016/j.jphotobiol.2010.03.010

Rowell, R. M. (2006). Chemical modification of wood: A short review. *Wood Material Science and Engineering*, *1*(1). https://doi.org/10.1080/17480270600670923

Soytürk, E. E., Kartal, S. N., Onses, M. S., & Celik, N. (2023). Preliminary evaluation of polydimethylsiloxane and hydrophobic silica nanoparticles to improve water repellency and boron leachability in wood. *European Journal of Wood and Wood Products*, *81*(1). https://doi.org/10.1007/s00107-022-01883-7

Svora, P., Svorová Pawełkowicz, S., Ecorchard, P., Plocek, J., Schieberová, A., Prošek, Z., Ptáček, P., Pošta, J., Targowski, P., Kuklík, P., & Jakubec, I. (2022). Study of Interactions between Titanium Dioxide Coating and Wood Cell Wall Ultrastructure. *Nanomaterials*, *12*(15). https://doi.org/10.3390/nano12152678

Venmalar, D. (2017). Screening of oils of Pongamia pinnata Linn., Jatropha curcas Linn. and Simarouba glauca D.C. for developing eco-friendly wood preservatives. In *Wood is Good: Current Trends and Future Prospects in Wood Utilization*. https://doi.org/10.1007/978-981-10-3115-1_24

Wang, L., Bai, Y., Lu, Y., & Wang, H. (2010). INDUSTRIE 4.0 READINESS (IMPULS). *Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering*, *26*(2).

Yi, T., & Morrell, J. J. (2023). Role of α/γ Fe2O3 and ZnO nano-particles in reducing photodegradation of wood components. *Wood Science and Technology*, *57*(2). https://doi.org/10.1007/s00226-023-01456-8

Zhu, X., Wu, Y., Tian, C., Qing, Y., & Yao, C. (2014). Synergistic effect of nanosilica aerogel with phosphorus flame retardants on improving flame retardancy and leaching resistance of wood. *Journal of Nanomaterials*, *2014*. https://doi.org/10.1155/2014/867106

Živković, V., Arnold, M., Radmanović, K., Richter, K., & Turkulin, H. (2014). Spectral sensitivity in the photodegradation of fir wood (Abies alba Mill.) surfaces: Colour changes in natural weathering. *Wood Science and Technology*, *48*(2). https://doi.org/10.1007/s00226-013-0601-4

Appendices

Table 2: Hygroscopicity samples weight and dimensions measurements

SampleID	InitialWeight	InitialLongitudinalLength	InitialRadialLength	InitialTangendialLength
I0-1	7,6475	30,78	19,94	20,11
I0-2	7,358	30,23	19,87	20,15
I0-3	8,1545	30,64	20,47	20,53
I0-4	8,3138	30,49	20,82	20,48
I0-5	8,3119	30,61	20,51	20,74
I0-6	7,447	30,43	19,83	20,17
I0-7	8,2433	30,21	20,44	20,81
I0-8	7,4465	30,37	19,88	19,85
I0-9	7,6861	30,64	19,85	20,08
I0-10	7,8759	30,5	19,94	19,87
I1-1	7,761	30,86	19,96	20,14
I1-2	7,4232	30,22	19,85	20
I1-3	8,4874	30,73	20,58	20,58
I1-4	7,0941	30,46	19,82	19,77
I1-5	7,2303	30,27	19,84	19,75
I1-6	7,5162	29,91	19,81	20,12
I1-7	7,5934	30,8	19,79	19,97
I1-8	7,2507	30,09	20,18	19,79
I1-9	7,6147	30,25	19,78	20,04
I1-10	7,2437	29,96	20,17	19,69
I2-1	8,2186	29,75	20,5	20,91
I2-2	7,568	31,06	20	20,13
I2-3	8,6711	29,94	20,64	20,57
I2-4	7,4341	30,19	20	20,08
I2-5	7,6909	30,67	19,98	19,92
I2-6	8,5492	30,61	20,58	20,59
I2-7	8,6272	30,67	20,66	20,67
I2-8	7,6954	30,55	19,83	19,9
I2-9	7,5538	30,16	19,89	20,09
I2-10	7,5538	30,17	19,9	20,1
I3-1	7,4141	29,63	19,87	19,95
I3-2	7,6413	30,5	19,97	20,2
I3-3	7,8788	30,22	20,1	20,07
I3-4	7,4934	30,27	20,01	20,07
I3-5	7,5773	29,92	19,8	19,85
I3-6	7,0469	30,25	20,01	20,14
I3-7	7,2284	30,59	19,86	20,1
I3-8	7,1974	30,64	20,08	19,72
I3-9	7,6329	30,55	19,92	20,18
I3-10	7,1973	30,63	20,01	19,69
I4-1	7,5232	29,98	20,15	20,22

I4-2	7,2928	29,95	19,89	19,81
I4-3	7,7702	30,69	19,9	19,9
I4-4	7,3713	30,83	20,04	20,09
I4-5	7,4942	30,23	19,76	19,7
I4-6	7,7298	30,17	19,96	19,92
I4-7	7,5806	30,19	20,03	20,09
I4-8	7,4611	30,29	19,67	19,84
I4-9	7,4177	29,42	19,89	20,07
I4-10	7,4942	30,23	19,76	19,7
I5-1	7,5956	30,05	19,75	19,93
I5-2	7,9947	30,71	19,95	20,11
I5-3	7,4892	30,26	20,01	20,1
I5-4	7,4952	30,5	20,12	19,75
I5-5	7,2944	30,3	19,72	19,79
I5-6	7,841	30,2	19,84	20,19
I5-7	7,7029	30,56	20,04	19,82
I5-8	8,3091	30,32	20,07	20,32
I5-9	7,2222	30,62	19,86	19,76
I5-10	7,2943	30,29	19,69	19,81
M0-1	5,0016	29,94	19,92	20,27
M0-2	4,8391	30,38	20,03	20,07
M0-3	4,9171	30,52	20,45	20,69
M0-4	4,9316	30,22	19,93	19,7
M0-5	4,9903	30,15	20,28	20,22
M0-6	5,0529	30,34	20,2	20,18
M0-7	5,1972	30,38	20,09	19,98
M0-8	4,9547	30,35	20,27	19,9
M0-9	4,9559	30,29	19,93	20,1
M0-10	5,0161	30,35	20,24	19,94
M1-1	5,0177	30,33	20,09	19,91
M1-2	4,7796	30,31	19,3	19,87
M1-3	5,1326	30,01	19,95	19,95
M1-4	4,763	30,34	19,89	19,81
M1-5	4,9919	30,47	20,04	19,95
M1-6	4,9485	30,46	19,95	19,96
M1-7	4,964	30,4	19,98	19,74
M1-8	5,0101	30,46	19,86	20,22
M1-9	4,9781	30,37	19,85	20,25
M1-10	4,763	30,34	19,89	19,81
M2-1	4,9219	30,1	19,75	19,37
M2-2	4,8672	30,4	19,42	19,72
M2-3	5,48	30,61	20,61	20,53
M2-4	4,8536	30,23	19,76	20,16
M2-5	4,5093	30,19	19,82	19,92
M2-6	4,7552	30,52	19,81	19,81
M2-7	4,7909	30,06	19,83	19,92

M2-8	5,0311	30,41	19,84	19,72
M2-9	5,0418	30,1	19,93	20,21
M2-10	5,48	30,61	20,61	20,53
M3-1	4,86	30,28	19,56	20,01
M3-2	5,1875	30,34	20,04	19,93
M3-3	4,8414	30,29	19,84	20,2
M3-4	5,5004	30,54	20,47	20,54
M3-5	5,4274	30,45	20,45	20,47
M3-6	5,3438	30,51	20,5	20,45
M3-7	4,9613	30,07	19,85	20,24
M3-8	5,4782	30,36	20,65	20,48
M3-9	4,8161	29,95	19,78	19,9
M3-10	5,3438	30,51	20,5	20,45
M4-1	4,8984	30,26	20,06	19,79
M4-2	4,8905	30,03	19,95	19,68
M4-3	4,8923	30,41	19,96	20,02
M4-4	4,9629	30,46	20,48	20,58
M4-5	5,0705	30,36	19,85	20,46
M4-6	4,6874	29,66	19,82	19,45
M4-7	5,3926	31,09	20,79	20,45
M4-8	4,9815	30,32	19,82	20,15
M4-9	5,4335	30,43	20,59	20,52
M4-10	5,3926	31,09	20,79	20,45
M5-1	4,9714	30,28	19,81	20,27
M5-2	4,8642	30,47	1,99	19,95
M5-3	5,0906	31,25	19,86	19,72
M5-4	5,0439	30,33	19,81	20,07
M5-5	5,0855	30,36	20,07	20,26
M5-6	4,8304	30,39	19,71	19,79
M5-7	5,0477	30,29	19,89	20,22
M5-8	4,9566	30,46	19,82	19,88
M5-9	4,8589	30,33	19,86	20,13
M5-10	5,0477	30,29	19,89	20,22
F0-1	5,228	30,25	20,09	20,79
F0-2	7,4128	30,41	20,67	20,84
F0-3	5,5665	30,47	20,61	20,75
F0-4	5,2818	30,34	20,62	20,76
F0-5	5,074	31,09	20,23	20,42
F0-6	5,5109	31,06	20,33	20,36
F0-7	5,0846	30,73	20,26	20,39
F0-8	5,4032	31,02	20,27	20,67
F0-9	5,4122	31,029	20,279	20,679
F0-10	5,4022	31,019	20,269	20,669
F1-1	5,1322	28,65	20,33	20,32
F1-2	5,4715	31,13	20,36	20,49
F1-3	5,5447	30,37	20,52	20,63

F1-4	5,5026	30,92	20,47	20,38
F1-5	5,6431	31,16	20,37	20,43
F1-6	5,6021	31,14	20,37	20,35
F1-7	5,3518	30,88	20,3	20,44
F1-8	5,3543	30,8825	20,3025	20,4425
F1-9	5,3562	30,8844	20,3044	20,4444
F1-10	5,3472	30,8754	20,2954	20,4354
F2-1	5,3297	30,98	20,15	20,44
F2-2	5,4569	30,86	20,28	20,36
F2-3	5,3784	30,89	20,23	20,46
F2-4	5,1491	29,8	20,2	20,45
F2-5	5,0078	31,44	20,33	20,45
F2-6	5,5609	30,75	20,48	20,36
F2-7	5,6457	31	20,48	20,53
F2-8	5,6267	30,981	20,461	20,511
F2-9	5,6457	31	20,48	20,53
F2-10	5,6647	31,019	20,499	20,549
F3-1	5,3745	31,46	20,26	20,43
F3-2	5,2575	31,04	20,29	20,46
F3-3	5,2175	31,39	20,22	20,44
F3-4	5,4935	31,15	20,26	20,43
F3-5	5,6449	31,16	20,29	20,42
F3-6	4,9066	28,55	20,21	20,66
F3-7	4,7491	30,25	20,23	20,43
F3-8	4,7301	30,231	20,211	20,411
F3-9	4,7491	30,25	20,23	20,43
F3-10	4,7681	30,269	20,249	20,449
F4-1	5,4494	30,34	20,42	20,71
F4-2	5,0597	31,09	20,21	20,41
F4-3	5,1561	30,98	20,28	20,36
F4-4	5,4028	30,98	20,81	20,36
F4-5	5,2414	31,29	20,08	20,56
F4-6	4,9726	31,22	20,23	20,36
F4-7	5,1098	29,09	20,37	20,37
F4-8	5,0908	29,071	20,351	20,351
F4-9	5,1098	29,09	20,37	20,37
F4-10	5,1098	29,09	20,37	20,37
F5-1	5,9131	30,36	20,89	20,68
F5-2	8,3067	31,62	19,88	21,17
F5-3	5,0691	30,72	20,27	20,44
F5-4	5,2674	30,96	20,13	20,41
F5-5	5,1406	30,95	20,1	20,56
F5-6	6,2995	30,11	20,05	19,42
F5-7	5,2815	30,62	20,32	20,1
F5-8	5,2625	30,601	20,301	20,081
F5-9	5,2815	30,62	20,32	20,1

F5-10	5,1098	29,09	20,37	20,37
P0-1	7,0903	30,25	20,06	20,55
P0-2	7,9899	31,09	20,01	20,68
P0-3	5,2983	30,39	19,84	19,23
P0-4	6,0689	30,62	19,41	19,72
P0-5	6,5027	29,74	20,45	20,48
P0-6	6,2986	30,68	19,98	19,52
P0-7	5,2483	30,18	19,62	19,89
P0-8	6,9333	31,18	20,38	20,75
P0-9	5,743	30,06	19,93	20,04
P0-10	5,6476	31,11	20,04	19,79
P1-1	6,9774	30,33	20,44	20,63
P1-2	6,0974	31,04	19,92	19,52
P1-3	5,4945	31,04	20	19,89
P1-4	6,695	30,34	20,55	20,81
P1-5	5,7287	31,17	19,74	19,56
P1-6	5,5054	30,72	19,87	19,67
P1-7	6,4591	31,07	20,16	19,18
P1-8	6,0978	30,09	19,05	20,22
P1-9	5,3989	31,14	19,94	19,99
P1-10	5,3799	31,121	19,921	19,971
P2-1	6,3141	30,38	20,46	20,28
P2-2	5,402	30,57	19,72	19,48
P2-3	7,0558	31,04	20,44	20,23
P2-4	6,765	31,02	19,79	19,85
P2-5	6,3557	30,47	20,68	20,32
P2-6	5,1491	30,86	19,08	19,61
P2-7	8,2559	31,06	19,88	20,8
P2-8	5,6034	30,53	20,05	19,86
P2-9	6,231	30,1	20,24	19,98
P2-10	6,212	30,081	20,221	19,961
P3-1	5,5316	31,1	20,08	19,76
P3-2	6,351	30,38	20,47	20,5
P3-3	6,6171	30,68	19,94	20,19
P3-4	6,6802	30,91	20,15	19,93
P3-5	5,6336	30,93	19,75	19,83
P3-6	6,598	30,42	19,89	20,29
P3-7	5,1168	31,04	18,89	19,86
P3-8	6,4109	30,87	20,01	19,58
P3-9	6,4408	30,3	19,97	19,99
P3-10	6,4218	30,281	19,951	19,971
P4-1	5,365	30,86	19,83	20
P4-2	6,4553	31,08	19,9	19,4
P4-3	5,3407	30,59	19,83	20,07
P4-4	5,3631	30,41	19,79	19,67
P4-5	6,208	31,18	19,88	20,1

P4-6	5,708	30,29	19,75	19,88
P4-7	6,799	31,01	20,31	20,22
P4-8	6,106	30,23	19,44	19,94
P4-9	6,6851	30,51	20,44	20,68
P4-10	6,6661	30,491	20,421	20,661
P5-1	6,2061	29,94	19,65	20,23
P5-2	6,9234	30,51	20,04	20,13
P5-3	5,3027	30,54	19,66	20,01
P5-4	6,3102	30,53	20,81	20,27
P5-5	5,6065	30,57	19,69	19,84
P5-6	6,0815	31,04	19,38	20,02
P5-7	6,3226	30,11	19,83	19,83
P5-8	6,3608	30,21	20,04	20,22
P5-9	5,409	30,8	19,7	19,45
P5-10	5,39	30,781	19,681	19,431

Table 3: Hygroscopicity samples roughness measurements

SampleID	RaRadial	RqRadial	RzRadial	RaTangendial	RqTangendial	RzTangendial
I0-1	3,735	4,898	23,97	4,625	5,667	26,483
I0-2	3,013	3,827	17,039	5,477	6,903	31,969
I0-3	1,827	2,452	12,639	2,991	3,773	16,576
I0-4	4,014	5,314	25,123	2,525	3,173	15,882
I0-5	2,414	3,102	15,246	2,36	3,025	14,458
I0-6	6,919	9,315	44,946	3,982	4,981	24,951
I0-7	2,422	3	14,044	2,836	3,595	17,646
I0-8	5,055	6,328	31,16	2,716	3,521	19,105
I0-9	2,369	3,091	14,399	2,155	2,825	15,35
I0-10	1,967	2,436	10,742	2,335	3,041	15,051
I1-1	6,353	7,857	34,913	3,98	4,903	21,962
I1-2	2,041	2,729	14,142	4,853	6,175	27,461
I1-3	3,21	3,88	17,879	3,758	4,677	21,785
I1-4	3,905	4,886	21,118	6,588	8,447	37,022
I1-5	5,156	6,686	31,977	1,923	2,528	12,42
I1-6	3,126	4,148	21,221	2,843	3,671	18,583
I1-7	2,438	3,089	14,888	3,045	3,758	18,046
I1-8	2,883	3,692	19,661	2,27	2,846	13,742
I1-9	3,49	4,367	23,545	3,604	4,774	27,472
I1-10	2,884	3,693	19,662	2,28	2,842	13,712
I2-1	2,159	2,644	13,324	1,947	2,436	11,847
I2-2	2,88	3,473	15,927	4,466	5,78	24,152
I2-3	3,552	4,931	23,206	2,712	3,38	15,201
I2-4	1,533	1,996	10,579	2,063	2,514	11,447
I2-5	50,89	6,988	30,24	3,03	3,835	18,059

I2-6	3,38	4,391	21,581	4,868	6,18	27,353
I2-7	4,048	5,265	24,889	4,86	6,464	32,933
I2-8	3,331	4,206	21,289	2,809	6,63	18,674
I2-9	2,139	2,681	13,347	2,955	3,855	17,769
I2-10	2,14	2,69	13,35	2,956	3,856	17,77
I3-1	3,396	4,263	20,542	2,203	2,778	13,473
I3-2	1,9	2,359	12,039	2,284	2,966	14,828
I3-3	3,147	4,008	19,676	2,769	3,38	15,075
I3-4	3,7	4,677	23,465	2,506	3,226	16,035
I3-5	1,723	2,186	11,418	1,54	2,018	10,936
I3-6	3,078	3,926	18,055	5,537	4,353	26,586
I3-7	2,412	3,127	17,133	5,051	6,833	30,579
I3-8	2,652	3,492	18,541	5,874	7,422	31,372
I3-9	3,01	3,679	16,746	4,226	5,356	25,648
I3-10	2,349	3,489	15,539	5,87	7,419	31,369
I4-1	11,028	13,401	54,902	2,301	2,982	16,011
I4-2	2,539	3,204	16,393	4,592	6,221	28,828
I4-3	2,314	2,994	16,005	2,338	3,018	16,019
I4-4	5,075	6,223	28,978	11,915	14,413	60,065
I4-5	3,875	5,033	22,901	1,819	2,325	10,405
I4-6	2,076	2,559	13,109	5,869	7,821	36,475
I4-7	2,073	2,608	12,626	4,109	4,951	22,786
I4-8	2,598	4,451	36,999	2,998	3,947	21,387
I4-9	1,65	2,079	9,674	1,818	2,238	10,823
I4-10	3,875	5,033	22,901	1,819	2,325	10,405
I5-1	3,189	3,885	17,933	9,214	11,625	49,877
I5-2	2,294	2,723	12,079	1,431	17,45	8,873
I5-3	2,364	2,978	17,107	3,336	4,256	21,016
I5-4	2,288	2,906	13,299	2,118	2,716	13,606
I5-5	1,906	2,342	11,458	2,236	2,833	14,43
I5-6	1,708	2,145	10,74	4,005	5,571	26,503
I5-7	2,031	2,535	12,135	4,589	5,984	29,014
I5-8	1,652	2,147	9,524	4,215	5,164	22,56
I5-9	3,75	5,264	27,209	3,06	3,809	17,99
I5-10	1,91	2,343	11,468	2,246	2,843	14,45
M0-1	1,833	2,321	10,453	2,061	2,605	11,854
M0-2	2,017	2,463	12,163	5,309	7,53	36,978
M0-3	1,77	2,307	12,327	4,883	7,132	31,423
M0-4	2,935	3,825	20,488	5,776	7,097	30,959
M0-5	7,52	9,79	48,868	7,774	9,722	45,88
M0-6	6,189	7,61	33,8	5,792	7,097	34,174
M0-7	5,466	6,971	38,004	7,09	9,862	53,047
M0-8	4,199	5,714	35,698	8,376	10,845	48,974
M0-9	3,089	3,822	19,778	6,045	7,522	35,77
M0-10	4,282	5,552	26,756	8,876	11,84	55,945
M1-1	3,075	4,053	24,361	1,881	2,415	12,45

M1-2	1,958	2,416	10,349	3,462	4,148	17,246
M1-3	2,949	3,776	18,628	5,638	7,383	32,596
M1-4	1,823	2,291	10,617	2,574	3,136	14,591
M1-5	1,86	2,365	11,32	2,6	3,183	14,101
M1-6	3,136	4,119	19,062	4,001	5,079	22,763
M1-7	2,461	3,01	12,854	5,569	7,357	34,509
M1-8	3,993	3,358	16,712	3,653	4,625	20,897
M1-9	1,776	2,254	11,966	2,706	3,286	13,706
M1-10	1,823	2,291	10,617	2,574	3,136	14,591
M2-1	3,074	3,838	17,194	2,471	3,214	15,901
M2-2	1,795	2,303	11,16	2,356	2,969	14,986
M2-3	1,789	2,261	11,468	2,526	3,316	16,978
M2-4	1,515	1,859	8,663	2,931	3,686	17,866
M2-5	1,944	2,297	9,645	1,806	2,182	10,276
M2-6	1,422	1,773	8,326	2,119	2,735	14,444
M2-7	2,73	3,541	15,277	4,092	5,014	22,841
M2-8	1,578	2,006	9,713	2,403	3,138	15,929
M2-9	1,927	2,35	11,238	2,429	3,06	13,556
M2-10	1,789	2,261	11,468	2,526	3,316	16,978
M3-1	1,821	2,272	11,376	2,359	2,932	15,196
M3-2	1,913	2,381	11,459	2,115	2,577	12,057
M3-3	1,319	1,699	8,214	2,316	3,025	16,625
M3-4	2,843	3,527	15,994	8,223	9,849	42,901
M3-5	2,455	3,018	12,927	2,06	2,627	13,907
M3-6	2,84	3,403	13,832	2,025	2,618	14,2
M3-7	1,485	1,81	8,755	2,246	2,894	14,754
M3-8	2,034	2,488	11,668	1,891	2,507	12,422
M3-9	2,353	2,948	14,435	2,808	3,712	17,706
M3-10	2,84	3,403	13,832	2,025	2,618	14,2
M4-1	2,676	3,223	14,482	3,326	4,248	20,337
M4-2	2,109	2,674	13,285	2,89	3,49	15,093
M4-3	2,278	2,83	12,258	7,046	8,788	39,031
M4-4	2,155	2,797	13,167	4,187	5,393	24,937
M4-5	2,364	3,101	16,552	3,349	4,099	17,871
M4-6	2,779	3,654	17,937	2,681	3,425	18,586
M4-7	2,794	3,526	15,542	2,313	3,124	17,347
M4-8	1,939	2,385	11,833	7,85	10,225	44,153
M4-9	2,781	3,604	16,658	7,543	9,187	37,283
M4-10	2,794	3,526	15,542	2,313	3,124	17,347
M5-1	2,455	3,198	18,979	4,359	5,606	24,195
M5-2	2,869	3,882	20,139	7,565	9,291	43,92
M5-3	2,086	2,708	13,572	2,406	3,054	16,167
M5-4	1,705	2,132	9,612	3,345	4,067	17,522
M5-5	2,639	3,269	15,471	2,232	2,949	15,593
M5-6	3,282	2,531	13,921	3,177	3,974	17,73
M5-7	2,719	3,401	16,795	5,669	7,384	30,075

M5-8	2,438	2,943	15,517	4,25	5,495	26,995
M5-9	2,577	3,305	16,882	4,421	5,295	20,789
M5-10	2,719	3,401	16,795	5,669	7,384	30,075
F0-1	2,957	3,616	16,13	2,399	3,006	13,989
F0-2	5,77	7,5	33,699	1,685	2,364	11,194
F0-3	3,689	4,875	23,324	0,757	1,061	5,121
F0-4	3,074	3,845	17,892	2,604	3,312	15,277
F0-5	1,814	2,385	11,461	2,344	3	14,143
F0-6	1,721	2,168	10,986	3,677	4,82	21,576
F0-7	3,58	4,922	25,431	2,073	2,646	11,837
F0-8	3,52	4,071	17,327	2,274	2,923	13,063
F0-9	3,529	4,08	17,336	2,283	2,932	13,072
F0-10	3,519	4,07	17,326	2,273	2,922	13,062
F1-1	3,43	4,218	17,427	4,85	6,98	35,824
F1-2	2,394	2,988	13,105	1,906	8,289	1,506
F1-3	3,767	4,876	24,066	1,752	2,123	9,27
F1-4	2,002	2,457	10,773	2,24	2,9	13,098
F1-5	3,975	5,38	25,444	2,552	3,23	14,692
F1-6	4,001	5,139	25,951	3,341	4,121	19,793
F1-7	1,641	2,047	9,817	1,6	2,135	11,633
F1-8	1,6435	2,0495	9,8195	1,6025	2,1375	11,6355
F1-9	1,6454	2,0514	9,8214	1,6044	2,1394	11,6374
F1-10	1,6364	2,0424	9,8124	1,5954	2,1304	11,6284
F2-1	1,748	2,218	10,893	2,701	3,37	16,097
F2-2	3,498	4,32	19,564	1,995	2,484	12,204
F2-3	4,068	5,267	23,693	3,065	4,06	19,3
F2-4	5,03	6,535	30,362	2,939	3,765	16,131
F2-5	1,864	2,257	9,717	3,023	3,819	16,699
F2-6	4,886	5,808	24,455	1,832	2,35	11,628
F2-7	2,243	2,99	13,935	3,961	5,022	22,47
F2-8	2,224	2,971	13,916	3,942	5,003	22,451
F2-9	2,243	2,99	13,935	3,961	5,022	22,47
F2-10	2,262	3,009	13,954	3,98	5,041	22,489
F3-1	2,753	3,465	15,518	1,957	2,486	12,261
F3-2	6,164	7,668	34,726	2,579	3,282	15,253
F3-3	3,707	4,581	20,773	1,961	2,57	13,704
F3-4	2,059	2,765	13,197	4,314	5,373	24,569
F3-5	1,602	2,09	10,271	3,226	3,963	17,512
F3-6	1,736	2,285	11,021	2,109	2,561	12,433
F3-7	1,943	2,492	12,357	3,389	4,229	18,984
F3-8	1,924	2,473	12,338	3,37	4,21	18,965
F3-9	1,943	2,492	12,357	3,389	4,229	18,984
F3-10	1,962	2,511	12,376	3,408	4,248	19,003
F4-1	2,237	3,051	15,449	2,326	2,904	12,826
F4-2	1,421	1,889	9,871	3,88	5,042	24,069
F4-3	3,304	4,412	20,382	3,378	4,392	22,718

F4-4	2,659	3,34	14,758	3,145	4,064	19,512
F4-5	1,732	2,189	10,401	2,193	2,799	12,66
F4-6	1,139	1,419	5,949	3,492	4,378	21,96
F4-7	2,91	4,026	19,151	2,561	3,467	16,694
F4-8	2,891	4,007	19,132	2,542	3,448	16,675
F4-9	2,91	4,026	19,151	2,561	3,467	16,694
F4-10	2,91	4,026	19,151	2,561	3,467	16,694
F5-1	7,487	9,457	40,413	4,795	5,953	29,748
F5-2	2,681	3,521	18,46	4,616	5,814	26,001
F5-3	1,941	2,592	14,363	2,765	3,472	15,647
F5-4	3,811	4,697	21,672	2,437	3,017	13,963
F5-5	3,036	3,738	16,22	2,01	2,548	11,257
F5-6	1,874	2,495	13,362	1,963	2,485	11,806
F5-7	5,862	7,647	37,632	5,107	6,749	32,951
F5-8	5,843	7,628	37,613	5,088	6,73	32,932
F5-9	5,862	7,647	37,632	5,107	6,749	32,951
F5-10	2,91	4,026	19,151	2,561	3,467	16,694
P0-1	2,573	3,1	14,283	8,228	10,35	44,313
P0-2	4,666	5,649	25,654	6,287	7,753	31,161
P0-3	3,358	4,143	18,38	1,831	2,448	11,584
P0-4	3,732	4,889	25,441	1,627	1,992	9,377
P0-5	2,764	3,674	19,978	2,342	2,926	13,94
P0-6	3,067	3,763	16,624	3,342	4,177	17,767
P0-7	1,617	1,971	8,366	2,032	2,492	11,61
P0-8	2,86	3,394	14,535	2,438	3,07	13,981
P0-9	4,218	5,637	29,404	3,167	3,894	16
P0-10	2,689	3,502	15,912	2,063	2,662	13,236
P1-1	3,349	4,318	19,593	1,623	2,049	10,285
P1-2	2,167	3,021	15,696	4,241	5,107	20,465
P1-3	2,291	2,876	13,051	1,561	2,113	11,677
P1-4	2,887	3,592	16,389	1,406	1,778	8,257
P1-5	3,903	5,218	24,979	2,18	2,79	14,031
P1-6	2,978	3,901	20,048	2,71	3,437	16,77
P1-7	2,996	3,741	18,668	3,01	3,914	20,131
P1-8	1,906	2,407	11,735	3,654	4,405	18,645
P1-9	2,311	2,905	13,465	4,097	4,995	21,224
P1-10	2,292	2,886	13,446	4,078	4,976	21,205
P2-1	2,63	3,247	13,309	3,135	3,818	17,087
P2-2	3,489	4,45	18,065	2,393	3,026	15,23
P2-3	3,344	4,593	24,873	1,81	2,291	11,479
P2-4	1,591	2,037	10,013	1,496	2,052	10,92
P2-5	1,194	1,495	8,196	2,77	3,65	18,174
P2-6	3,784	4,821	25,177	2,582	3,304	17,128
P2-7	1,721	2,219	10,965	2,3	2,858	13,739
P2-8	2,596	3,34	16,404	2,009	2,572	12,293
P2-9	1,787	2,245	10,888	3,412	4,393	20,694

P2-10	1,768	2,226	10,869	3,393	4,374	20,675
P3-1	2,417	3,089	15,763	2,986	3,897	19,327
P3-2	2,836	3,567	17,471	3,194	3,995	19,48
P3-3	2,606	3,265	14,225	2,057	2,59	12,764
P3-4	1,691	2,092	9,741	2,831	3,561	17,717
P3-5	4,229	5,178	24,305	1,964	2,657	14,134
P3-6	2,497	3,295	17,098	2,118	2,74	12,146
P3-7	3,006	3,896	19,676	3,261	4,053	18,484
P3-8	3,521	4,779	25,156	1,925	2,736	14,172
P3-9	3,142	3,974	17,885	3,008	3,887	20,33
P3-10	3,123	3,955	17,866	2,989	3,868	20,311
P4-1	2,469	3,037	12,962	2,294	2,957	14,226
P4-2	2,882	3,526	15,4	2,292	3,138	16,424
P4-3	2,185	2,645	11,547	2,756	3,497	17,094
P4-4	3,934	4,668	18,864	3,066	3,825	18,219
P4-5	2,17	2,92	14,823	1,171	1,488	7,943
P4-6	4,123	5,097	21,986	7,092	9,341	38,822
P4-7	2,855	3,541	16,336	1,205	1,497	7,45
P4-8	1,524	1,905	9,116	4,786	6,028	25,607
P4-9	1,078	1,441	7,921	2,384	3,09	15,727
P4-10	1,059	1,422	7,902	2,365	3,071	15,708
P5-1	2,346	3,097	15,704	1,723	2,149	9,653
P5-2	1,871	2,393	10,656	3,637	4,586	21,116
P5-3	2,922	3,831	19,879	2,313	2,961	14,649
P5-4	3,709	5,058	24,593	1,166	1,528	9,144
P5-5	1,308	1,758	8,309	3,94	4,651	19,763
P5-6	2,014	2,489	11,088	1,413	1,833	9,237
P5-7	2,438	3,236	15,834	2,259	3,007	18,148
P5-8	1,145	1,43	6,715	4,972	6,115	30,581
P5-9	4,814	5,663	21,99	3,942	5,193	21,651
P5-10	4,795	5,644	21,971	3,923	5,174	21,632

Table 4: Hygroscopicity samples initial color measurements

SampleID	L	a	b	c	h
I0-1	66,85	6,02	29,9	30,5	78,62
I0-2	64,15	7,66	29,79	30,76	75,59
I0-3	53,01	11,18	25,98	28,28	66,72
I0-4	52,21	9,77	24,46	26,34	68,22
I0-5	48,46	11,09	23,51	25,99	64,73
I0-6	46,51	9,65	28,21	29,82	71,13
I0-7	50,92	11,46	15,05	27,54	65,42
I0-8	54,24	10,47	26,61	28,59	68,52
I0-9	63,96	7,1	29,94	30,77	76,66

I0-10	62,73	8,08	29,73	30,81	74,79
I1-1	66,88	7,6	33,97	34,81	77,39
I1-2	55,3	11,2	30,45	32,45	69,8
I1-3	53,54	11,34	29,23	31,36	68,8
I1-4	67,37	6,57	32,08	32,75	78,43
I1-5	66,74	7,55	33,69	34,53	77,37
I1-6	52,55	12,55	29,61	32,16	67,03
I1-7	62,25	7,28	28,37	29,29	75,6
I1-8	53,13	11,51	28,72	30,97	68,16
I1-9	59,54	9,17	29,1	30,51	72,51
I1-10	54,98	11,53	28,75	30,88	68,2
I2-1	53,34	11	28,41	30,47	68,83
I2-2	66,07	7,29	31,16	32,01	76,83
I2-3	54,09	13,71	32,99	35,73	67,44
I2-4	62,86	8,72	31,25	32,44	74,41
I2-5	62,58	8,84	31,95	33,15	74,54
I2-6	49,58	13,58	28,23	31,33	64,3
I2-7	50,16	12,57	26,75	29,56	64,84
I2-8	64,72	7,76	30,78	31,74	75,85
I2-9	66,32	7,7	33,32	34,23	77
I2-10	66,33	7,71	33,36	34,24	77,1
I3-1	61,33	7,91	28,04	29,13	74,24
I3-2	57,7	9,96	28,61	30,3	70,81
I3-3	55,66	1062	28,14	30,07	69,33
I3-4	58,32	10,37	32,49	34,11	72,31
I3-5	66,11	7,83	31,23	32,2	75,92
I3-6	53,02	12,24	28,34	30,87	66,64
I3-7	56,25	9,96	28,06	29,78	70,46
I3-8	59,67	8,93	28,5	29,87	72,61
I3-9	54,45	11,03	28,08	30,17	68,55
I3-10	59,64	8,65	28,54	29,84	72,63
I4-1	66,2	8,07	33,94	34,93	76,64
I4-2	58,02	9,34	28,13	29,64	71,63
I4-3	64,73	6,5	27	27,77	76,45
I4-4	51,06	10,92	25,83	28,04	67,09
I4-5	68,58	6,98	33,55	34,23	78,57
I4-6	59,91	9,05	28,84	30,23	72,58
I4-7	54,43	10,75	28,82	30,76	69,54
I4-8	66,61	7,18	33,01	33,79	77,73
I4-9	64,41	7,71	31,31	32,25	76,16
I4-10	68,58	6,98	33,55	34,23	78,57
I5-1	59,64	10,23	32,14	33,72	72,34
I5-2	60,92	8,7	29,27	30,54	73,46
I5-3	58,58	9,55	30	31,49	72,34
I5-4	62,72	8,5	31,01	32,15	74,67
I5-5	64,57	6,41	31,9	32,8	76,58

I5-6	60,65	9,3	30,7	32,07	73,15
I5-7	60,71	8,28	28,7	29,78	73,9
I5-8	61,46	9,12	30,25	31,59	73,23
I5-9	57,13	10,34	30,26	31,98	71,14
I5-10	64,58	6,42	31,9	32,8	76,58
M0-1	67,77	9,36	19,31	21,46	64,14
M0-2	67,24	10,07	20,19	22,56	63,49
M0-3	68,74	9,75	20,33	22,55	64,37
M0-4	66,09	10,41	21,61	23,99	64,27
M0-5	66,07	11,02	19,93	22,77	61,06
M0-6	62,11	12,66	21,79	25,2	59,65
M0-7	65,94	10,45	20,51	23,02	63
M0-8	63,54	10,6	19,4	22,1	61,36
M0-9	69,89	7,83	18,54	20,13	67,11
M0-10	70,14	8,54	18,21	20,11	64,87
M1-1	69,86	9,59	21,01	23,1	65,46
M1-2	64,37	10,16	20,55	22,92	63,69
M1-3	69,74	9,42	9,76	21,89	64,52
M1-4	68,04	10,5	21,04	23,52	63,47
M1-5	64,96	12,02	21,29	24,45	60,56
M1-6	69,12	9,54	18,83	21,11	63,14
M1-7	62,62	11,14	20,82	23,61	61,86
M1-8	70,58	9,12	18,72	20,82	64,01
M1-9	69,35	9,65	19,01	21,23	63,08
M1-10	68,04	10,5	21,04	23,52	63,47
M2-1	66,68	10,47	20,88	23,35	63,38
M2-2	66,38	10,49	20,9	23,38	63,36
M2-3	67,84	8,77	21,81	23,58	68,17
M2-4	68,15	10,15	19,52	22	62,53
M2-5	66,15	11,02	21,1	23,8	62,42
M2-6	67,52	10,38	20,41	22,89	63,04
M2-7	69,94	9,09	19,03	21,09	64,47
M2-8	68,54	9,92	19,93	22,27	63,55
M2-9	69,45	9,98	19,64	22,03	63,06
M2-10	67,84	8,77	21,81	23,58	68,17
M3-1	55,69	14,2	20,38	24,84	55,13
M3-2	64,44	11,7	21,5	24,48	61,44
M3-3	71,28	9,29	18,97	21,12	63,92
M3-4	68,17	10,09	20,88	23,19	64,22
M3-5	68,21	9,92	20,34	22,64	64
M3-6	71,42	9,68	19,12	21,43	63,15
M3-7	67,39	10,51	21,02	23,5	63,44
M3-8	69,5	9,87	20,37	22,64	64,16
M3-9	68,87	10,16	19,74	22,2	62,77
M3-10	71,42	9,68	19,12	21,43	63,15
M4-1	62,4	10,8	19,35	22,16	60,82

M4-2	66,21	10,6	20,25	22,86	62,37
M4-3	70,43	10,01	20,13	22,48	63,56
M4-4	63,86	11,17	20,17	23,06	61,02
M4-5	63,21	12	21,4	24,53	60,72
M4-6	64,04	10,86	22,11	24,63	63,85
M4-7	68,55	9,89	19,91	22,23	63,57
M4-8	67,68	10,69	20,79	23,38	62,78
M4-9	64,81	7,56	25,04	26,16	73,2
M4-10	68,55	9,89	19,91	22,23	63,57
M5-1	67,26	10,05	20,44	22,78	63,83
M5-2	62,24	10,51	20,86	23,36	63,26
M5-3	64,34	10,07	20,74	23,06	64,09
M5-4	64,55	10,22	21,16	23,5	64,23
M5-5	65,56	11,14	20,09	22,97	61
M5-6	67,34	10,67	20,97	23,53	63,02
M5-7	67,81	9,42	19,35	21,52	64,03
M5-8	64,59	10,72	20,34	22,99	62,22
M5-9	69,53	9,64	19,5	21,76	63,69
M5-10	67,81	9,42	19,35	21,52	64,03
F0-1	81,91	6,14	20,17	21,08	73,07
F0-2	78,62	6,75	21,14	22,19	72,3
F0-3	82,75	6,22	20,16	21,1	72,86
F0-4	76,95	7,16	25,07	26,07	74,06
F0-5	84,37	5,65	19,69	20,48	73,99
F0-6	84,68	5,37	21,05	21,72	75,69
F0-7	83,95	5,65	19,23	20,05	73,64
F0-8	81,26	6,4	21,74	22,66	73,6
F0-9	81,269	6,409	21,749	22,669	73,609
F0-10	81,259	6,399	21,739	22,659	73,599
F1-1	85,02	5,29	19,37	20,08	74,72
F1-2	83,88	5,64	19,7	19,88	7353
F1-3	71,98	9,36	31,26	32,63	73,34
F1-4	84,47	5,54	19,31	20,08	74
F1-5	83,17	5,76	19,97	20,78	73,91
F1-6	84,83	5,53	19,88	20,63	74,44
F1-7	82,65	6,2	20,66	21,57	73,29
F1-8	82,6525	6,2025	20,6625	21,5725	73,2925
F1-9	82,6544	6,2044	20,6644	21,5744	73,2944
F1-10	82,6454	6,1954	20,6554	21,5654	73,2854
F2-1	84,39	5,41	19,56	20,29	74,54
F2-2	85,15	5,69	20,01	20,8	74,12
F2-3	84,96	5,6	19,73	20,51	74,17
F2-4	84,61	5,86	20,32	21,14	73,92
F2-5	85,44	5,54	19,92	20,67	74,45
F2-6	83,41	5,25	21,21	21,89	76,13
F2-7	84,73	5,45	19,41	20,16	74,32

F2-8	84,711	5,431	19,391	20,141	74,301
F2-9	84,73	5,45	19,41	20,16	74,32
F2-10	84,749	5,469	19,429	20,179	74,339
F3-1	85,07	5,44	18,96	19,73	73,98
F3-2	84,56	5,57	18,75	19,56	73,46
F3-3	83,45	5,53	20,16	20,9	74,67
F3-4	84,73	5,38	19,29	20,03	74,42
F3-5	84,75	5,57	20,28	21,03	74,65
F3-6	84,96	5,71	19,51	20,32	73,69
F3-7	85,26	5,46	19,3	20,06	74,2
F3-8	85,241	5,441	19,281	20,041	74,181
F3-9	85,26	5,46	19,3	20,06	74,2
F3-10	85,279	5,479	19,319	20,079	74,219
F4-1	81,85	5,87	19,84	20,69	73,52
F4-2	81,99	6,45	24,72	25,54	75,37
F4-3	84,81	5,38	19,49	20,22	74,55
F4-4	84,92	5,56	19,37	20,16	73,99
F4-5	80,37	6,53	22,53	23,46	73,83
F4-6	85,45	5,64	18,1	18,96	72,69
F4-7	81,82	5,78	21,15	21,92	74,71
F4-8	81,801	5,761	21,131	21,901	74,691
F4-9	81,82	5,78	21,15	21,92	74,71
F4-10	81,82	5,78	21,15	21,92	74,71
F5-1	81,97	6,1	20,08	20,99	73,11
F5-2	72,96	7,2	25,48	20,48	74,22
F5-3	85,29	5,63	19,8	20,58	74,12
F5-4	84,11	5,55	19,49	20,26	74,09
F5-5	83,32	6	20,38	21,24	73,6
F5-6	82,1	5,86	22,35	23,1	75,31
F5-7	84,05	5,26	19,01	19,72	74,54
F5-8	84,031	5,241	18,991	19,701	74,521
F5-9	84,05	5,26	19,01	19,72	74,54
F5-10	81,82	5,78	21,15	21,92	74,71
P0-1	73,9	7,56	24,97	26,09	73,16
P0-2	71,43	7,83	27,27	23,38	73,99
P0-3	80,9	8,21	22,52	23,97	69,97
P0-4	79,45	8,72	22,55	24,18	68,85
P0-5	64,27	12,55	31,49	33,9	68,28
P0-6	78,98	7,68	23,05	24,29	71,57
P0-7	79,04	8,74	24,4	25,92	70,28
P0-8	78,02	8,28	25,22	26,55	71,83
P0-9	76,56	9,97	27,73	29,47	70,22
P0-10	78,07	9,46	23,83	25,64	68,34
P1-1	77,19	8,96	24,77	26,34	70,12
P1-2	75,81	9,69	29,64	31,19	71,89
P1-3	79,11	9,21	20,64	22,6	65,95

P1-4	77,88	10,3	26,46	28,39	68,73
P1-5	78,88	9,49	23,2	25,07	67,75
P1-6	78,56	8,27	20,87	22,45	68,39
P1-7	78,18	8,2	20,92	22,47	68,59
P1-8	78,01	8,04	21,41	22,87	69,42
P1-9	77,05	7,08	20,88	22,05	71,26
P1-10	77,031	7,061	20,861	22,031	71,241
P2-1	76,75	9,15	25,23	26,84	70,07
P2-2	79,5	8,74	22,26	23,92	68,56
P2-3	76,89	8,74	24,36	25,88	70,27
P2-4	79,05	8,98	21,06	22,89	66,9
P2-5	76,75	9,44	23,23	25,08	67,9
P2-6	77,83	8,63	24,91	26,36	70,9
P2-7	89,98	7,13	25,83	26,8	74,56
P2-8	77,65	9,12	26,56	28,09	71,04
P2-9	76,63	8,53	21,52	23,15	68,37
P2-10	76,611	8,511	21,501	23,131	68,351
P3-1	74,95	9,53	25,95	27,64	69,83
P3-2	79,12	8,07	24,25	25,56	71,61
P3-3	76,79	8,04	23,39	24,74	71,03
P3-4	79,61	8,05	22,15	23,56	70,03
P3-5	78,91	8,23	20,8	22,37	68,41
P3-6	73,81	8,37	24,44	25,83	71,09
P3-7	78,18	7,57	22,17	23,43	71,15
P3-8	79,84	5,28	22,16	22,79	76,59
P3-9	78,46	7,88	22,17	23,52	70,44
P3-10	78,441	7,861	22,151	23,501	70,421
P4-1	79,34	8,75	23,55	25,12	69,62
P4-2	79,89	7,84	21,13	22,54	69,64
P4-3	78,79	8,58	22,27	8,58	68,92
P4-4	79,82	7,88	20,19	21,67	68,67
P4-5	78,16	8,19	22,37	23,82	69,89
P4-6	77,39	7,17	20,51	21,73	70,72
P4-7	78,1	8,44	22,61	24,14	69,54
P4-8	78,74	7,93	22,68	24,03	70,73
P4-9	76,05	9,23	22,63	24,44	67,8
P4-10	76,031	9,211	22,611	24,421	67,781
P5-1	78,43	8,55	20,55	22,25	67,41
P5-2	74,48	9,5	24,74	26,5	69
P5-3	78,09	7,79	22,55	23,86	70,93
P5-4	78,12	8,66	24,35	25,84	70,42
P5-5	78,92	8,67	22,1	23,74	68,58
P5-6	78,48	8,36	23,28	24,74	70,24
P5-7	77,82	7,71	21,26	22,62	70,06
P5-8	76,3	8,77	23,15	24,75	69,25
P5-9	76,22	7,9	26,12	27,29	71,17

P5-10	76,201	7,881	26,101	27,271	71,151

Table 5: Xenon samples weight and dimensions measurements.

SampleID	InitialWeight	InitialLongitudinalLength	InitialRadialLength	InitialTangendialLength
I1-1-X	7,5127	30,36	19,94	19,69
I1-2-X	7,3062	30,44	20,02	19,5
I1-3-X	8,261	30,34	19,94	20,41
I1-4-X	7,5107	29,96	19,93	20,22
I1-5-X	7,2721	30,39	19,78	20,13
I2-1-X	7,1104	30,23	20,06	20,22
I2-2-X	7,6163	30,97	19,96	20,03
I2-3-X	7,1125	29,86	19,85	19,94
I2-4-X	7,5344	30,11	20,24	20,18
I2-5-X	7,5696	30,6	20	19,89
I3-1-X	7,2602	30,4	19,9	20,1
I3-2-X	7,8128	30,36	20,23	20,13
I3-3-X	7,5383	31,02	20,02	20,24
I3-4-X	7,322	30,5	19,76	20,13
I3-5-X	7,7106	30,26	20,01	20,09
I4-1-X	7,8959	30,99	19,87	20,26
I4-2-X	7,3967	30,48	19,83	20,2
I4-3-X	7,1598	30,27	19,73	20,13
I4-4-X	7,6912	30,09	20,04	20,24
I4-5-X	7,4783	30,43	19,97	20,19
I5-1-X	7,4267	30,43	19,88	19,84
I5-2-X	7,7301	29,71	20,01	19,95
I5-3-X	7,5324	30,64	19,95	20,15
I5-4-X	7,7988	30,74	19,92	20,24
I5-5-X	7,6055	30,33	19,82	20,13
I0-1-X	8,3379	30,51	20,38	20,52
I0-2-X	8,429	30,7	20,49	20,68
I0-3-X	8,4017	30,47	20,47	20,48
I0-4-X	7,4905	31,2	19,79	20,28
I0-5-X	7,8378	30,82	19,95	20,22
M1-1-X	4,8587	30,14	20,06	19,93
M1-2-X	4,9981	30,44	20,2	20,05
M1-3-X	5,0694	30,4	19,86	20,19
M1-4-X	4,569	29,98	19,44	19,95
M1-5-X	4,9433	30,17	19,89	19,62
M2-1-X	4,986	30,51	19,67	20,19
M2-2-X	5,0241	30,25	19,83	20,36
M2-3-X	4,7982	30,29	19,83	19,66
M2-4-X	4,8316	30,22	19,58	19,94
M2-5-X	4,7083	30,34	19,59	19,71

M3-1-X	5,0235	30,22	19,76	20,18
M3-2-X	5,0299	30,45	20,34	20
M3-3-X	4,8741	30,17	20,02	20,08
M3-4-X	4,8455	30,31	19,82	19,77
M3-5-X	4,9924	30,25	19,92	20,32
M4-1-X	4,7873	30,21	20,08	19,71
M4-2-X	4,9678	30,32	19,84	20,15
M4-3-X	4,9885	30,42	19,81	20,31
M4-4-X	4,8905	30,05	20,15	19,74
M4-5-X	4,9419	30,31	19,91	20,1
M5-1-X	4,5418	30	19,7	19,76
M5-2-X	5,3661	30,81	20,55	20,51
M5-3-X	4,5619	30,01	19,59	19,68
M5-4-X	4,9534	30,32	19,79	20,16
M5-5-X	5,0981	30,57	19,85	20,29
M0-1-X	4,8123	29,72	19,49	19,98
M0-2-X	4,7881	30,24	19,66	20,01
M0-3-X	4,9515	30,45	19,95	20,09
M0-4-X	5,0971	30,68	19,94	20,02
M0-5-X	4,7112	30,41	19,76	19,92
F1-1-X	5,1846	31,18	20,15	20,48
F1-2-X	5,8662	29,72	20,48	20,74
F1-3-X	5,571	31,44	20,27	20,41
F1-4-X	5,6985	31,6	20,32	20,39
F1-5-X	5,672	31,63	20,4	20,45
F2-1-X	5,5249	31,32	20,28	20,36
F2-2-X	5,4272	31,12	20,32	20,24
F2-3-X	5,341	30,37	20,48	20,38
F2-4-X	5,1039	28,32	20,36	20,43
F2-5-X	5,4774	30,5	20,53	20,65
F3-1-X	5,5497	30,96	20,29	20,38
F3-2-X	5,2485	31,17	20,34	20,4
F3-3-X	5,4046	31,22	20,32	20,16
F3-4-X	5,5297	30,88	20,35	20,32
F3-5-X	5,5554	31,24	20,31	20,51
F4-1-X	5,5642	31,3	20,32	20,44
F4-2-X	5,5156	30,69	20,35	20,6
F4-3-X	5,6078	30,88	20,27	20,4
F4-4-X	5,5044	30,92	20,42	20,36
F4-5-X	5,1196	30,8	20,35	20,45
F5-1-X	5,5431	31,67	20,48	20,3
F5-2-X	6,0204	30,72	20,37	20,66
F5-3-X	5,6482	31,42	20,4	20,42
F5-4-X	5,0897	30,72	20,13	20,35
F5-5-X	5,5063	30,14	20,55	21,03
F0-1-X	5,1263	31,15	20,21	20,36

F0-2-X	5,2092	31,46	20,19	20,42
F0-3-X	6,5288	30,76	20,4	20,83
F0-4-X	5,0724	31,01	20,22	20,5
F0-5-X	4,9673	30,62	20,3	20,68
P1-1-X	5,2841	30,35	19,67	19,95
P1-2-X	5,7116	31,01	19,66	19,68
P1-3-X	5,4018	30,96	19,81	19,47
P1-4-X	6,3364	31,01	19,96	19,53
P1-5-X	6,7155	30,45	20,59	20,67
P2-1-X	6,7411	30,25	20,85	20,85
P2-2-X	6,1053	30,37	19,63	20,09
P2-3-X	5,7095	30,31	20,15	19,5
P2-4-X	5,375	30,77	19,93	19,94
P2-5-X	6,2365	30,39	19,84	20,37
P3-1-X	6,0381	30,44	19,49	20,05
P3-2-X	5,5935	30,68	19,97	19,94
P3-3-X	6,5921	30,75	19,98	20,19
P3-4-X	6,1425	30,96	19,95	20,07
P3-5-X	6,2462	30,04	20,77	20,44
P4-1-X	6,6791	30,68	20,35	20,75
P4-2-X	7,0669	32,01	20,6	20,89
P4-3-X	5,2901	30,18	19,95	19,85
P4-4-X	5,4814	31,04	19,35	19,56
P4-5-X	5,3518	31,02	19,96	20,09
P5-1-X	6,7747	30,45	20,74	20,68
P5-2-X	6,4221	31,02	19,42	19,95
P5-3-X	5,6937	31,38	19,8	19,62
P5-4-X	6,2409	30,98	19,83	19,88
P5-5-X	6,0966	30,11	19,62	20,14
P0-1-X	6,6147	30,82	20,27	19,92
P0-2-X	5,409	30,97	19,86	19,27
P0-3-X	5,9931	30,61	20,7	20,89
P0-4-X	5,3353	31	19,55	19,73
P0-5-X	5,3736	30,51	19,84	19,36

Table 6: Xenon samples color measurements

SampleID	InitialL	Initiala	Initialb	Initialc	Initialh	FinalL	Finala	Finalb	Finalc	Finalh
I1-1-X	61,20	8,91	33,04	33,18	76,19	55,36	7,43	19,03	20,43	68,68
I1-2-X	64,07	8,21	32,72	32,11	72,55	50,21	11,10	26,89	29,09	67,56
I1-3-X	60,47	7,37	30,32	32,68	71,93	58,60	8,74	25,60	27,05	71,15
I1-4-X	58,00	14,07	33,46	32,24	72,96	59,61	6,10	18,37	19,36	71,63
I1-5-X	55,18	10,20	29,89	33,02	74,59	60,33	6,83	22,36	23,38	73,01

I2-1-X	57,37	13,55	34,95	30,79	78,90	50,12	11,62	27,65	29,99	67,21
I2-2-X	48,80	7,33	27,69	34,12	70,53	62,26	6,72	21,27	22,30	72,47
I2-3-X	43,34	9,05	33,86	32,80	75,13	46,87	12,63	27,55	30,31	65,38
I2-4-X	54,92	10,35	31,73	32,20	79,66	56,83	7,11	20,39	21,60	70,78
I2-5-X	59,95	6,69	30,86	29,61	79,92	50,34	12,16	29,76	32,15	67,77
I3-1-X	56,52	9,21	30,69	29,90	74,25	57,04	7,38	20,97	22,23	70,61
I3-2-X	57,36	8,80	26,77	32,11	75,04	56,67	8,49	22,61	24,15	69,43
I3-3-X	61,11	10,97	26,99	30,87	68,70	53,92	11,15	26,56	28,80	67,23
I3-4-X	63,76	7,81	29,82	30,71	73,32	46,18	13,38	28,48	31,47	64,84
I3-5-X	49,04	9,91	28,20	30,11	70,26	44,80	13,34	24,52	27,91	61,46
I4-1-X	53,08	8,58	33,17	31,60	71,00	52,81	11,36	27,95	30,17	67,89
I4-2-X	52,04	8,15	32,35	37,65	73,22	50,90	11,15	26,81	29,03	67,41
I4-3-X	63,33	7,65	26,72	36,45	75,78	48,71	12,03	28,03	30,50	66,78
I4-4-X	65,71	8,99	36,97	26,37	66,21	55,34	8,17	20,21	21,80	67,98
I4-5-X	61,72	9,14	32,65	28,42	72,80	50,64	12,26	29,53	31,98	67,46
I5-1-X	61,02	7,34	30,07	31,19	75,98	51,46	12,00	30,02	32,33	68,22
I5-2-X	62,27	9,19	28,42	31,36	75,16	57,89	6,60	19,30	20,40	71,12
I5-3-X	64,87	9,99	29,99	31,05	74,05	49,88	12,01	27,70	30,19	66,56
I5-4-X	64,78	8,83	32,52	31,92	73,37	49,57	12,42	28,38	30,98	66,37
I5-5-X	60,29	8,68	32,42	31,44	74,99	48,96	12,85	26,84	29,76	64,42
I0-1-X	52,37	9,28	23,84	27,61	66,16	45,90	12,58	25,36	28,31	63,62
I0-2-X	61,48	11,61	31,84	31,73	66,68	45,61	12,77	25,81	28,80	63,68
I0-3-X	64,15	7,68	34,53	28,48	66,64	55,66	10,61	32,31	34,01	71,82
I0-4-X	54,44	8,62	26,34	26,92	73,35	56,33	10,78	33,09	34,81	73,96
I0-5-X	64,49	8,62	28,95	30,15	71,13	58,55	7,37	21,90	23,11	71,39
M1-1-X	67,36	9,63	22,87	22,29	62,32	61,33	######	18,93	21,67	60,84
M1-2-X	68,88	11,17	22,49	22,41	64,52	66,75	5,55	21,62	22,32	75,61
M1-3-X	71,17	10,40	16,77	21,49	64,58	56,96	11,16	19,97	22,88	60,80
M1-4-X	66,27	10,16	18,08	23,06	63,98	57,62	11,89	19,09	22,49	58,08
M1-5-X	67,43	10,36	20,25	23,99	63,79	61,25	9,94	22,74	24,81	66,39
M2-1-X	66,91	10,57	20,21	22,02	64,19	69,12	4,79	21,26	21,79	77,29
M2-2-X	67,99	9,64	19,83	22,93	66,23	59,13	8,93	18,57	20,60	64,31
M2-3-X	68,43	9,89	19,39	23,84	66,07	57,56	11,36	19,74	22,77	60,09
M2-4-X	67,27	10,61	20,11	23,37	62,75	56,32	10,94	19,21	22,10	60,34
M2-5-X	70,06	9,59	20,69	23,74	62,63	64,15	9,90	18,84	21,28	62,28
M3-1-X	71,24	11,57	20,33	22,10	62,04	62,88	9,31	19,00	21,16	63,90
M3-2-X	69,42	11,62	21,17	24,55	65,59	59,35	10,31	18,44	21,12	60,79
M3-3-X	64,84	9,57	21,46	22,24	63,40	58,95	11,04	19,70	22,58	60,74
M3-4-X	67,69	10,42	19,91	24,78	56,82	61,91	10,46	19,66	22,27	61,98
M3-5-X	71,95	9,81	20,50	23,65	61,72	62,87	8,50	20,37	22,07	67,35
M4-1-X	61,50	10,34	21,36	23,49	59,94	58,13	11,41	19,55	22,64	59,73
M4-2-X	63,41	12,49	22,03	23,04	65,63	61,81	9,60	18,97	21,26	63,15
M4-3-X	68,12	11,04	19,64	23,79	63,02	63,34	9,10	18,54	20,65	63,87
M4-4-X	68,50	10,72	20,58	23,24	65,85	60,55	9,39	17,91	20,22	62,33
M4-5-X	61,64	11,41	20,34	23,50	61,85	60,80	11,29	19,79	22,78	60,29
M5-1-X	63,37	10,71	21,12	23,10	64,61	60,37	11,06	19,39	22,33	60,30

M5-2-X	64,83	9,66	19,80	21,79	64,37	54,45	10,61	22,82	25,17	65,07
M5-3-X	66,33	9,74	20,84	23,35	63,37	58,02	11,28	19,92	22,89	60,47
M5-4-X	64,86	10,00	20,71	23,08	62,46	65,28	8,30	20,58	22,19	68,04
M5-5-X	66,00	9,52	21,77	23,72	62,63	63,43	9,40	21,42	23,39	66,30
M0-1-X	63,36	9,88	21,53	21,68	62,20	57,86	10,94	19,71	22,54	60,95
M0-2-X	68,87	8,15	20,18	22,27	61,82	58,93	11,32	21,27	24,09	61,98
M0-3-X	68,28	8,84	20,97	24,37	64,87	67,31	4,93	21,88	22,43	77,30
M0-4-X	68,57	8,56	19,08	23,44	64,05	60,89	10,79	20,17	22,88	61,85
M0-5-X	64,80	10,10	19,59	23,37	61,47	60,57	10,41	18,75	21,45	60,96
F1-1-X	86,59	4,74	23,51	15,79	74,59	67,36	8,61	32,25	33,38	75,05
F1-2-X	81,65	4,77	17,73	23,17	73,72	68,07	8,18	35,55	36,48	77,05
F1-3-X	77,54	3,39	21,81	17,32	73,32	70,79	7,49	27,50	28,51	74,77
F1-4-X	79,20	6,42	26,49	21,41	73,34	62,09	12,35	37,40	39,39	71,73
F1-5-X	89,51	5,14	21,79	18,81	73,51	68,30	9,06	30,94	32,24	73,68
F2-1-X	85,79	5,52	20,09	20,56	74,14	66,34	8,67	29,98	31,21	73,86
F2-2-X	85,65	5,76	20,19	20,82	74,44	67,54	8,66	33,98	35,07	75,71
F2-3-X	85,09	5,57	21,00	21,07	75,05	67,07	7,37	26,12	27,14	74,24
F2-4-X	85,27	5,57	20,11	20,45	75,55	68,07	8,08	28,70	29,81	74,28
F2-5-X	84,75	5,74	19,99	20,20	74,21	67,64	8,27	29,07	30,23	74,11
F3-1-X	84,78	5,63	18,21	21,49	74,57	71,69	7,60	33,04	33,90	77,05
F3-2-X	84,44	5,59	19,20	20,00	74,14	67,24	7,65	28,12	29,14	74,79
F3-3-X	84,55	5,31	18,51	19,59	74,28	69,97	8,18	33,94	34,94	76,45
F3-4-X	84,20	5,66	19,82	20,39	74,65	73,15	7,42	31,86	32,72	76,89
F3-5-X	84,70	5,40	19,81	20,51	74,77	70,67	8,96	37,54	38,59	76,58
F4-1-X	82,87	6,10	22,07	20,09	73,56	69,30	7,62	35,15	35,97	77,77
F4-2-X	80,84	5,54	20,44	21,32	75,36	69,08	8,54	33,49	34,56	75,69
F4-3-X	82,75	5,73	18,59	21,46	74,12	69,98	7,42	31,84	32,69	76,89
F4-4-X	82,90	6,02	21,31	19,72	73,01	71,15	7,42	27,19	28,19	74,73
F4-5-X	85,64	5,83	21,06	20,15	74,39	75,09	7,40	34,79	35,57	78,00
F5-1-X	83,63	5,39	23,64	20,71	75,11	70,37	9,51	39,43	40,56	76,44
F5-2-X	80,59	5,85	20,60	21,31	75,08	59,88	10,95	31,96	33,79	71,09
F5-3-X	79,04	5,90	23,88	22,23	73,98	68,63	8,22	28,61	29,77	73,97
F5-4-X	72,66	6,47	21,17	21,06	73,49	68,82	8,30	34,89	35,86	76,61
F5-5-X	84,82	5,76	21,16	22,33	74,88	70,72	10,21	38,81	40,13	75,26
F0-1-X	78,90	5,53	20,06	23,04	73,33	69,79	7,61	34,34	35,18	77,50
F0-2-X	82,24	6,81	21,23	22,04	73,88	68,95	8,26	33,86	34,85	76,29
F0-3-X	83,14	6,21	19,09	24,01	73,09	65,52	8,67	34,25	35,33	75,79
F0-4-X	74,27	5,98	23,54	22,24	73,41	70,45	7,70	35,07	35,91	77,61
F0-5-X	86,64	7,35	18,39	23,70	75,32	66,52	8,27	34,05	35,39	75,69
P1-1-X	77,15	10,55	22,47	28,62	68,39	76,31	8,21	24,95	26,27	71,78
P1-2-X	78,96	9,10	22,67	22,90	65,69	68,33	10,18	33,82	35,32	73,25
P1-3-X	77,58	9,38	25,22	23,64	68,87	65,28	11,48	37,07	38,81	72,79
P1-4-X	77,78	10,17	19,78	28,90	69,91	64,19	10,83	35,35	36,97	72,97
P1-5-X	77,17	8,21	21,74	25,97	67,55	64,79	8,79	29,35	30,63	73,38
P2-1-X	79,97	8,25	25,08	26,88	69,48	63,22	12,63	37,92	39,96	71,58
P2-2-X	79,32	9,15	20,43	26,21	71,06	58,06	11,80	33,39	35,41	70,53

P2-3-X	80,46	8,69	23,68	25,91	70,61	57,95	14,89	37,44	40,29	68,31
P2-4-X	70,76	9,56	25,16	25,80	70,84	62,16	9,63	29,69	31,21	72,04
P2-5-X	74,87	8,76	22,99	24,04	71,52	63,31	11,16	35,08	36,82	72,35
P3-1-X	74,95	9,53	25,95	27,64	78,46	59,40	11,83	32,26	34,36	69,87
P3-2-X	79,12	8,07	24,25	25,56	79,61	63,69	10,80	32,99	34,71	71,87
P3-3-X	76,79	8,04	23,39	24,74	73,81	62,54	9,92	31,07	32,62	72,29
P3-4-X	79,61	8,05	22,15	23,56	78,18	64,72	12,13	37,91	39,80	72,26
P3-5-X	78,91	8,23	20,80	22,37	79,84	52,69	16,69	36,73	40,34	65,56
P4-1-X	79,96	8,69	22,33	22,98	67,25	65,42	11,39	34,44	36,27	71,70
P4-2-X	78,05	7,54	21,75	17,20	69,73	62,61	11,82	34,25	36,23	70,96
P4-3-X	78,64	8,24	22,45	27,30	69,20	67,23	8,67	29,54	30,79	73,65
P4-4-X	79,31	9,32	22,42	9,72	69,34	64,15	10,08	33,89	35,35	73,44
P4-5-X	78,56	8,69	21,49	15,45	68,22	69,52	8,83	30,94	32,18	74,07
P5-1-X	79,96	8,69	22,33	22,98	67,25	64,82	9,15	34,69	35,88	75,22
P5-2-X	78,05	7,54	21,75	17,20	69,73	63,18	11,00	35,36	37,03	72,02
P5-3-X	78,64	8,24	22,45	27,30	69,20	63,62	9,92	33,25	34,70	73,39
P5-4-X	79,31	9,32	22,42	9,72	69,34	61,68	11,06	32,03	33,88	70,95
P5-5-X	78,56	8,69	21,49	15,45	68,22	56,77	14,96	36,91	39,82	67,94
P0-1-X	73,90	7,56	24,97	26,09	73,16	59,72	11,72	35,05	36,96	71,50
P0-2-X	71,43	7,83	27,27	23,38	73,99	69,41	8,48	32,98	34,05	75,58
P0-3-X	80,90	8,21	22,52	23,97	69,97	60,85	11,21	36,87	38,53	73,09
P0-4-X	79,45	8,72	22,55	24,18	68,85	65,65	10,53	35,51	37,04	73,49
P0-5-X	64,27	12,55	31,49	33,90	68,28	70,49	7,42	26,72	27,73	74,48

Table 7: Xenon samples roughness measurements

SampleID	InitialL	Initiala	Initialb	Initialc	Initialh	FinalL	Finala	Finalb	Finalc	Finalh
I1-1-X	61,20	8,91	33,04	33,18	76,19	55,36	7,43	19,03	20,43	68,68
I1-2-X	64,07	8,21	32,72	32,11	72,55	50,21	11,10	26,89	29,09	67,56
I1-3-X	60,47	7,37	30,32	32,68	71,93	58,60	8,74	25,60	27,05	71,15
I1-4-X	58,00	14,07	33,46	32,24	72,96	59,61	6,10	18,37	19,36	71,63
I1-5-X	55,18	10,20	29,89	33,02	74,59	60,33	6,83	22,36	23,38	73,01
I2-1-X	57,37	13,55	34,95	30,79	78,90	50,12	11,62	27,65	29,99	67,21
I2-2-X	48,80	7,33	27,69	34,12	70,53	62,26	6,72	21,27	22,30	72,47
I2-3-X	43,34	9,05	33,86	32,80	75,13	46,87	12,63	27,55	30,31	65,38
I2-4-X	54,92	10,35	31,73	32,20	79,66	56,83	7,11	20,39	21,60	70,78
I2-5-X	59,95	6,69	30,86	29,61	79,92	50,34	12,16	29,76	32,15	67,77
I3-1-X	56,52	9,21	30,69	29,90	74,25	57,04	7,38	20,97	22,23	70,61
I3-2-X	57,36	8,80	26,77	32,11	75,04	56,67	8,49	22,61	24,15	69,43
I3-3-X	61,11	10,97	26,99	30,87	68,70	53,92	11,15	26,56	28,80	67,23
I3-4-X	63,76	7,81	29,82	30,71	73,32	46,18	13,38	28,48	31,47	64,84
I3-5-X	49,04	9,91	28,20	30,11	70,26	44,80	13,34	24,52	27,91	61,46
I4-1-X	53,08	8,58	33,17	31,60	71,00	52,81	11,36	27,95	30,17	67,89
I4-2-X	52,04	8,15	32,35	37,65	73,22	50,90	11,15	26,81	29,03	67,41
I4-3-X	63,33	7,65	26,72	36,45	75,78	48,71	12,03	28,03	30,50	66,78

I4-4-X	65,71	8,99	36,97	26,37	66,21	55,34	8,17	20,21	21,80	67,98
I4-5-X	61,72	9,14	32,65	28,42	72,80	50,64	12,26	29,53	31,98	67,46
I5-1-X	61,02	7,34	30,07	31,19	75,98	51,46	12,00	30,02	32,33	68,22
I5-2-X	62,27	9,19	28,42	31,36	75,16	57,89	6,60	19,30	20,40	71,12
I5-3-X	64,87	9,99	29,99	31,05	74,05	49,88	12,01	27,70	30,19	66,56
I5-4-X	64,78	8,83	32,52	31,92	73,37	49,57	12,42	28,38	30,98	66,37
I5-5-X	60,29	8,68	32,42	31,44	74,99	48,96	12,85	26,84	29,76	64,42
I0-1-X	52,37	9,28	23,84	27,61	66,16	45,90	12,58	25,36	28,31	63,62
I0-2-X	61,48	11,61	31,84	31,73	66,68	45,61	12,77	25,81	28,80	63,68
I0-3-X	64,15	7,68	34,53	28,48	66,64	55,66	10,61	32,31	34,01	71,82
I0-4-X	54,44	8,62	26,34	26,92	73,35	56,33	10,78	33,09	34,81	73,96
I0-5-X	64,49	8,62	28,95	30,15	71,13	58,55	7,37	21,90	23,11	71,39
M1-1-X	67,36	9,63	22,87	22,29	62,32	61,33	######	18,93	21,67	60,84
M1-2-X	68,88	11,17	22,49	22,41	64,52	66,75	5,55	21,62	22,32	75,61
M1-3-X	71,17	10,40	16,77	21,49	64,58	56,96	11,16	19,97	22,88	60,80
M1-4-X	66,27	10,16	18,08	23,06	63,98	57,62	11,89	19,09	22,49	58,08
M1-5-X	67,43	10,36	20,25	23,99	63,79	61,25	9,94	22,74	24,81	66,39
M2-1-X	66,91	10,57	20,21	22,02	64,19	69,12	4,79	21,26	21,79	77,29
M2-2-X	67,99	9,64	19,83	22,93	66,23	59,13	8,93	18,57	20,60	64,31
M2-3-X	68,43	9,89	19,39	23,84	66,07	57,56	11,36	19,74	22,77	60,09
M2-4-X	67,27	10,61	20,11	23,37	62,75	56,32	10,94	19,21	22,10	60,34
M2-5-X	70,06	9,59	20,69	23,74	62,63	64,15	9,90	18,84	21,28	62,28
M3-1-X	71,24	11,57	20,33	22,10	62,04	62,88	9,31	19,00	21,16	63,90
M3-2-X	69,42	11,62	21,17	24,55	65,59	59,35	10,31	18,44	21,12	60,79
M3-3-X	64,84	9,57	21,46	22,24	63,40	58,95	11,04	19,70	22,58	60,74
M3-4-X	67,69	10,42	19,91	24,78	56,82	61,91	10,46	19,66	22,27	61,98
M3-5-X	71,95	9,81	20,50	23,65	61,72	62,87	8,50	20,37	22,07	67,35
M4-1-X	61,50	10,34	21,36	23,49	59,94	58,13	11,41	19,55	22,64	59,73
M4-2-X	63,41	12,49	22,03	23,04	65,63	61,81	9,60	18,97	21,26	63,15
M4-3-X	68,12	11,04	19,64	23,79	63,02	63,34	9,10	18,54	20,65	63,87
M4-4-X	68,50	10,72	20,58	23,24	65,85	60,55	9,39	17,91	20,22	62,33
M4-5-X	61,64	11,41	20,34	23,50	61,85	60,80	11,29	19,79	22,78	60,29
M5-1-X	63,37	10,71	21,12	23,10	64,61	60,37	11,06	19,39	22,33	60,30
M5-2-X	64,83	9,66	19,80	21,79	64,37	54,45	10,61	22,82	25,17	65,07
M5-3-X	66,33	9,74	20,84	23,35	63,37	58,02	11,28	19,92	22,89	60,47
M5-4-X	64,86	10,00	20,71	23,08	62,46	65,28	8,30	20,58	22,19	68,04
M5-5-X	66,00	9,52	21,77	23,72	62,63	63,43	9,40	21,42	23,39	66,30
M0-1-X	63,36	9,88	21,53	21,68	62,20	57,86	10,94	19,71	22,54	60,95
M0-2-X	68,87	8,15	20,18	22,27	61,82	58,93	11,32	21,27	24,09	61,98
M0-3-X	68,28	8,84	20,97	24,37	64,87	67,31	4,93	21,88	22,43	77,30
M0-4-X	68,57	8,56	19,08	23,44	64,05	60,89	10,79	20,17	22,88	61,85
M0-5-X	64,80	10,10	19,59	23,37	61,47	60,57	10,41	18,75	21,45	60,96
F1-1-X	86,59	4,74	23,51	15,79	74,59	67,36	8,61	32,25	33,38	75,05
F1-2-X	81,65	4,77	17,73	23,17	73,72	68,07	8,18	35,55	36,48	77,05
F1-3-X	77,54	3,39	21,81	17,32	73,32	70,79	7,49	27,50	28,51	74,77
F1-4-X	79,20	6,42	26,49	21,41	73,34	62,09	12,35	37,40	39,39	71,73

F1-5-X	89,51	5,14	21,79	18,81	73,51	68,30	9,06	30,94	32,24	73,68
F2-1-X	85,79	5,52	20,09	20,56	74,14	66,34	8,67	29,98	31,21	73,86
F2-2-X	85,65	5,76	20,19	20,82	74,44	67,54	8,66	33,98	35,07	75,71
F2-3-X	85,09	5,57	21,00	21,07	75,05	67,07	7,37	26,12	27,14	74,24
F2-4-X	85,27	5,57	20,11	20,45	75,55	68,07	8,08	28,70	29,81	74,28
F2-5-X	84,75	5,74	19,99	20,20	74,21	67,64	8,27	29,07	30,23	74,11
F3-1-X	84,78	5,63	18,21	21,49	74,57	71,69	7,60	33,04	33,90	77,05
F3-2-X	84,44	5,59	19,20	20,00	74,14	67,24	7,65	28,12	29,14	74,79
F3-3-X	84,55	5,31	18,51	19,59	74,28	69,97	8,18	33,94	34,94	76,45
F3-4-X	84,20	5,66	19,82	20,39	74,65	73,15	7,42	31,86	32,72	76,89
F3-5-X	84,70	5,40	19,81	20,51	74,77	70,67	8,96	37,54	38,59	76,58
F4-1-X	82,87	6,10	22,07	20,09	73,56	69,30	7,62	35,15	35,97	77,77
F4-2-X	80,84	5,54	20,44	21,32	75,36	69,08	8,54	33,49	34,56	75,69
F4-3-X	82,75	5,73	18,59	21,46	74,12	69,98	7,42	31,84	32,69	76,89
F4-4-X	82,90	6,02	21,31	19,72	73,01	71,15	7,42	27,19	28,19	74,73
F4-5-X	85,64	5,83	21,06	20,15	74,39	75,09	7,40	34,79	35,57	78,00
F5-1-X	83,63	5,39	23,64	20,71	75,11	70,37	9,51	39,43	40,56	76,44
F5-2-X	80,59	5,85	20,60	21,31	75,08	59,88	10,95	31,96	33,79	71,09
F5-3-X	79,04	5,90	23,88	22,23	73,98	68,63	8,22	28,61	29,77	73,97
F5-4-X	72,66	6,47	21,17	21,06	73,49	68,82	8,30	34,89	35,86	76,61
F5-5-X	84,82	5,76	21,16	22,33	74,88	70,72	10,21	38,81	40,13	75,26
F0-1-X	78,90	5,53	20,06	23,04	73,33	69,79	7,61	34,34	35,18	77,50
F0-2-X	82,24	6,81	21,23	22,04	73,88	68,95	8,26	33,86	34,85	76,29
F0-3-X	83,14	6,21	19,09	24,01	73,09	65,52	8,67	34,25	35,33	75,79
F0-4-X	74,27	5,98	23,54	22,24	73,41	70,45	7,70	35,07	35,91	77,61
F0-5-X	86,64	7,35	18,39	23,70	75,32	66,52	8,27	34,05	35,39	75,69
P1-1-X	77,15	10,55	22,47	28,62	68,39	76,31	8,21	24,95	26,27	71,78
P1-2-X	78,96	9,10	22,67	22,90	65,69	68,33	10,18	33,82	35,32	73,25
P1-3-X	77,58	9,38	25,22	23,64	68,87	65,28	11,48	37,07	38,81	72,79
P1-4-X	77,78	10,17	19,78	28,90	69,91	64,19	10,83	35,35	36,97	72,97
P1-5-X	77,17	8,21	21,74	25,97	67,55	64,79	8,79	29,35	30,63	73,38
P2-1-X	79,97	8,25	25,08	26,88	69,48	63,22	12,63	37,92	39,96	71,58
P2-2-X	79,32	9,15	20,43	26,21	71,06	58,06	11,80	33,39	35,41	70,53
P2-3-X	80,46	8,69	23,68	25,91	70,61	57,95	14,89	37,44	40,29	68,31
P2-4-X	70,76	9,56	25,16	25,80	70,84	62,16	9,63	29,69	31,21	72,04
P2-5-X	74,87	8,76	22,99	24,04	71,52	63,31	11,16	35,08	36,82	72,35
P3-1-X	74,95	9,53	25,95	27,64	78,46	59,40	11,83	32,26	34,36	69,87
P3-2-X	79,12	8,07	24,25	25,56	79,61	63,69	10,80	32,99	34,71	71,87
P3-3-X	76,79	8,04	23,39	24,74	73,81	62,54	9,92	31,07	32,62	72,29
P3-4-X	79,61	8,05	22,15	23,56	78,18	64,72	12,13	37,91	39,80	72,26
P3-5-X	78,91	8,23	20,80	22,37	79,84	52,69	16,69	36,73	40,34	65,56
P4-1-X	79,96	8,69	22,33	22,98	67,25	65,42	11,39	34,44	36,27	71,70
P4-2-X	78,05	7,54	21,75	17,20	69,73	62,61	11,82	34,25	36,23	70,96
P4-3-X	78,64	8,24	22,45	27,30	69,20	67,23	8,67	29,54	30,79	73,65
P4-4-X	79,31	9,32	22,42	9,72	69,34	64,15	10,08	33,89	35,35	73,44
P4-5-X	78,56	8,69	21,49	15,45	68,22	69,52	8,83	30,94	32,18	74,07

P5-1-X	79,96	8,69	22,33	22,98	67,25	64,82	9,15	34,69	35,88	75,22
P5-2-X	78,05	7,54	21,75	17,20	69,73	63,18	11,00	35,36	37,03	72,02
P5-3-X	78,64	8,24	22,45	27,30	69,20	63,62	9,92	33,25	34,70	73,39
P5-4-X	79,31	9,32	22,42	9,72	69,34	61,68	11,06	32,03	33,88	70,95
P5-5-X	78,56	8,69	21,49	15,45	68,22	56,77	14,96	36,91	39,82	67,94
P0-1-X	73,90	7,56	24,97	26,09	73,16	59,72	11,72	35,05	36,96	71,50
P0-2-X	71,43	7,83	27,27	23,38	73,99	69,41	8,48	32,98	34,05	75,58
P0-3-X	80,90	8,21	22,52	23,97	69,97	60,85	11,21	36,87	38,53	73,09
P0-4-X	79,45	8,72	22,55	24,18	68,85	65,65	10,53	35,51	37,04	73,49
P0-5-X	64,27	12,55	31,49	33,90	68,28	70,49	7,42	26,72	27,73	74,48

Table 8: Normality Tests for Initial Wood Dimensions

Tests of Normality						
	Kolmogorov-Smirnova			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
INITIAL LONGITUDINAL LENGTH	0,091	240	<,001	0,941	240	<,001
INITIAL RADIAL LENGTH	0,339	240	<,001	0,2	240	<,001
INITIAL TANGENTIAL LENGTH	0,072	240	0,004	0,991	240	0,156
a Lilliefors Significance Correction						

Table 9: Normality Test Results for Initial Weight of Different Wood Types

Tests of Normality							
	WOOD TYPE	Kolmogorov-Smirnova			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
INITIAL WEIGHT	Iroko	0,162	60	<,001	0,901	60	<,001
	Meranti	0,171	60	<,001	0,916	60	<,001
	Fir	0,244	60	<,001	0,662	60	<,001
	Pine	0,107	60	0,087	0,936	60	0,004
a Lilliefors Significance Correction							

Table 10: Normality Test Results for Weight Difference Over Time

Tests of Normality							
	WOOD TYPE	Kolmogorov-Smirnova			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Weight Difference % 2h	Iroko	0,145	60	0,003	0,943	60	0,008
	Meranti	0,138	60	0,006	0,937	60	0,004
	Fir	0,151	60	0,002	0,879	60	<,001
	Pine	0,156	60	<,001	0,891	60	<,001
Weight Difference % 4h	Iroko	0,135	60	0,008	0,93	60	0,002
	Meranti	0,199	60	<,001	0,881	60	<,001
	Fir	0,089	60	,200*	0,958	60	0,04
	Pine	0,145	60	0,003	0,91	60	<,001
Weight Difference % 8h	Iroko	0,124	60	0,023	0,963	60	0,066
	Meranti	0,183	60	<,001	0,884	60	<,001
	Fir	0,081	60	,200*	0,947	60	0,012
	Pine	0,127	60	0,018	0,912	60	<,001
Weight Difference % 24h	Iroko	0,074	60	,200*	0,974	60	0,219
	Meranti	0,212	60	<,001	0,877	60	<,001
	Fir	0,125	60	0,021	0,947	60	0,012
	Pine	0,097	60	,200*	0,912	60	<,001
* This is a lower bound of the true significance.							
a Lilliefors Significance Correction							

Table 11: Kruskal-Wallis Test Results for Initial Weight and Weight Differences Over Time

Test Statistics					
	INITIAL WEIGHT	Weight2h	Weight4h	Weight8h	Weight24h
Kruskal-Wallis H	184,889	179,61	175,21	176,224	175,398
df	3	3	3	3	3
Asymp. Sig.	<,001	<,001	<,001	<,001	<,001
a Kruskal Wallis Test					
b Grouping Variable: WOOD TYPE					

Table 12: Pairwise Comparisons of Wood Types Based on Weight Differences Over Time Using the Mann-Whitney U Test

Test Statisticsa					
	INITIAL WEIGHT	Weight2h	Weight4h	Weight8h	Weight24h
Mann-Whitney U	0	0	0	0	0
Wilcoxon W	1830	1830	1830	1830	1830
Z	-9,448	-9,448	-9,448	-9,448	-9,448
Asymp. Sig. (2-tailed)	<,001	<,001	<,001	<,001	<,001
Mann-Whitney U	67	185	251	188	124
Wilcoxon W	1897	2015	2081	2018	1954
Z	-9,096	-8,477	-8,13	-8,461	-8,797
Asymp. Sig. (2-tailed)	<,001	<,001	<,001	<,001	<,001
Mann-Whitney U	104	402	404	397	180
Wilcoxon W	1934	2232	2234	2227	2010
Z	-8,902	-7,338	-7,327	-7,364	-8,503
Asymp. Sig. (2-tailed)	<,001	<,001	<,001	<,001	<,001
Mann-Whitney U	686	5	44	55	166
Wilcoxon W	2516	1835	1874	1885	1996
Z	-5,847	-9,422	-9,217	-9,159	-8,577
Asymp. Sig. (2-tailed)	<,001	<,001	<,001	<,001	<,001
Mann-Whitney U	116	58	64	87	268
Wilcoxon W	1946	1888	1894	1917	2098

Z	-8,839	-9,143	-9,112	-8,991	-8,041
Asymp. Sig. (2-tailed)	<,001	<,001	<,001	<,001	<,001
Mann-Whitney U	556,5	1602	1746	1757	1570
Wilcoxon W	2386,5	3432	3576	3587	3400
Z	-6,527	-1,039	-0,283	-0,226	-1,207
Asymp. Sig. (2-tailed)	<,001	0,299	0,777	0,821	0,227

Table 13: Kruskal-Wallis Test Results for Dimensional Changes Across Wood Types

Test Statisticsa,b							
	INITIAL LONGITUDINAL LENGTH	INITIAL RADIAL LENGTH	INITIAL TANGENTIAL LENGTH	Longitudinal2h	Radial 2h	Tangendial2H	Longitudinal4h
Kruskal-Wallis H	34,784	55,484	61,341	29,709	88,185	93,984	41,837
df	3	3	3	3	3	3	3
Asymp. Sig.	<,001	<,001	<,001	<,001	<,001	<,001	<,001
a Kruskal Wallis Test							
b Grouping Variable: WOOD TYPE							