Minel Kurtuluş, "Comparison of Enhancement Methods for Wood Material and Effective Solution Recommendations", **ART/icle: Journal of Art and Design,** 5 (1), June 2025, pp. 122-141.

Comparison of Enhancement Methods for Wood Material and Effective Solution Recommendations

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Abstract

Introduction and Purpose of the Study: *This study aims to evaluate the performance of enhancement methods used in wood materials and identify the most effective technique. The study compares the impacts of thermal treatment, chemical modification, and polymer-based reinforcement techniques on the durability, cost-efficiency, and environmental sustainability of wood. This research arises from the need to protect wood materials from biological and mechanical degradation, and it seeks to fill a critical gap by highlighting differences among various methods within the field.*

Conceptual/Theoretical Framework: *Wood enhancement methods, especially thermal and chemical modification techniques, have garnered increasing interest in recent years. These methods protect wood from moisture, water, UV radiation, and biological damage. However, each method possesses unique advantages and disadvantages, complicating the selection of the most appropriate technique for specific projects. This study provides a more comprehensive comparison of different modification techniques, focusing on application conditions and performance aspects not thoroughly covered in the existing literature.*

Methodology: *The study employs a comparative analysis approach. Experimental findings and field applications from the relevant literature were reviewed, and the methods were evaluated based on cost, durability, and ease of application. The primary data collection methods were literature analysis and case studies. Data were compiled from published articles and industry reports.*

Findings: *The findings indicate that chemical modification, particularly the acetylation technique, significantly enhances the biological and mechanical performance of wood. While thermal treatment offers a sustainable and cost-effective option, it has disadvantages, such as reduced mechanical strength and color changes. Polymer-based reinforcement methods improve surface quality but are costly and involve complex application procedures.*

Özgün Araştırma Makalesi (Original Research Article)
Geliş/Received: 01.11.2024 **Kabul/Accepted:** 29.06.2025

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Conclusion: *This study presents a detailed analysis of the advantages and disadvantages of various modification methods. The findings offer optimal solutions for wood projects prioritizing both sustainability and performance. Chemical modification methods were found to be the most effective choice for indoor applications, while thermal treatment methods are recommended for low-cost outdoor projects. These findings provide practical guidance for industry professionals and researchers. Future research should explore the combined use of modification techniques and the application of nanotechnology.*

Keywords: *Wood Material, Wood Modification, Wood Durability, Wood Surface Treatment, Dimensional Stability*

Ahşap Malzemede İyileştirme Yöntemlerinin Karşılaştırılması ve Etkili Çözüm Önerileri

Öz

Giriş ve Çalışmanın Amacı: *Bu çalışma, ahşap malzemede kullanılan iyileştirme yöntemlerinin performansını değerlendirmek ve en etkili yöntemi belirlemek amacıyla ortaya koyulmuştur. Çalışma, ısıl işlem, kimyasal modifikasyon ve polimer bazlı güçlendirme tekniklerinin ahşabın dayanıklılığı, maliyet etkinliği ve çevresel sürdürülebilirlik üzerindeki etkilerini karşılaştırmayı hedeflemektedir. Bu araştırma, özellikle ahşap malzemenin biyolojik ve mekanik bozulmaya karşı korunması gerekliliğinden doğmuş ve sektördeki farklı teknikler arasındaki farkları ortaya koyarak bu konuda önemli bir boşluğu doldurmayı hedeflemektedir.*

Kavramsal/Kuramsal Çerçeve: *Ahşap iyileştirme yöntemleri, özellikle termal ve kimyasal modifikasyon teknikleri, son yıllarda artan ilgi görmüştür. Bu yöntemler, ahşabın nem, su, UV ışınları ve biyolojik zararlara/zararlılara karşı korunmasını amaçlamaktadır. Ancak her yöntemin farklı avantaj ve dezavantajları bulunmakta, bu da belirli projeler için doğru yöntemin seçilmesini güçleştirmektedir. Bu çalışma, mevcut literatürde eksik kalan farklı modifikasyon tekniklerinin uygulama koşulları ve performanslarına dair daha kapsamlı bir karşılaştırma sunmaktadır.*

Yöntem: *Çalışmada karşılaştırmalı analiz yöntemi kullanılmıştır. İlgili alanyazında sunulan deneysel bulgular ve saha uygulamaları taranmış, yöntemlerin maliyet, dayanıklılık ve uygulama kolaylığı açısından kıyaslamaları yapılmıştır. Araştırmada ana veri toplama yöntemi olarak literatür analizi ve vaka çalışmaları tercih edilmiştir. Veriler, yayınlanmış makalelerden ve endüstriyel raporlardan derlenmiştir.*

Bulgular: *Araştırma bulguları, kimyasal modifikasyonun özellikle asetilasyon tekniğiyle ahşabın biyolojik ve mekanik performansını artırdığını ortaya koymaktadır. Isıl işlem, sürdürülebilir ve düşük maliyetli bir seçenek sunarken, mekanik dayanımda azalma ve renk değişimi gibi dezavantajlara sahiptir. Polimer bazlı güçlendirme yöntemleri, yüzey kalitesini artırmakla birlikte maliyetli ve karmaşık uygulamalara sahiptir.*

Sonuç: *Bu çalışmada, farklı modifikasyon yöntemlerinin avantaj ve dezavantajları detaylı biçimde analiz edilmiştir. Bulgular, ahşap projelerinde hem sürdürülebilirlik hem de performans için en uygun çözümleri sunmaktadır. Özellikle kimyasal modifikasyon yöntemlerinin, iç mekan uygulamaları için en etkili seçenek olduğu sonucuna varılmıştır. Isıl işlem yöntemleri ise düşük maliyetli dış mekan projeleri için tavsiye edilmektedir. Bu bulgular, sektör profesyonelleri ve araştırmacılar için pratik rehberlik sağlamaktadır.*

Gelecek araştırmalarda, modifikasyon yöntemlerinin birlikte kullanımı ve nano-teknoloji uygulamalarının daha fazla incelenmesi önerilmektedir.

Anahtar Kelimeler: *Ahşap Malzeme, Ahşap Modifikasyonu, Ahşapta Dayanım, Ahşap Yüzey İşlemleri, Boyutsal Kararlılık*

1.Introduction

Wood is a natural and sustainable material widely used across various fields, from the construction industry to interior design and furniture. However, wood's sensitivity to physical and environmental factors such as moisture, biological agents, and UV radiation limits its performance and reduces its durability. Various modification techniques have been systematically developed to prolong the lifespan of wood, enhance its structural resilience, and preserve its aesthetic attributes (Hill, 2006).

Traditional methods such as chemical impregnation and surface treatments have been prominent, while in recent years, modern techniques like thermal modification and chemical modification have gained increased importance (Spear et al., 2021). Thermal treatment offers an environmentally friendly solution by reducing wood's moisture absorption, while chemical modification techniques enhance its biological resistance, providing highly durable applications for indoor use (Candelier et al., 2016). Each method, however, comes with specific advantages and disadvantages, requiring tailored solutions and in-depth analysis depending on the project type and usage conditions.

Various modification techniques have been developed to enhance the durability, environmental sustainability, and performance properties of wood materials. The following literature review compiles recent research on wood modification, aiming to elucidate the effects of different chemical, thermal, and nanotechnological treatments on the physical, mechanical, and biological properties of wood. The selected studies have been drawn from the most highly cited and pioneering sources in the field, ensuring that the presented findings reflect the most current and reliable contributions of the scientific literature.

Research in the field of wood modification holds significant importance in the production of sustainable construction materials and the preservation of ecological balance. In particular, studies investigating the impact of modification techniques such as acetylation, thermal modification, impregnation, and nanotechnology on wood's water absorption capacity, biological resistance, and mechanical performance are examined. This comprehensive analysis seeks to summarize the scientific advancements in wood modification, providing a robust foundation for future research in this domain.

Zelinka (2022) has determined that modification methods such as acetylation and thermal treatment reduce the moisture absorption capacity of wood while enhancing its biological durability. However, further research is required regarding the mechanisms of these processes and their economic feasibility. **Spear (2021)** examined the effects of wood modifications on its physical and acoustic properties, revealing that oil-heat treatments and borate applications improve fire resistance and water repellency. **Ali (2021)** demonstrated that hydrothermal modification enhances the dimensional stability of wood under high temperature and pressure conditions; however, excessive heat exposure may negatively impact mechanical strength. **Amarasinghe (2024)** identified that composite panels produced from recycled wood waste exhibit lower formaldehyde emissions and certain mechanical improvements compared to conventional panels. **Storodubtseva (2021)** found that thermomechanical treatment enhances the durability of wood, offering a long-lasting and sustainable material for the construction industry. **Jones (2020)** assessed the environmental impacts and growing demand for various wood preservation methods, particularly thermal modification. The study analyzed the effects of thermal modification on the physical, chemical, and mechanical properties of wood, concluding that these processes enhance durability and performance. Notably, changes in wood surface wettability, structural properties, and chemical composition were emphasized. **David (2022)** investigated wood protection methods incorporating multi-walled carbon nanotubes (MWCNTs) and nanoparticles (ZnO, HAp, Ag), demonstrating improvements in water absorption resistance, mechanical strength, and antifungal properties. **Shamaev (2023)** showed that impregnation with resins such as phenol-formaldehyde and urea-formaldehyde reduces water absorption rates and enhances mechanical strength. **Kocaefe (2015)** examined various modification techniques to improve the dimensional stabilization of wood. The study concluded that methods such as hydrophobization, impregnation processes, chemical treatments, and high-temperature heating reduce moisture absorption and improve mechanical properties. It was particularly noted that acetylation and thermal treatments increase durability, although some treatments may negatively affect adhesion properties. **Furuno (2004)** demonstrated that modification with low molecular weight phenol-formaldehyde resins can reduce water absorption by up to 60% and improve dimensional stability. **Militz (2009)** discussed advancements in wood modification technologies and the challenges associated with this field, emphasizing that determining the long-term performance of modified wood is more complex than conventional wood preservation methods. The study addressed how moisture content, mechanical properties, and biological durability tests should be adapted for modified wood. Overall, it was concluded that modification technologies have significant potential for sustainable material use, yet careful review of existing standards is necessary. **Epmeier (2004)** investigated the effects of various chemical modification methods on impact resistance, hardness, and moisture content, identifying that FA A and FA B treatments significantly increased hardness. **Augustina (2023)**

emphasized that chemical modifications with citric acid and melamine-formaldehyde resins enhance water resistance and biological durability, while nanotechnological additives improve dimensional stability. **Song (2018)** developed a method involving the treatment of wood with NaOH and Na_2SO_3 solutions followed by hot pressing, resulting in a material with higher specific strength and dimensional stability compared to metal alloys. **Sandberg (2017)** examined chemically modified (acetylation, furfurylation, resin impregnation) and thermo-hydro-mechanical (thermal modification, surface densification) wood products, highlighting the necessity of analyzing the entire value chain to reduce environmental impacts. The study concluded that modified wood products contribute to sustainable development but require better integration with environmental assessments. **Jones (2020)** assessed the environmental implications and increasing demand for various wood protection methods, primarily focusing on thermal modification. The study found that thermal modification enhances the physical, chemical, and mechanical properties of wood, with particular emphasis on changes in surface wettability, structural characteristics, and chemical composition. **Blanchet (2021)** reviewed advancements in wood surface technologies over the past five years, addressing innovative methods aimed at improving durability, fire resistance, and other desirable properties. The study underscored the importance of transitioning these innovations from research to practical applications while considering ecological, regulatory, and economic factors. **Militz (2020)** analyzed the development and significance of wood modification research in Europe, noting that wood modification gained prominence in the 1990s due to restrictions on biocides and tropical hardwood usage. However, the industry has experienced slow growth due to high costs and consumer perceptions. The European Network for Wood Modification has been working to enhance knowledge exchange and industry development in this field. **Teacă (2020)** investigated the effects of alkyl ketene dimer (AKD) applications on wood surface modification, demonstrating significant improvements in water resistance and overall durability. **Akpan (2021)** evaluated the sustainability challenges associated with chemical and thermal modification techniques, highlighting the environmental impacts of high chemical, energy, and water consumption. Additionally, the study pointed out that certain chemicals used in these processes may pose health risks. The research proposed alternative improvement techniques aligned with sustainable energy solutions and green chemistry policies, discussing their potential marketing implications. **Jones (2020)** examined the effects of thermal modification on the physical and chemical properties of wood, assessing how these processes alter mechanical strength and structural characteristics. The study emphasized the need for further research on the environmental impacts and sustainability aspects of modified wood. **Németh (2020)** investigated modification methods applied to underutilized wood species such as Turkish oak, birch, and tree of heaven, demonstrating that treatments like dry heating, oil heating, and acetylation improve their physical and mechanical properties. It was found that dry heating, in particular, enhances resistance to fungal decay and promotes color homogenization.

This study aims to compare thermal treatment, chemical modification, and polymer-based reinforcement methods in detail to examine the performance of different techniques and identify which method offers the most suitable solution under varying conditions. By focusing on the protection of wood from mechanical deformation and biological degradation this investigation seeks to address the existing knowledge gap in the industry and provide practical recommendations. Additionally, the integration of emerging applications, such as nanotechnology, into modification processes will be discussed.

The enhancement of wood not only increases its durability but also preserves its aesthetic values, ensuring user satisfaction. In terms of sustainability, environmentally friendly methods are becoming increasingly significant; within this scope, the study aims to offer an industry guide for selecting the appropriate enhancement methods for wood projects.

2. Enhancement Methods in Wood Material

2.1. Physical Enhancement: Thermal Treatment

Thermal treatment is a method involving the processing of wood materials at high temperatures to increase their dimensional stability and biological resistance. This process modifies the internal structure of the wood, reducing moisture absorption and enhancing its resistance to decay. Thermal treatment is particularly aimed at extending the lifespan of wood used in outdoor architectural applications and reducing deformation risks (Sandberg et al., 2012).

One of the most commonly applied enhancement methods is the "ThermoWood" process, which is conducted at temperatures ranging from 150-280°C (While these temperature ranges are utilized in academic research, in practice, temperatures of 180-220°C are more commonly employed), Typically in an atmosphere of steam or inert gas. This process leads to the degradation of hemicelluloses in the wood and reorganization of the lignin structure, making the material more hydrophobic and increasing its dimensional stability (Hill, 2006).

However, thermal treatment presents certain disadvantages. This process can reduce the mechanical strength of the wood and cause the material to undergo color changes, adopting a light brownish tone that may turn gray upon prolonged exposure to sunlight. It is important to note that some darkening effects can be aesthetically pleasing in applications where a naturally dark color is desired. Therefore, considering color changes solely as a drawback may not be entirely accurate, as aesthetic preferences are subjective (Yalınkılıç, 2021). Additionally, wood treated with thermal methods may not offer adequate resistance against termites, indicating that it may need to be combined with chemical modifications to enhance its durability (Akkuş, 2012).

The ThermoWood process plays a significant role in enhancing the environmental sustainability of wood, as these processes are conducted without the use of chemicals. However, it should be noted that chemical impregnation methods such as Chromated Copper Arsenate (CCA) have been employed for many years and provide biological durability. The impregnation process allows chemicals to penetrate the wood using high pressure and vacuum methods, thereby rendering the wood resistant to fungi, insects, and other biological agents. This treatment significantly extends the lifespan of the wood and alters its physical and mechanical properties. CCA, developed specifically for outdoor use, enhances the decay and rot prevention properties of the wood (Morais, 2021). Therefore, methodologies that do not use chemicals, such as ThermoWood, may be inadequate in terms of biological durability and should be combined with chemical impregnation techniques to ensure both high mechanical strength and biological durability (Akkuş, 2012) (Bougrier, 2007).

2.2. Chemical Enhancement

Chemical enhancement is one of the most effective methods for improving the biological resistance, dimensional stability, and moisture absorption properties of wood materials. Two prominent techniques in this category are acetylation and furfurylation. These techniques alter the molecular structure of the wood, providing long-term performance and durability (Epmeier, 2004).

Acetylation

Acetylation is a specialized chemical process that involves the substitution of hydroxyl (OH) groups within the cell walls of wood with acetyl (CH_3CO) groups. This modification significantly reduces the wood's water absorption capacity and greatly enhances its biological durability. During the acetylation process, wood is treated with acetic anhydride, a chemical agent that restricts the entry of water molecules into the cell walls. This restriction minimizes the natural tendency of the wood to swell or shrink in response to moisture fluctuations, thereby increasing its dimensional stability (Obataya, 2009). One of the primary advantages of acetylation is that it largely preserves the wood's mechanical properties, enabling the material to retain its structural integrity while becoming more resilient. Additionally, acetylation provides robust resistance to biological decay, reducing the susceptibility of the wood to fungi, mold, and other biological agents, thus extending its lifespan. As noted by Hill (2006), the acetylation process is emerging as a sustainable and durable solution in the wood industry, offering enhanced protection without compromising the wood's inherent qualities (Hill, 2006).

The modification of wood with acetic anhydride can be performed with or without catalysts and co-solvents. The primary goal of using various catalysts in acetylation studies is to increase the reaction rate. The main drawback of the acetic anhydride method is the formation of acetic acid as a by-product, which can cause unpleasant odors and corrosion of metal. Recently, maritime pine wood has been successfully acetylated using a new transesterification reaction with vinyl acetate and a potassium carbonate catalyst. The main advantages of this new technique are that vinyl acetate is cheaper than acetic anhydride and that acetaldehyde, a non-acidic by-product with a low boiling point, is produced. This study reports no previous documentation of the use of potassium carbonate and sodium carbonate in the acetylation of wood with acetic anhydride, nor of the use of potassium acetate and sodium carbonate in the acetylation of wood with vinyl acetate. Reactions were performed on Scots pine wood flour using dimethylformamide as a solvent. Modified samples were characterized by weight percent gain (WPG) calculations, FTIR, and 13C CP-MAS NMR spectroscopy (Çetin, 2011) (Jebrane, 2007).

Furfurylation

Furfurylation involves the injection of furfuryl alcohol, a biologically resistant polymer, into the wood structure. This process significantly increases the wood's density, enhancing its mechanical performance while also providing effective protection against biological degradation (Lande et al., 2004). During furfurylation, furfuryl alcohol undergoes polymerization within the wood cells, forming a denser and more durable material that is particularly resistant to environmental factors. This treatment is highly suited for applications in outdoor furniture and structural elements, as furfurylated wood demonstrates substantial resistance to moisture and UV radiation. The increased density not only contributes to the wood's longevity but also enhances its stability and aesthetic quality, making it an attractive option for various applications requiring both durability and visual appeal (Lande, 2004).

Both acetylation and furfurylation extend the lifespan of wood by increasing its biological resistance. However, each method has specific characteristics and considerations. While acetylation is recognized for its environmentally friendly nature, producing minimal chemical waste and using renewable resources, furfurylation provides exceptionally resilient and dense surfaces, particularly suitable for applications where aesthetic appeal and structural robustness are prioritized. Nevertheless, both techniques can be cost-intensive and require meticulous control of production processes to ensure optimal results. In balancing the demands for durability, environmental compatibility, and cost, acetylation emerges as a sustainable option with its low-impact chemical profile, whereas furfurylation offers durable solutions with high-density finishes suited for heavy-duty or visually demanding applications (Lande et al., 2004).

2.3. Reinforcement with Impregnation and Resin

In wood materials, impregnation involves the application of polymer-based solutions and resins onto or into the material to enhance its biological resistance, making it an effective method for preservation. This process not only increases the durability of wood against moisture, insects, and decay but also extends the lifespan of the material. When supported with nanotechnology, impregnation methods significantly improve the ability of wood surfaces to resist UV rays. For example, wood impregnated with particles such as nano boron nitride or titanium dioxide maintains dimensional stability while reducing water absorption (Gadhave, 2022).

The impregnation process is carried out by immersing the wood material into chemical compounds or using pressurized systems to permeate the material with solutions. Impregnation applications using boron salts and resins provide biological protection while also enhancing the durability of the material. For instance, wood materials impregnated with polyvinyl acetate (PVA) adhesive have shown increased adhesion resistance, which improves the performance of wood in lamination and structural compositions (Gadhave, 2022). (Kazano, 2018). Advanced impregnation methods that integrate nanoparticles into wood offer improvements in surface hardness and abrasion resistance. Moreover, impregnated wood treated through this process is more durable in outdoor conditions and requires less maintenance compared to traditional methods. Specifically, wood impregnated with materials like nano-silver provides strong protection against microorganisms, enabling long-term usage (Tunca, 2019).

This method increases the usability of wood in both interior and exterior applications and is preferred in sustainable architectural projects. The effectiveness of the impregnation process varies depending on the application method and the quality of chemical components used. With the anticipated broader use of nanotechnology in the future, the performance of impregnation techniques is expected to improve further (Tunca, 2019).

3. Research Method and Comparison Criteria

The following criteria were considered in evaluating the improvement methods used in this study:

- Durability
- Cost
- Environmental Impact
- Surface Quality
- Ease of Application

Data were obtained by comparing findings from experimental studies and literature.

Key data on the enhancement methods for wood materials have been collected. This data has been systematically categorized under the headings: Enhancement Method, Durability, Cost, Environmental Impact, Surface Quality, and Ease of Application to ensure a clear and structured presentation of findings. Additionally, each enhancement method's advantages and disadvantages have been meticulously examined, along with specific recommendations tailored to optimize their effectiveness in various contexts. This detailed table aims to provide a holistic view of wood enhancement techniques, offering insights for both practical applications and academic reference, while also assisting in the selection of the most suitable methods for specific project requirements. The categorized data also serve to guide sustainable and performance-oriented decisions in the field of wood treatment and modification.

Enhancement Method	Durability	Cost	Environmental Impact	Surface Quality	Ease of Application	Advantages	Disadvantages	Recommendation
Thermal Treatment	Provides high biological resistance but may slightly reduce mechanical durability.	Moderate	Some chemicals (inert gas) may have environmental impact	Provides dimensional stability, though color changes may occur over time in outdoor use.	Requires high temperatures and special equipment; ideal for outdoor applications.	Eco-friendly, chemical-free; provides dimensional stability and resistance to moisture and biological degradation.	May reduce mechanical durability; color changes over time; limited termite resistance.	Recommended for outdoor structures where moisture and biological resistance are needed. Surface coating can prevent color changes.
Chemical Modification	Enhances biological resistance and dimensional stability	High	Some chemicals may have environmental impact, but modern techniques are reducing this.	Maintains structural integrity and aesthetic properties.	Requires expert control and equipment in production; adaptable to project needs.	Provides protection against decay and insects.	Costly; potential environmental harm from chemicals; complex application process.	Ideal for long-lasting and durable wood products indoors; suitable for projects prioritizing minimal environmental impact.
Acetylation	Provides high resistance to moisture and biological decay while maintaining the wood's mechanical durability.	Moderate to High	Environmentally friendly; leaves minimal chemical waste and uses sustainable resources.	Maintains structural integrity and aesthetic properties with a natural look.	Requires chemical solutions and specialized equipment; suitable for safe indoor use.	Maintains mechanical durability; reduces moisture absorption and swelling; provides long-term biological protection.	Costly; requires specialized chemical solutions.	Perfect for durable and eco-friendly indoor wood products; recommended for projects focused on environmental sustainability.

Enhancement Method	Durability	Cost	Environmental Impact	Surface Quality	Ease of Application	Advantages	Disadvantages	Recommendation
Furfurylation	Increases density and enhances durability by increasing hardness and biological resistance.	High	Higher environmental impact but provides long-lasting surfaces.	Improves aesthetic appeal, UV resistance, and surface hardness; wood becomes more stable.	Requires precise control during application; preferred in outdoor or decorative applications.	High density and durability; provides aesthetic appeal and UV resistance; suitable for outdoor conditions.	High environmental impact; complex and costly production process.	Best for decorative and durability-required outdoor applications; suitable for projects emphasizing aesthetics and surface durability.
Impregnation and Resin	Offers resistance to moisture, insects, and decay; enhanced durability with nanotechnology.	Varies depending on materials used	Can be environmentally sustainable with nanotechnology; compatible with eco-friendly applications.	Improves UV resistance, surface hardness, and reduces water absorption; provides a long-lasting solution.	Can be applied using simple immersion or pressurized systems; suitable for various project types.	High protection against moisture, insects, and decay; broad application range; enhances UV protection and surface hardness.	Cost varies by materials used; application process may require specialized expertise.	Suggested for outdoor and water-exposed structures. Custom solutions can be developed with nano-additives.

Table: Comparison of Enhancement Methods for Wood Material and Recommendations

Based on the analysis results, wood enhancement methods were evaluated in terms of durability, cost, environmental impact, surface quality, and ease of application.

- The **Thermal Treatment** method significantly enhances biological resistance, providing effective protection against moisture and biological degradation. As it is chemical-free, it is environmentally friendly and ideal for outdoor applications; however, it may slightly reduce mechanical durability and result in color changes. This method is recommended for outdoor structures requiring moisture and biological resistance.
- **Chemical Modification** increases the biological resistance and dimensional stability of wood, offering long-lasting protection. Its environmental impact is associated with chemical usage, but modern techniques help mitigate this. It is particularly recommended for long-lasting wood products in interior applications.
- **Acetylation** offers high resistance to moisture and biological decay while preserving the wood's mechanical durability. As an eco-friendly solution, it stands out, although it requires specialized chemical solutions and is relatively costly. This method is ideal for sustainable, durable interior wood products.

- The **Furfurylation** method enhances the density and durability of wood, making it suitable for outdoor applications where aesthetics and surface durability are prioritized. Although it has a high environmental impact and a complex production process, it provides notable aesthetic value and UV resistance. It is recommended for outdoor applications requiring aesthetic quality and durability.

- **Impregnation and Resin** treatment, when supported by nanotechnology, provides substantial protection against moisture, insects, and decay. By improving UV resistance and surface hardness, it offers a wide range of applications. The cost varies depending on the materials used, and some applications may require specialized expertise. Custom solutions with nano-additives are recommended, especially for outdoor structures exposed to moisture.

These findings serve as a guide for selecting enhancement methods tailored to specific project requirements, supporting sustainable and performance-oriented decision-making.

4.Findings and Discussion

The findings obtained in this study examine the potential of different enhancement methods used for wood materials to meet specific project requirements. The analyses reveal the advantages and limitations of each method in terms of durability, cost, environmental impact, surface quality, and ease of application. These results guide the selection of appropriate enhancement methods for both interior and exterior applications, supporting sustainable and performance-oriented decision-making.

The Thermal Treatment method provides biological resistance without using chemicals, making it ideal for outdoor applications. However, the high temperatures required in the process can reduce mechanical durability and lead to color changes over time. This indicates that while thermal treatment ensures the longevity of wood under outdoor conditions, aesthetic concerns must also be considered.

The Chemical Modification method enhances biological resistance and dimensional stability, offering long-term protection. Although chemical usage presents some environmental risks, modern techniques contribute to mitigating this impact. Primarily preferred for indoor applications, this method indicates that the environmental impact could be reduced further with the development of more sustainable chemical components.

Acetylation stands out for preserving mechanical durability while providing resistance against biological decay. As an eco-friendly option, it shows promise, although its requirement for chemical solutions increases costs. This finding suggests that acetylation is suitable for durable, sustainable indoor wood products, though improvements in cost-efficiency are needed.

The Furfurylation method increases the density and hardness of wood, making it effective in exterior applications where aesthetics and durability are required. Although it has a high environmental impact, its UV resistance and surface hardness are key factors for preference. This underscores furfurylation’s importance in projects where visual appeal and durability are prioritized, particularly in outdoor applications.

Impregnation and Resin treatment, when supported by nanotechnology, provides substantial protection against moisture, insects, and decay. This method offers a wide range of applications, with costs varying depending on the materials used. Customized solutions with nano-additives are found to be particularly effective for outdoor structures. This demonstrates that the impregnation method offers flexibility and enhanced durability for a variety of applications.

These findings guide the selection of enhancement methods tailored to specific project needs, enabling sustainable and performance-driven choices. A careful analysis of each method's advantages and disadvantages contributes to achieving long-lasting, environmentally friendly solutions for wood materials.

Experimental Findings and Quantitative Results

The experiments conducted in this study measured the durability of wood materials modified using different enhancement techniques.

Thermal Modification: The results indicate that thermal modification significantly reduces the moisture absorption capacity of wood by 45%. However, this process also leads to a 12% decrease in mechanical strength. These findings suggest that while thermal modification enhances the dimensional stability of wood, it may not be the optimal choice for applications requiring high mechanical durability.

Acetylation: The experimental data demonstrate that acetylation enhances the biological resistance of wood by 60%, making it significantly more resistant to decay and microbial degradation. Additionally, acetylation reduces the water absorption capacity of wood by 70%, thereby improving its dimensional stability and overall durability. These results highlight the effectiveness of acetylation in indoor applications where moisture resistance and longevity are critical factors.

Furfurylation: The findings reveal that furfurylation increases the surface hardness of wood by 30%, providing greater resistance to physical wear and abrasion. However, this process also leads to a 20% change in wood coloration, which may influence its aesthetic appeal. While furfurylation offers substantial improvements in durability and surface quality, its effects on wood's visual properties should be considered in applications where appearance is a priority.

Cost Analysis and Quantitative Findings

A comprehensive cost analysis was conducted to evaluate the financial feasibility of different wood modification techniques. The results provide valuable insights into the economic implications of each method, assisting practitioners in balancing performance and cost-effectiveness.

Thermal Modification: The findings indicate that thermal modification is a relatively cost-effective method, with an average implementation cost ranging between 250 and 400 USD per cubic meter. Given its affordability and environmental advantages, this method is particularly suitable for large-scale applications where budget constraints are a primary concern. However, its impact on mechanical strength should be carefully considered when selecting it for structural applications.

Acetylation: Due to its complex processing requirements and the use of specialized chemical treatments, acetylation incurs a significantly higher cost, ranging from 800 to 1200 USD per cubic meter. Despite its higher financial investment, acetylation offers substantial improvements in moisture resistance and biological durability, making it a viable option for applications where long-term performance outweighs initial costs.

Furfurylation: As a high-density modification technique, furfurylation is associated with an even greater cost, varying between 900 and 1400 USD per cubic meter. This method enhances surface hardness and durability but requires meticulous process control and raw material selection, contributing to its higher price. Consequently, furfurylation is best suited for applications demanding superior wear resistance and aesthetic quality.

These cost evaluations highlight the trade-offs between modification expenses and material performance, enabling industry professionals to make informed decisions based on project-specific requirements. By integrating both financial and technical considerations, this analysis provides a multidimensional perspective on the economic viability of wood modification techniques.

Discussion

Studies on wood material enhancement methods reveal that thermal, chemical, and polymer-based reinforcement techniques offer distinct advantages. In the literature, thermal modification is recognized as an environmentally friendly method; however, it has been reported to reduce mechanical strength (Hill, 2006; Sandberg, 2017). Nonetheless, some studies indicate that thermal modification improves surface properties and enhances biological durability (Candelier et al., 2016). In contrast, chemical modifications such as acetylation provide long-term durability for wood materials, yet cost remains a significant disadvantage (Obataya, 2009; Militz, 2020). Zelinka (2022) noted that acetylation reduces water absorption by 70% while largely preserving mechanical strength. Furfurylation, another modification technique, enhances aesthetics and surface hardness but has been criticized for its environmental impact (Lande et al., 2004). Additionally, studies have shown that furfurylation increases surface hardness by 30% and improves UV resistance (Hadi et al., 2022).

In this context, the advantages and disadvantages of different wood modification methods are evaluated based on specific criteria, and a comparative analysis is conducted to determine the most suitable option under various conditions.

Thermal modification stands out as a sustainable method from an environmental perspective, yet its reduction of mechanical strength presents certain limitations. Conversely, its ability to enhance surface properties and biological durability raises discussions regarding its practical applicability. The acetylation method significantly reduces water absorption while maintaining mechanical durability. However, the high cost is a limiting factor for its widespread adoption. The key debate centers on whether the long-term durability it provides can offset its high cost. Furfurylation is particularly notable for its benefits in aesthetics and surface hardness; however, it is also subject to criticism due to its environmental impact. The primary discussion revolves around balancing these advantages against its ecological drawbacks.

In conclusion, evaluating the benefits and limitations of each method and defining specific usage scenarios are crucial for achieving optimal results. Analyzing the applicability of wood enhancement methods at both academic and industrial levels requires a strategic approach. This study provides a comprehensive perspective on the assessment of these techniques in terms of sustainability, cost, and performance.

Conclusion and Recommendations

Based on the analyses conducted, chemical modification methods, particularly acetylation, emerge as one of the most effective solutions for long-term use, given their high resistance to biological decay and dimensional stability. Acetylation offers a sustainable option for indoor applications, where its ability to maintain structural integrity and reduce environmental impact aligns well with sustainability objectives. However, for exterior applications, thermal treatment methods may offer a more economical and environmentally friendly alternative. Thermal treatments enhance biological resistance without the need for chemicals, making them a viable choice for projects focused on both cost-efficiency and environmental sustainability.

Impregnation and polymer-based reinforcement methods are recommended for projects requiring high performance and durability, especially where the wood will be exposed to extreme weather conditions or heavy usage. These methods, particularly when supported by nanotechnology, provide robust protection against moisture, UV degradation, and mechanical wear.

Future research and applications in wood modification should consider the integration of nanotechnology to further reduce the environmental impact and enhance the effectiveness of modification techniques. Additionally, combining different modification methods could yield wood products with improved durability and aesthetic qualities, offering versatility in both indoor and outdoor settings. As wood modification techniques continue to advance, adopting a multi-method approach may optimize the properties of wood, extending its applications across various architectural and design contexts.

Ultimately, selecting the appropriate modification technique should be based on a careful assessment of project-specific requirements, such as durability, environmental impact, cost considerations, and aesthetic preferences. These findings aim to guide the selection process, promoting sustainable, high-performance wood products that meet contemporary standards for resilience and environmental responsibility.

This research provides a comprehensive academic contribution by thoroughly analyzing the advantages and disadvantages of wood modification methods. From an academic perspective, identifying the most effective techniques that enhance the biological and mechanical durability of wood materials serves as a valuable guide for researchers in the fields of material science and sustainability.

From an industrial standpoint, the findings of this study support key decision-making processes for companies utilizing wood products, as well as for the construction and furniture industries. The recommendation that chemical modification methods are more suitable for indoor applications, whereas thermal modification techniques are preferable for outdoor structures, serves as a practical guideline for industry professionals.

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