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Article

Development and Application of a Sustainability Indicator (WPSI) for Wood Preservative Treatments in Chile

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Abstract

This study presents the Wood Protection Sustainability Index (WPSI), a novel decision-support tool aimed at evaluating wood preservatives utilized in Chile and facilitating a shift toward more sustainable wood protection practices. WPSI encompasses four essential attributes: protection treatment, wood durability, in-service risk, and sustainability. These are assessed under two distinct scenarios. Scenario 1 represents current market practices, where chromated copper arsenate (CCA) remains prevalent due to its accessibility and affordable cost. In contrast, Scenario 2 prioritizes sustainability, demonstrating that copper azole (CA) and alkaline copper quaternary (ACQ) surpass CCA in performance, with CCA ranking lowest due to its environmental implications. Furthermore, a SWOT analysis accompanies the index, identifying key challenges and opportunities within Chile's wood preservation industry. The findings highlight the importance of aligning national strategies with Environmental, Social, and Governance (ESG) frameworks, as well as the Sustainable Development Goals (SDGs), through performance-based regulations and safer alternatives. The WPSI can be integrated with local standards, regional risk classifications, and national preservative approval systems, allowing for meaningful comparison across diverse global contexts. This approach promotes more sustainable construction practices while ensuring both technical and economic viability.

Keywords: chromated copper arsenate; copper azole; ESG criteria; preservative regulations; SDGs integration; sustainability; wood preservatives

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1. Introduction

The growing global commitment to achieving climate neutrality, as evidenced by agreements such as the Paris Agreement and the European Green Deal, has intensified pressure on nations to reduce emissions and enhance the sustainability of their construction sectors. While these frameworks set important benchmarks, it is crucial to translate their implications into actionable strategies at the national level. In Chile, the construction sector ranks among the seven most significant economic activities, contributing 7% to the country's GDP and providing 8.5% of national employment. However, the local productivity growth rate within this sector falls short of the average observed in countries belonging to the Organization for Economic Cooperation and Development (OECD) [1]. Additionally, the construction sector is responsible for 33% of the country's energy consumption and contributes 30% to the generation of greenhouse gases [1]. As a member of the UN, Chile also committed to the Paris Agreement in 2015, pledging to reduce GHG emissions and enhance resilience to climate change. Further, Chile endorsed the 2030 Agenda for Sustainable Development to reach carbon neutrality by 2052, which is being pursued through enacting the Framework Law on Climate Change. This context underscores the urgent need for Chile to adopt materials and strategies that align with climate goals and improve efficiency. Wood is a key renewable material with a lower carbon footprint than concrete or steel [2–5], making it a vital component in sustainable construction. However, to ensure its long-term performance, especially under demanding service conditions, wood must be adequately protected against biotic and abiotic degradation agents [6,7]. In Chile, a considerable portion of construction-grade timber is derived from *Pinus radiata* species [8]. This wood is characterized by its low natural durability and is classified as non-durable (Table A4). Consequently, it necessitates treatment to meet the service risk standards specified in NCh819:2019 [9].

To fully realize the advantages of wood as a sustainable building material, it is essential to provide adequate protection. Products such as primers, non-film or stain formers, varnishes, and paints address esthetic and protective requirements but offer limited long-term durability for the wood substrate. Their effectiveness may diminish without the incorporation of reliable biocides and organic coatings [10]. These protective products are widely used on wood components; some enhance resistance to solar radiation, fluctuations in humidity, chemical and mechanical stresses, and the proliferation of harmful organisms, such as fungi, while maintaining the wood's esthetic appeal [11]. In this context, surface protectants must be replaced regularly to ensure continued effectiveness [12–14]. Moreover, when timber or wood elements are in service, the material is affected by the weather. Weathered wood is highly susceptible to degradation, leading to increased damage and a decline in its structural stability and performance. Abiotic agents, including temperature, sunlight, wind, and rain, can cause wood to crack and erode its surface layer. Conversely, biotic factors involve living organisms that attack wood, such as chromogenic fungi, which can alter its color without impacting its mechanical properties. However, this change in appearance may signal the presence of rot fungi, resulting in the progressive deterioration of the wood's qualities over time. Such degradation creates conditions that attract xylophagous insects, which can feed on damp and dry wood, including species like subterranean termites. This deterioration can result in premature failure, pose safety risks, and lead to inefficient resource utilization.

In Chile, the preservative industry has an estimated overall capacity of 1,000,000 cubic meters of treated wood, distributed among approximately 200 processing plants. According to a timber biocide supplier, the allocation of the treated wood by sector is as follows: 50% is designated for construction, 37% for agricultural poles, 5% for remanufacturing, 6% for transmission poles, and 2% for plywood. Currently, the usage distribution of preservatives is as follows: 73% consists of copper chrome arsenate (CCA), 23% is light organic solvent preservative (LOSP), and 4% is micronized copper (μCA-C). Notably, 80% of the LOSP produced is exported. This situation emphasizes a critical challenge: how can the Chilean wood preservation industry transition to more sustainable practices without compromising technical performance and economic viability? A significant obstacle is the absence of a standardized framework for comparative evaluation that takes into account both performance and sustainability factors. It is essential to identify which preservatives and protective treatments should be adopted, as well as those that are currently being utilized [13,15].

Despite global restrictions on its use in residential and public applications [16–18], chromated copper arsenate (CCA) remains widely accessible and cost-effective in the

Chilean market. In contrast, adopting more sustainable alternatives, such as copper azole (CA), alkaline copper quaternary (ACQ), and wood modification techniques, has been limited due to a lack of policy incentives and perceptions of high costs. This reality presents a broader challenge: how to steer the Chilean wood protection industry toward sustainability while ensuring that solutions remain both technically and economically viable. In this study, sustainability is defined as the ability to achieve lasting protection results (effectiveness) while optimizing resource use and minimizing environmental impacts (efficiency), following the approach proposed by Schalock et al. [19]. The Environmental, Social, and Governance (ESG) framework offers a broader perspective for evaluating the performance and responsibility of products or industries beyond just economic returns. It emphasizes factors such as emissions reduction, user health and safety, and regulatory compliance. Closely aligned with ESG principles are Sustainable Development Goals (SDGs), a set of 17 global objectives established by the United Nations to promote a fairer and more sustainable future. In this context, incorporating ESG and SDG considerations into the Wood Protection Sustainability Index (WPSI) enhances its relevance as a decision-support tool. This integration captures not only the technical performance of wood protection but also addresses the evolving social and environmental expectations placed on the industry.

Analyzing ESG criteria reveals that wood preservation represents a significant opportunity to enhance sustainability, resulting in more appealing and environmentally friendly investments. The transition toward environmentally safe wood preservatives has substantial economic, social, and environmental implications. It is crucial to opt for safer chemical or bio-based products to safeguard the health and safety of workers and the broader community, thereby emphasizing our social responsibility. There are distinct differences in the application of chemical preservatives, which must undergo stringent testing to validate their effectiveness. In contrast, environmentally friendly bio-based products can be utilized with greater freedom. However, these alternatives often diminish effectiveness over time, leaving structural components vulnerable to degradation. This lack of protection can lead to potential collapse or cause chemical and biological leaching, which lessens their effectiveness and adversely impacts the environment [20–22].

In our previous work [23], we analyzed how several modern wood preservatives and modification technologies conceptually align with ESG and SDG principles. A summary of this analysis is presented in Table 1. Notably, SDGs 3 (health and well-being), 6 (clean water and sanitation), 8 (decent work and economic growth), 12 (responsible consumption and production), 13 (climate action), 16 (peace, justice, and strong institutions), and 17 (need for partnerships) highlight the urgency of transitioning to safer and more sustainable technologies. The study was restricted to qualitative mapping and failed to establish a standardized framework for comparative evaluation. Chile can advance by implementing a plan to phase out CCA used in construction while providing incentives for bio-based or copper micronized systems, which could enhance sustainability branding and access to higher-value timber markets. The current research builds up this foundation by introducing a novel and quantitative tool to evaluate and rank wood preservative systems.

Table 1. Linking wood preservative strategies to ESG criteria and targeted SDGs (adapted from [23]).

Preservative Strategy	ESG Dimension	SDG Supported	Impact Explanation
Use of low-leaching formulations	Environmental	SDG 6	Reduces contamination of groundwater and surrounding ecosystems
Extension of wood service life	Environmental	SDGs 12 and 13	Reduces the frequency of replacement and lowers carbon and material footprints

Table 1. *Cont.*

Preservative Strategy	ESG Dimension	SDG Supported	Impact Explanation
Use of bio-based or less toxic compounds	Environmental/Social	SDGs 3 and 12	Minimizes worker exposure and consumer health risks; supports circular economy
Transparent product labeling and certifications	Governance	SDGs 16 and 17	Improves trust, facilitates compliance, and fosters stakeholder collaboration
Support for local treatment facilities and training	Social/Governance	SDG 8	Enhances decent employment and promotes inclusive industry development

The Organizational Effectiveness and Efficiency Scale (OEES), developed by the International Consortium on Evidence-Based Practices and published by Schalock et al. in 2015 [19], was selected as the conceptual framework for this study due to its direct applicability to performance evaluation on the growing needs of the wood preservative industry and the timber construction sector. The OEES is particularly pertinent in this context, as it defines sustainability as the intersection of three organizational attributes: (i) Effectiveness, referring to the achievement of long-term protection outcomes; (ii) Efficiency, understood as the optimal use of resources to avoid premature wood degradation or restoration; and (iii) Adaptability, defined as the capacity to respond to changing environmental, technical, and regulatory conditions. This structured and pragmatic interpretation of sustainability is particularly well-suited to the Chilean wood preservative industry, which faces growing pressures to improve environmental performance while maintaining economic viability. This integration is visually summarized in Figure 1, which guides the rationale for the development of the WPSI under ESG and SDG criteria.

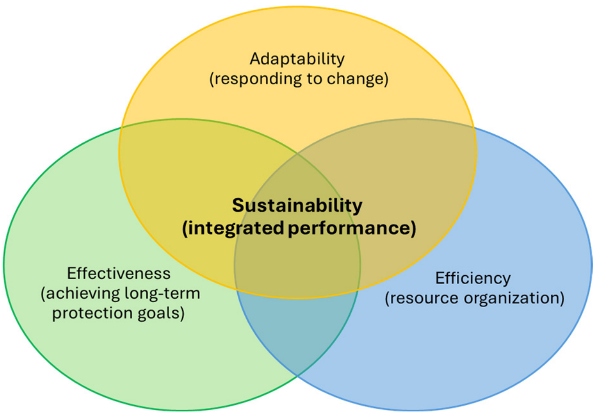

Figure 1. Conceptual model of sustainability with the integration of effectiveness, efficiency, and adaptability (adapted from [19]).

At present, there is no comprehensive or standardized framework for comparing wood preservative systems based on sustainability, performance, and efficiency metrics. This gap hinders stakeholders from making informed decisions that align with ESG criteria. The absence of a standardized evaluation method for preservative systems complicates the decision-making process, particularly in light of growing market pressures related to ESG compliance and the necessity to adhere to international best practices. To address this challenge, this study presents the Wood Protection Sustainability Index (WPSI), an innovative decision-support tool designed to evaluate and compare wood preservatives. This index takes into account various factors mandated by current regulations, including the durability of different wood species and the appropriate protective measures based on the risks they will encounter during service. Moreover, it highlights the importance of utilizing products and processes that minimize environmental impact, thereby prioritizing sustainability. The WPSI serves as a quantitative tool that facilitates the comparison of protection systems assessed under consistent criteria, producing WPSI values that can be ranked according to market demands and expectations, all while ensuring alignment with national and international governance standards. In this context, sustainability stands out as a crucial differentiating factor. The WPSI is dedicated to promoting the use of wood and highlighting its structural, technical, and sustainability advantages. In particular, this research aimed to assess and compare the sustainability of registered wood preservative treatments by applying the WPSI across two distinct scenarios. The objective was to rank the wood preservation systems available in Chile and identify those most aligned with evolving standards of ESG, as well as the SDGs. This process involved analyzing the technical performance, environmental and social impacts, governance practices, and associated costs of each preservative system. Through this comprehensive evaluation, the study aimed to provide substantial evidence to support informed decision-making in selecting wood protection systems that align with sustainable construction standards.

2. Materials and Methods

2.1. Developing a Wood Protection Sustainability Index (WPSI)

In our previous study, we analyzed the wood preservation regulations of seven countries, including Chile, highlighting the importance of knowing the biocides currently in use and the regulations adopted to comply with the standards established by the regulatory agencies [23]. Here, we developed a ranking of preservatives and protection systems in Chile by constructing a Wood Protection Sustainability Index (WPSI) under two decision-making scenarios using the analytic hierarchy process established by Saaty [24].

The ranking was designed to distinguish between wood preservative products and in-service risk conditions to recommend the most appropriate solution. The WPSI integrated four core attributes: (1) protection treatment (PT), including biocides already registered and used in Chile and chemical modification techniques with high potential for adoption; (2) wood durability (WD), as defined by the national standard NCh789:2023 [25] for species such as *Pinus radiata*; (3) in-service risk (RS), referring to the exposure level defined by NCh819:2019 [9] use classes; and (4) sustainability (S), which integrates efficiency and effectiveness, as reported by the companies and according to Schalock et al. [19]. The development of the tool used in this study was based on criteria defined by previous researchers [26–28], with slight modifications to fulfill Chilean standards. Each attribute was scored using a Likert scale from 1 (low) to 5 (high), based on our previous studies [29–31]. The relative weight of each attribute was adjusted across two scenarios to reflect different strategic priorities, as appears in Table 2.

Table 2. Classification of wood protection on the Likert scale according to the attributes Protection Treatment (PT), In-Service Risk (RS), Wood Durability (WD), and Sustainability (S).

Attribute	Level [1]	Description	Likert Scale [2]
Protection Treatment (PT)	Low	Wood protection is achieved by design-based protection, enveloping and surface treatments, and anti-stain baths.	1
	Moderate	Application of preservative impregnation for various levels of in-service risk, including chemical modification treatments.	3
	High	Cumulative combinations of the above solutions, incorporating sustainability into the approach.	5

Table 2. *Cont.*

Attribute	Level [1]	Description	Likert Scale [2]
Wood Durability (WD)	Low	Wood protection according to intrinsic durability, e.g., less durable *Pinus radiata* in Chile.	1
	Moderate	Wood protection by applying chemically modified wood.	3
	High	Wood protection by using durable native woods.	5
In-Service Risk (RS)	Low	Wood protection must match the appropriate risk class for its use. If risks are not addressed, the treatment's effectiveness is compromised.	1
	Moderate	Current wood protection measures do not adequately align with the risk classification and require improvement. While the wood is preserved, it lacks a surface treatment, making it vulnerable to abiotic factors. Thus, enhancements are necessary.	3
	High	Wood protection has analyzed the factors contributing to damage and assessed risk classifications across various service conditions. The goal was to identify the most effective option to minimize environmental impact, with a focus on sustainability for risk classes 1 to 6, including marine environments.	5
Sustainability (S)	Low	Utilizes bio-based compounds that effectively resist biological organisms, offering short-term protection against fungi, insects, and other wood-degrading organisms (1 year or less).	1
	Moderate	The treatment has proven its durability in performance tests, requiring periodic reapplication every one to two years or using in situ reapplication technology. It is characterized by ease of application and the minimal time and resources needed for protection.	3
	High	The treatment is cost-effective in terms of duration and protection. It has a low environmental impact due to its low toxicity, minimal leaching, and biodegradability under continuous water exposure throughout its service period, demonstrating effective.	5

[1] The moderate rating is applied when the attribute is not evident in the reviewed literature. [2] This scale was used to assess the level of development, effectiveness, or technical relevance of each attribute associated with the following four criteria: Low (1)—basic or ineffective solutions; Moderate (3)—intermediate solutions with significant improvements; and High (5)—robust, integrated solutions, or those with a high positive impact.

The WPSI, expressed as a percentage, was calculated using Equation (1).

$$\text{WPSI (\%)} = (\text{PT} \times Xi + \text{WD} \times Yi + \text{RS} \times Zi + \text{S} \times Ui) \times 100 \quad (1)$$

where PT corresponded to Protection Treatment, WD represented Wood Durability, RS accounted for In-Service Risk, and S represented Sustainability (efficiency and effectiveness); Xi, Yi, Zi, and Ui corresponded to weighting coefficients by scenario, as indicated in Table 3. The performance indicators utilized in this study were validated through prior research and adjusted to suit this industrial sector [29,30]. The scoring process for the WPSI attributes is thoroughly detailed in Appendix A.1. This section explains the rationale for employing the Analytic Hierarchy Process (AHP) for each criterion associated with wood preservatives, including Protection Treatment, Wood Durability, In-Service Risk, and Sustainability. Furthermore, we have included the matrix utilized in our calculations to enhance the transparency of the process.

Table 3. Attribute weights to different scenarios.

Attribute	Symbol	Scenario 1 (%)	Scenario 2 (%)
Protection treatment (PT)	*Xi*	50	20
Wood durability (WD)	*Yi*	15	10
In-Service Risk (RS)	*Zi*	15	10
Sustainability (S)	*Ui*	20	60

Table 3 outlines the weights assigned to each attribute across the analyzed scenarios. In Chile, Radiata Pine is the most widely utilized species for construction purposes. As stipulated by the NCh819:2019 standard, this wood requires specific preservative treatments based on the designated risk classes specified in the same standard. In scenario 1, Protection Treatment (PT) was assigned a weight of 50%; however, in scenario 2, this weight was adjusted to 20% to emphasize the Sustainability (S) attribute. The aim was to demonstrate that by improving the solution's efficiency and effectiveness, it is possible to achieve sustainable protection while still utilizing low-durability wood species. In scenario 1, the weight assigned to the Wood Durability (WD) was set at 15%, reflecting the expectation that timber will be treated instead of being used without any protection treatment. In scenario 2, this weight was reduced to 10%, considering the anticipated use of more effective and efficient wood biocides. In the case of the in-service risk (RS) attribute, the simulation was conducted with the understanding that most of the timber is employed for construction purposes, where the associated in-service risks are relatively low (levels 1, 2, and 3 according to Table A5). As a result, the weight levels assigned were 15% and 10% for scenarios 1 and 2, respectively.

The classification based on WPSI values allowed wood preservatives and protection systems to be grouped into three levels of compliance, as shown in Table 4. Products with a WPSI of 75% or higher were classified as high compliance, those between 50% and 75% as medium compliance, and those between 1% and 50% as low compliance.

Table 4. The three levels of compliance used in this study.

Level of Compliance	WPSI (%)
High	(75–100)
Medium	(50–75)
Low	(1–50)

2.2. Assessment of Economic Viability, Industry Challenges, and ESG Criteria

The economic feasibility and market barriers were assessed following an interview with an expert from one of Chile's two largest wood preservatives suppliers. This analysis included a comprehensive review of Chilean regulatory frameworks and ESG (Environmental, Social, and Governance) criteria. The findings were then utilized to develop a SWOT analysis of the wood preservative industry in Chile, highlighting internal strengths and weaknesses as well as external opportunities and threats. The objective was to facilitate a transition towards safer and more environmentally responsible wood protection methods.

3. Results and Discussion

3.1. Classification of Protection Mechanisms Using a Wood Protection Sustainability Index (WPSI)

This classification was carried out to comprehend the complexities associated with transitioning from the intensive use of CCA (Chromated Copper Arsenate) in Chile to alternative wood preservatives. The primary objective of the analysis was to identify the key protection mechanisms against biotic agents currently being explored in international markets, while excluding early-stage or exploratory research on agents that lack formal registration or have not demonstrated proven effectiveness. The wood preservatives that are approved and registered for use in Chile are B_2O_3 (SBX, boron oxide-based preservative), CA-B (Copper plus tebuconazole type B), CCA (Chromated Copper Arsenate), Creosote, LOSP (Light Organic Solvent Preservative), MCA (Micronized Copper plus Tebuconazole), and μCA-C (Micronized Copper Azole, copper particles dispersed in water plus Tebuconazole and Propiconazole) [23]. The standard that specifies the appropriate type of preservative for each risk classification is NCh819:2019 [9]. This standard is related to the natural durability of various exotic and native wood species and mandates the treatment of radiata pine due to its limited durability in structural applications. In Chile, the regulatory standard NCh789:2023 [25] classifies wood species based on their intrinsic durability against biological degradation agents (Table A4), necessitating the treatment of timber intended for construction purposes. Sawn radiata pine (*Pinus radiata* D. Don) is the most widely utilized timber in this sector. According to the General Urban Planning and Construction Ordinance (MINVU Art. 5.6.8), when pine wood is employed as a structural material, it must be preserved in accordance with NCh819:2019 [9] due to its classification as a non-durable wood according to NCh789:2023 [25].

3.1.1. Scenario 1

The first scenario highlights the current landscape in which protection treatment (PT) plays a crucial role in decision-making. However, sustainability (S) remains low in Chile, as this attribute is not yet highly considered. This is largely attributed to the absence of regulations or laws that promote the adoption of more sustainable wood preservation products by construction companies. Figure 2 presents the results obtained for the WPSI for the five wood protection treatments, including CA, μCA, ACQ, CCA, and chemical modification. It can be observed that CA reached the highest score (74%), followed by ACQ (70%), chemical modification (68%), CCA (67%), and μCA (66%). CCA slightly outperforms μCA, primarily because this protection method has successfully adapted to the Chilean market. It is well-established, readily available, and faces no restrictions for use in construction. However, this should not lead to the neglect of sustainability criteria in the development of wood protection mechanisms against biotic agents. On the contrary, future advancements must prioritize sustainability, and it is anticipated that the significance of these criteria will continue to increase over time, in accordance with ESG principles and global trends in this field.

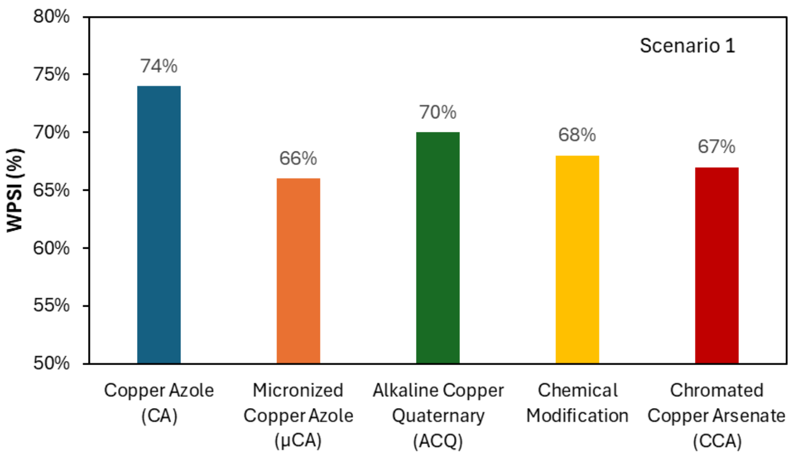

Figure 2. WPSI classification according to the level of compliance for five wood preservative treatments based on Scenario 1.

The relatively high ranking of CCA in Scenario 1 underscores the current dynamics of the Chilean wood preservation market, where CCA has been the dominant preservative for decades due to historical, regulatory, and economic factors. CCA treatment is supported by a well-established supply chain and cost-effective production methods. In contrast, more sustainable alternatives, such as μCA, have only recently emerged in the market, resulting in limited adoption. In Chile, the use of preservative-treated structural wood remains uncommon, with much of the preserved wood designated for utility poles and agricultural posts. Within the construction sector, a mere fraction of the radiata pine that should be treated according to regulations (e.g., NCh819:2019) is actually preserved, largely due to inconsistent enforcement of these requirements in the private sector. Compliance is mostly driven by public infrastructure projects, where state agencies mandate adherence. This situation reveals a significant gap in regulatory adoption and enforcement. Furthermore, emerging construction strategies, such as the promotion of engineered wood products (EWPs) like Glulam and CLT, do not currently mandate preservative treatment for the raw materials, despite the known presence of subterranean termites in Chile. This regulatory and market gap allows CCA to maintain its competitiveness, not because it offers superior sustainability performance, but due to its established position within the system and a lack of comprehensive technical standards for newer applications. These realities highlight the importance of decision-support tools like the Wood Protection Sustainability Index (WPSI), which are designed to convey the broader sustainability benefits of properly protected wood in construction, ultimately facilitating a more informed transition toward improved practices.

3.1.2. Scenario 2

We conducted an analysis to assess the effects of placing greater emphasis on sustainability relative to other attributes by adjusting the weighting values in Equation (1) and recalculating the Wood Protection Sustainability Index (WPSI). In this study, the emphasis on sustainability (S) was raised to 60%, while the weight assigned to Product Treatment (PT) was decreased to 20%. Moreover, the weights for Wood Durability (WD) and in-service risks (RS) were both reduced to 10%. The findings of the WPSI are presented in Figure 3. The highest score was achieved by CA, which scored 60%, closely followed by ACQ at 59%. Both μCA and chemical modification received scores of 56%, while CCA ranked the lowest at 52%. This indicates that when sustainability is prioritized, CCA emerges as the least favorable option in terms of WPSI. It is crucial to recognize that the use of CCA-treated wood can lead to significant environmental concerns, particularly due to the leaching of chromium, arsenic, and copper into surrounding soils and groundwater. The maximum allowable concentrations for these substances in drinking water are 50 μg/L for chromium, 2 mg/L for copper, and 10 μg/L for arsenic [32]. Exceeding these levels can have adverse effects on vital organs, including the liver and kidneys [33]. Consequently, wood impregnation processes are carefully monitored to prevent incidents that may pose risks to both the environment and public health.

The comparative analysis of both scenarios highlights how the prioritization of sustainability criteria can significantly impact the performance of wood preservative systems. Scenario 1 represents the current regulatory and market conditions in Chile, which favor established treatments like CCA due to their availability and cost-effectiveness. In contrast, Scenario 2 demonstrates that when environmental and efficiency factors are prioritized, more sustainable alternatives such as CA (copper azole) and ACQ (alkaline copper quaternary) emerge as favorable options. Currently, ACQ is the most widely used wood preservative for residential applications in the United States [17] and is also utilized in countries like Canada, Germany, Japan, New Zealand, and Sweden [34]. Although ACQ was authorized for use in Chile, its benefits did not lead to widespread adoption, nor did it manage to compete with CCA.

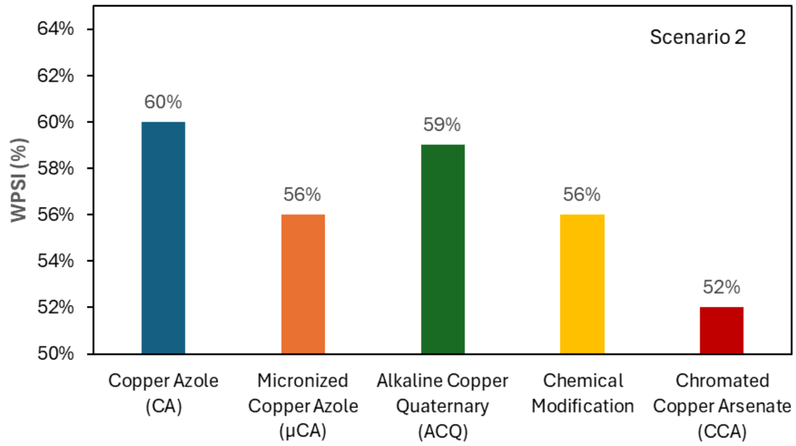

Figure 3. WPSI classification according to the level of compliance for five wood preservative treatments based on scenario 2.

This transition toward more favorable alternatives underscores the increasing need to align wood protection strategies with ESG principles and SDGs. However, the transition to these alternatives is complicated by material constraints. For example, Scenario 1 relies on native wood species with high natural durability (as noted in Table A4), which are increasingly rare, often of suboptimal quality for structural applications, and economically impractical. As a result, Scenario 2 emerges as a more balanced and forward-looking solution, integrating sustainability without compromising productivity. This is particularly evident in the strong performance of copper-azole (CA) in the WPSI, where it is recognized as a viable and lower-impact substitute for CCA, especially when paired with water-repellent additives that mitigate metal leaching [22]. Nevertheless, the application of CA in engineered wood products is still under investigation. While CA demonstrates effectiveness against biological degradation, it may adversely affect mechanical properties due to its negative impact on surface bonding quality [35–37]. The following sections will delve deeper into the potential of these integrated systems and their implications for wood protection practices in Chile.

3.2. Assessing the Market Viability of Alternatives to CCA in Chile

The introduction of new wood preservatives is currently hindered by the common perception that they are more expensive, primarily due to the higher concentrations of active ingredients required. Without regulatory mandates to promote or enforce this transition, the market tends to rely on established practices, such as the continued use of CCA. This dependence poses significant disposal challenges for treated timber at the end of its lifecycle. To address this issue, a circular economy strategy offers a promising avenue for valorizing treated wood waste [38,39]. In 2009, Janin et al. [40] proposed a cost-effective leaching method to remove arsenic, chromium, and copper from CCA-treated wood, demonstrating a low-cost approach for recycling CCA-treated wood waste by effectively decontaminating it. Moreover, in response to global trends, companies are increasingly adopting ESG criteria, along with socially responsible investment (SRI) principles, irrespective of local regulatory pressures. Therefore, it is strategically important to reassess and redesign preservation strategies. Even a voluntary shift away from CCA can enhance a company's performance in ESG areas and strengthen its reputation, aligning with international sustainability expectations and ultimately benefiting the organization as a whole. From a cost perspective, CCA remains advantageous for wood treatment due to established processes, economies of scale, and market availability. However, the necessity of re-drying wood introduces environmental and financial challenges that could undermine these benefits. To clarify the cost considerations further, Table 5 provides a comparative analysis of cost ratios within the Chilean market. It highlights CCA, the most commonly used wood preservative, alongside the µCA protection method. The µCA method exhibits significant potential to replace CCA, as it has achieved the highest WPSI value.

Table 5. Comparison of costs and retention of CCA and µCA preservatives for different risk levels in wood applications according to the Chilean standard (NCh819:2019 [9]).

Wood Preservative	Active Ingredient (A.I) Concentration (%)	Risk Class (Uses) [1]	Retention (kg A.I/m^3)	Product Retention (kg Product/m^3)	Cost [2]
CCA	60	Risk levels 1, 2, 3 (construction)	4	6.67	34 USD/m^3 (5 USD/kg)
		Risk level 4 (agricultural use)	6.4	10.67	54 USD/m^3 (5 USD/kg)
		Risk level 5 (utility poles)	9.6	16	80 USD/m^3 (5 USD/kg)
µCA	26	Risk levels 1, 2, 3 (construction)	1	3.85	33 USD/m^3 (8.5 USD/kg)
		Risk level 4 (agricultural use)	2.4	9.23	79 USD/m^3 (8.5 USD/kg)
		Risk level 5 (utility poles)	3.7	14.23	121 USD/m^3 (8.5 USD/kg)

[1] Risk classes according to NCh819:2019. [2] The cost values presented correspond to average market prices in Chile for the period 2024–2025. These prices were provided by an expert from one of the two largest wood preservative suppliers in the country and reflect typical industrial-scale applications. Cost data was cross-verified to ensure accuracy. The concentrations of active ingredients are based on standard formulations currently used in field conditions.

According to Table 5, the costs per cubic meter for both CCA and µCA treatments are comparable in the low-risk classes (1, 2, and 3). However, transitioning to µCA in facilities currently designed for CCA treatment may necessitate specific technical adjustments to the production process. These modifications could result in additional implementation costs, which are generally reflected in the final production price of the new µCA-treated product.

The data presented in Table 5 illustrates the concentrations of active ingredients alongside their corresponding retention values in kilograms per cubic meter. While CCA maintains a steady concentration of 60%, µCA has a lower concentration of 26%. Consequently, a greater quantity of µCA is needed per cubic meter to achieve equivalent protection. This distinction becomes especially pronounced in high-risk applications, such as agricultural uses (risk class 4), where CCA treatment proves to be the more cost-effective choice, providing savings of approximately USD 25 per cubic meter compared to µCA. In the case of utility or transmission poles (risk class 5), which face high levels of biodegradation, the cost advantage of CC becomes even more significant, with a difference in USD 41 per cubic meter in favor of CAA over µCA. As a result, the combination of higher retention requirements and the elevated cost per kilogram of µCA renders this treatment considerably more expensive than CCA in high-risk contexts. In construction applications (risk classes 1, 2, and 3), when evidence indicates that the costs of CCA and µCA are similar, the choice between the two treatments may hinge on additional factors such as durability, environmental impact, regulatory constraints, and confidence in the effectiveness of µCA formulations. For agricultural applications, CCA remains the most cost-effective option, which is particularly relevant in projects where budget considerations are paramount. Similarly, for transmission poles, CCA continues to offer significant economic advantages, making it a justified choice for large-scale infrastructure projects. CCA has consistently demonstrated superior performance in laboratory and field degradation tests, solidifying its status as the benchmark preservative for high-risk applications [18]. In comparison to international practices, Chile might consider aligning its use of CCA with countries like Canada, the United States, and New Zealand, where its application is limited to high decay-risk situations and banned in residential areas [34,41]. Although CCA is currently favored due to its lower costs, μCA remains a viable alternative in construction applications, especially when specific performance characteristics are required that CCA may not offer. Ultimately, such decisions should be informed by comprehensive cost–benefit analyses. Beyond cost, other market barriers have been identified through expert interviews and regulatory reviews. These include the limited enforcement of preservation standards, a lack of incentives for innovation, and cultural resistance to wood protection practices in construction. This study seeks to advance the exploration of decision-making tools, particularly the Wood Protection Sustainability Index (WPSI), to support future evaluations. Additionally, it will examine integrated solutions that incorporate protection by design, chemical modification treatments, and the use of preservatives when alternative options do not meet technical requirements, as outlined in Section 3.3. The discussion further establishes the foundation for the SWOT analysis presented in Section 3.4. This analysis builds upon the findings discussed earlier to delineate strategic directions aimed at enhancing sustainability within the Chilean wood preservation industry.

3.3. Alignment of Advanced Wood Preservatives with ESG Criteria and SDG Targets

As outlined in Table 3, the low sustainability score highlights a significant challenge due to the limited emphasis on sustainability among the wood preservatives methods in the Chilean market. This situation arises from the insufficient adoption of sustainability practices, largely due to the absence of laws or regulations mandating their implementation in Chile. The low adoption rate, reflected in a diminished importance of weighting, indicates a prevalent belief that natural wood is the optimal environmental choice. Furthermore, there is a common perception that sustainability initiatives are primarily limited to benchmarking exercises rather than yielding tangible, measurable commitments. The lack of regulatory oversight exacerbates this issue, making it unlikely that sustainable practices will be effectively integrated into the construction sector.

To enhance our understanding of how advanced wood preservatives align with sustainability standards, we conducted an analysis of their impact on key Environmental, Social, and Governance (ESG) criteria, as well as their relevance to Sustainable Development Goals (SDGs). Table 6 presents a summary of this relationship by detailing the performance of innovative preservative technologies across each ESG domain and identifying areas where Chile's regulatory and market environment could be strengthened. This analysis presents a strategic perspective that allows us to evaluate not only the environmental and social benefits of transitioning to less hazardous preservatives but also the institutional and reputational advantages associated with adopting more transparent, performance-based frameworks in line with international best practices. This is especially significant as Chile advances the construction of medium-rise social housing made from wood and seeks to foster confidence in the market.

Here, the environmental criteria (E) concern the release of toxic compounds into soil and water through leaching, as well as their connection to polluting emissions, including heavy metals and volatile organic compounds. To mitigate this issue, it is essential to utilize non-metal alternative preservatives that are free from heavy metals such as chromium (Cr) or arsenic (As). Additionally, employing μCA-based systems with reduced leaching properties can significantly help in addressing this challenge. Techniques such as acetylation and thermal treatments can also greatly enhance the durability of wood, either separately [42–45] or in combination [46]. Chile has the potential to accelerate the adoption of more sustainable preservatives, such as μCA, particularly in Class 4 applications where wood is in contact with the ground or exposed to high humidity, including agricultural and external structural uses. Furthermore, promoting the establishment of a pilot plant for acetylation could advance research and boost the use of modified wood with enhanced durability, especially for species like *Pinus radiata*, similar to projects already underway in countries like New Zealand and Finland.

Table 6. ESG and SDG alignment of wood preservation strategies in the Chilean context.

ESG Criteria	How Advanced Wood Preservatives Score	Areas Where Chile Must Focus on Improvement
E Emissions/leaching	Non-metal chemistries and modification routes cut Cr/As runoff, align with SDGs 6 and 13.	Fast-track µCA (Cu-azole) in class 4 uses; pilot acetylated radiata pine.
S Worker and end-user health	New generation preservatives (such as MCA, µCu, ACQ) avoiding the use of dangerous heavy metals, lowering VOCs → SDG 3 benefits.	Mandate safer products in housing; launch public education to shift consumer demand.
G Regulatory and reputational risk	EU-style performance testing + transparent LCA data reduces future liability.	Move from "active-substance list" to performance-based approvals; integrate third-party certification (e.g., NWPC model).

In terms of social criteria (S), new-generation wood preservatives, such as µCA and ACQ, eliminate the use of hazardous heavy metals such as arsenic (As) and hexavalent chromium (Cr^{6+}), which are present in CCA, thus reducing toxic risks for workers and users. Chile could establish regulatory requirements or incentives to ensure that only safer products are used in residential construction, including schools, social housing, and public buildings. This approach is already being practiced in the US and the EU, where the use of CCA in residential environments is prohibited. Moreover, launching information campaigns to encourage consumers, builders, and distributors to make informed decisions is crucial, even in the absence of regulatory mandates. Educating consumers about the risks associated with CCA and the advantages of cleaner alternatives can facilitate a quicker transition to safer options.

In addition, incorporating governance criteria (G) is essential for effectively managing regulatory and reputational risks in the wood preservatives industry. This sector frequently develops products tailored to meet market demands and specifications. The primary risks stem from the use of toxic substances or products that fail to adhere to international standards. Additionally, a lack of transparency and traceability concerning the environmental impacts of products, such as CCA, exacerbates these concerns. In the European Union, performance testing for wood preservatives goes beyond merely evaluating active ingredients; it also assesses how well a product performs under real-world conditions (in-service conditions). This approach emphasizes durability, safety, and efficacy, providing a more scientific and flexible assessment than simply listing approved ingredients. Consequently, new products must include transparent and verifiable Life Cycle Assessment (LCA) [47,48] data, enabling a thorough evaluation of their environmental impact from production to end-of-life, thereby enhancing product traceability and credibility. Lastly, Chile could consider adopting third-party certification models, such as that established by the Nordic Wood Preservation Council (NWPC), which certifies the durability, quality, and reliability of treated wood. These actions could increase market trust and facilitate export opportunities. The low adoption of sustainability practices in Chile is shaped not only by regulatory gaps but also by historical and cultural influences [49]. For many years, a prevalent belief has been that natural, untreated wood is the most environmentally responsible choice. This perception has overshadowed the long-term advantages of durability and resource efficiency that modern wood preservatives offer. Additionally, the preservation of wood has often been associated with toxicity and environmental harm due to the legacy of heavy metal-based treatments like CCA. Despite the availability of safer, advanced alternatives, these negative associations continue to persist. Economically, smaller enterprises may lack the necessary resources or incentives to transition to newer technologies without support from the government. Industry-led initiatives are decisively emerging in public sector construction, particularly in social housing and public schools, where the use of environmentally friendly and durable wood products is gaining significant recognition. These projects will serve as powerful demonstration platforms, building trust and driving demand in the broader market over time.

3.4. Strategic SWOT Analysis of Chile's Wood Preservative Sector Considering ESG Criteria

Figure 4 illustrates the intricate landscape confronting the wood preservation industry in Chile. While this sector faces considerable challenges, it also presents strategic opportunities to align with global trends in sustainability and responsibility. The ESG and Sustainable Finance framework provides a comprehensive strategy to mitigate risks and capitalize on emerging opportunities through the following five key areas: (1) revenue growth, (2) cost reduction, (3) mitigation of legal and regulatory interventions, (4) enhanced staff productivity, and (5) asset and investment optimization [50]. It is noteworthy that the fourth attribute, enhanced staff productivity, could not be evaluated in this assessment. Moreover, it is not assured that all these attributes will be applicable or manifest in the same way across different contexts [50].

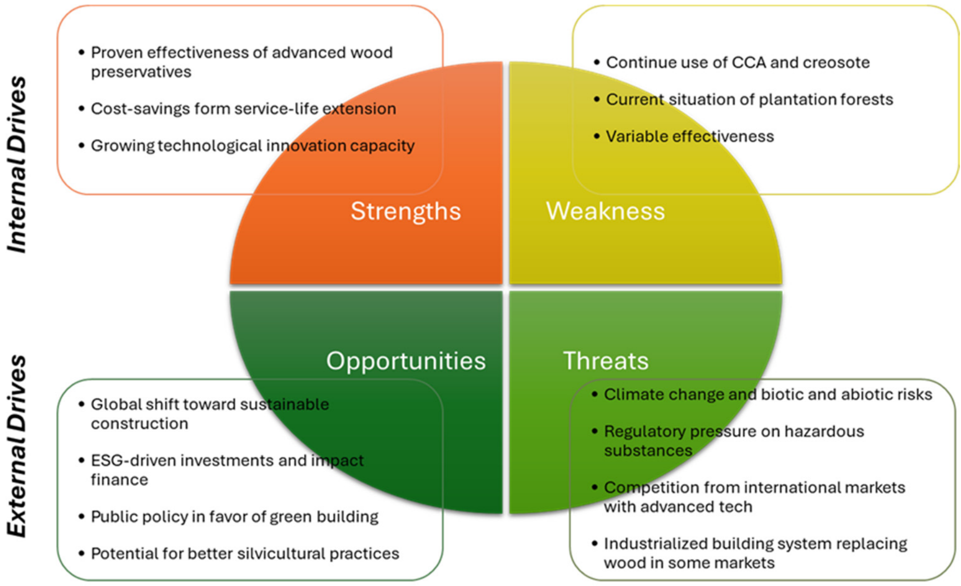

Figure 4. Sustainability-based SWOT analysis of wood protection in Chile.

3.4.1. Strengths

The Chilean wood preservative sector boasts several internal advantages that facilitate a transition toward more sustainable practices. Notably, the effectiveness of established treatments such as CA, μCA, ACQ, MCA, chemical modifications, and design-based protection has been thoroughly documented, demonstrating their ability to resist wood-degrading agents [51–53]. This establishes a compelling value proposition within the framework of ESG principles, as the durability of these solutions helps optimize capital allocation toward resilient and sustainable investments [50]. Furthermore, extending the service life of timber through suitable protective methods can significantly lower long-term operational costs by reducing the necessity for premature replacements [48]. Technological innovation within the industry, particularly in the development of safer and more efficient preservation strategies, enhances this value by promoting waste-reducing production chains that align with ESG objectives. Innovation in this context encompasses advancements in developing new protective strategies and cumulative combinations. These developments have resulted in treatments that are both safer and more effective [54]. When implemented in harmony with ESG principles, these approaches can substantially lower operational costs by fostering more efficient and loss-free production chains [50].

3.4.2. Weaknesses

While Chilean plantations possess certain strengths, they also face significant internal weaknesses. In Scenario 1, CCA demonstrated a competitive ranking due to its established availability and low market cost, underscoring a structural dependency on this preservative. This finding reinforces critical weaknesses, particularly the persistent utilization of toxic preservatives and the misalignment of regulatory practices with international sustainability standards. Data reveals that a large portion of these forests is primarily managed for the production of sawn timber used in manufacturing, including processing and carpentry. A smaller percentage is allocated to structural sawn timber, with an even more limited quantity designated for classified structural sawn timber [8]. Nevertheless, demand is expected to rise in the coming years due to new regulations established in 2023, which mandate the use of structural wood in timber construction. Projections regarding future timber availability indicate that in response to market demand, the country's timber supply is likely on a downward trajectory [8]. Moreover, the ongoing use of toxic preservatives such as CCA and creosote, which are allowed under Chilean regulations for both residential and industrial purposes [55], presents considerable environmental and health risks [41]. This regulatory misalignment with international standards diminishes Chile's competitiveness in global markets that prioritize environmental, social, and governance (ESG) factors, potentially leading to investment risks in the future [50]. Additionally, the efficacy of preservative treatments is inconsistent, influenced by the durability of wood species, climatic conditions, and specific biotic and abiotic stressors [25]. This inconsistency is further complicated by a lack of regulatory oversight, which undermines quality assurance and product standardization.

3.4.3. Opportunities

Chile stands to gain from the global shift towards sustainable construction, which aligns with SDG 11. This goal underscores the necessity for safe, resilient, inclusive, and sustainable cities and communities, thus highlighting the critical need for solutions to address wood degradation [56]. From an ESG perspective, wood protection presents a significant opportunity, offering potential avenues for revenue growth, cost efficiency, and enhanced optimization of assets and investments [50]. Wood protection technologies play a vital role in this trend by providing increased durability, resource optimization, and alignment with impact investment strategies. In Scenario 2 of the WPSI, which prioritizes sustainability, treatments such as μCA have outperformed CCA. This demonstrates the potential for Chile's industry to align with ESG-driven demands. The findings suggest that, although certain high-risk applications may incur higher costs, alternative solutions are both technically and environmentally feasible for various construction applications. This is particularly relevant when factoring in long-term benefits and objectives associated with the circular economy. Notably, impact investments reached USD 1.164 trillion in 2022 [57]. This trend is particularly pertinent for Chile, where the forestry industry is vital and the appetite for sustainable solutions is rapidly increasing. By implementing preservation practices that adhere to international standards, such as NWPC [58] and ESG, Chilean companies can establish themselves as leaders in a competitive global market. This strategy will not only attract foreign investment but also strengthen their position within the global supply chain. Moreover, favorable public policy represents a key opportunity. Regulations promoting sustainable building practices and ecological neighborhood development can incentivize the adoption of wood protection solutions, thus reducing legal uncertainties and enhancing strategic planning [50]. Furthermore, advances in silvicultural planning, such as cultivating radiata pine in high site index areas, may enhance productivity and the physical and mechanical properties of the material, thereby expanding its potential for structural applications [59–61].

3.4.4. Threats

The sector is currently confronted with several external threats. Climate change is heightening the vulnerability of forests, resulting in the proliferation of pests and fungi that can compromise wood quality [62–65]. Additionally, forest fires significantly affect productivity, an issue that Chile has confronted over the past decade because of severe drought, among other factors, hence causing a contraction in the timber sector [66]. This challenge is particularly pronounced at the wildland-urban interface, where the consequences of such disasters can be particularly detrimental [67]. Furthermore, emerging environmental regulations may impose stricter controls on certain active ingredients, potentially limiting the number of available treatment options. On the international stage, competition from countries with advanced wood protection technologies and more cost-effective production models [34] poses a risk to Chile's market share. Concurrently, the growing trend of industrialized construction utilizing materials like concrete and steel, often marketed as "sustainable" through their own certification schemes, presents another challenge. This situation underscores the urgent need to highlight the unique sustainability and performance advantages of treated wood products.

Therefore, this study aimed not only to present specific data but also to establish a new framework for validating treated wood in service through the Wood Protection Sustainability Index (WPSI). By assessing and standardizing preservation strategies based on four key attributes, the WPSI enables the construction industry to make informed and sustainable material choices. This index directly contributes to the sustainable construction agenda by offering measurable, high-quality, and efficient preservation solutions that enhance comfort, reliability, and market credibility.

The findings highlight significant weaknesses identified in the SWOT analysis, such as regulatory gaps and limited adoption of sustainability practices, while also emphasizing strengths like increased productivity across the value chain. Additionally, the WPSI promotes better alignment among producers, suppliers, and end-users by clarifying performance expectations and encouraging standardization. This initiative fosters a more interconnected and responsive wood value chain, helping to overcome technical barriers, reshape perceptions, and support long-term industry transformation.

3.5. Limitations and Transferability

The application of indicators is vital for validating claims, as they provide valuable insights that can effectively influence decision-makers. While technical data sheets for individual products have traditionally been available, there are currently no tools that allow for comparisons based on weighted attributes that reflect the ever-changing demands of the market. Given that most countries have regulations and official registrations for chemical products, the development of a standardized application indicator, such as our WPSI, can significantly enhance market transparency and facilitate informed decision-making.

This indicator illustrates that sustainable compliance can be achieved both effectively and efficiently in response to protection challenges. It dispels the misconception that addressing issues related to final wood finishes, such as preservation, can be deferred, emphasizing instead that such considerations should be integrated into the initial planning process. For instance, the index shows that μCA ranks highest when sustainability is prioritized (Scenario 2), positioning it as an excellent candidate for fast-tracking in risk class 4 applications, where current reliance on CCA remains prevalent. Similarly, acetylated radiata pine has emerged as a promising option for improving long-term durability while reducing environmental impact, warranting its implementation in selected projects. These insights are particularly pertinent in Chile, where wood is often viewed as a precarious material, limiting its broader acceptance in construction. This duality, where wood is seen as both a luxury and a low-end material, can be addressed by promoting the WPSI as a standard decision-support tool. Essentially, it allows the market to establish credibility through a comparative analysis of the sustainability of preservatives that comply with specific national or regional standards. This analysis considers technical, environmental, social, governance, and cost factors, thus providing a robust foundation for decision-makers.

To ensure international applicability, the WPSI framework could be enhanced by incorporating local standards for wood durability (e.g., EN 350 [68] in the EU; AWPA [69] in the U.S.), revising risk classifications based on regional use categories and aligning with country-specific preservative approval systems. Furthermore, ESG-related indicators could be fine-tuned to reflect national sustainability targets and certification schemes. This approach would enable meaningful comparisons across diverse contexts and support the development of credible, performance-based wood protection strategies.

4. Conclusions

This study demonstrates that Chile's wood preservative market, currently dominated by CCA due to its established infrastructure and low cost, holds significant potential for enhancement when evaluated under sustainability criteria. The application of the WPSI indicates that treatments like copper azole (CA) and alkaline copper quaternary (ACQ) demonstrated superior environmental performance, aligning with ESG principles and SDG targets. Nevertheless, the Chilean market remains largely cost-driven, with sustainability receiving low priority unless mandated by law or demanded by consumers. The findings suggest that prioritizing sustainability, alongside effectiveness, efficiency, and a supportive regulatory framework, is both feasible and essential for achieving long-term resilience in the sector. The WPSI developed in this study serves as a robust tool for informing strategic decisions, enabling the wood protection industry to make meaningful contributions to national and global sustainability goals.

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Appendix A

Appendix A.1. Analytic Hierarchy Process (AHP) for Prioritizing Decision Criteria

We employed the Analytic Hierarchy Process (AHP), developed by Thomas Saaty [24], to evaluate the relative importance of four critical factors influencing the use of preserved wood. This multicriteria decision-making technique facilitates pairwise comparisons and allows for the derivation of weighted priorities through matrix normalization and consistency evaluation. Our goal was to assess the significance of the following key attributes: preservative treatments (PT), wood durability (WD), in-service risk classes (RS), and sustainability (S), all of which play a vital role in decision-making regarding the selection and use of preserved wood. A description of each attribute is provided in Table A1.

Table A1. Stepwise description of the AHP Method.

Step	Description
1. Definition of Goal and Criteria	The main objective was defined, and four evaluation criteria were established: PT, WD, RS (as per NCh819:2019), and S.
2. Pairwise Comparison Matrix Construction	Experts performed pairwise comparisons using Saaty's fundamental scale (1–9) to express the relative importance of each factor. Expert judgment prioritized PT as the most important, followed by S, with WD and RS considered equally important.
3. Matrix Normalization	Each matrix column was normalized by dividing individual values by the column sum. Then, the average of each row yielded the relative weight of each factor.
4. Consistency Check	The consistency of expert judgments was assessed using the Consistency Ratio (CR). We calculated the maximum average value (λmax), Consistency Index (CI), and Random Index (RI), confirming that the condition CR < 0.1 was satisfied, indicating acceptable consistency.
5. Application of Weights	The finalized weights were used to prioritize the decision criteria in further analysis or decision-making models.

Initial Pairwise Comparison Matrix: The first step in the AHP involved constructing a pairwise comparison matrix based on expert judgment, reflecting the relative importance of the attributes. We prioritized the criteria as follows:

1. Preservative Treatments (PT) were deemed the most critical, with significantly higher importance than the other criteria.
2. Sustainability (S) was considered the second most important, due to increasing regulatory and environmental concerns.
3. Wood Durability (WD) and In-Service Risk Classes (RS) were viewed as equally important and less influential than PT and S.

Based on this qualitative ranking, the matrix was quantified using Saaty's fundamental scale, which assigns numerical values to relative importance:

- PT was assessed as 4 times more important than WD and RS
- PT was 3 times more important than S
- S was 1.5 times more important than WD and RS
- WD and RS were equally important

Appendix A.1.1. Pairwise Comparison Matrix (A)—Scenario 1

Matrix A served as the input for normalization and weight derivation steps. Its logical consistency was validated, as detailed next.

$$A = \begin{bmatrix} 1 & 4 & 4 & 3 \\ 1/4 & 1 & 1 & 0.67 \\ 1/4 & 1 & 1 & 0.67 \\ 1/3 & 1.5 & 1.5 & 1 \end{bmatrix}$$

Matrix A was normalized by dividing each value by the sum of the respective columns, resulting in the final weight values shown in Table A2.

Table A2. Final weight results.

Attribute	Final Weight	Expert Expected Weight
Preservative Treatments (PT)	0.543	0.50
Wood Durability (WD)	0.132	0.15
Service Risk Classes (RS)	0.132	0.15
Sustainability (S)	0.192	0.20

The findings reveal a significant correlation between expert expectations and priorities derived from the Analytic Hierarchy Process (AHP). This correlation substantiates the reliability of the AHP method in the evaluation of complex decision-making factors within the field of wood preservation.

Consistency Verification of the Pairwise Comparison Matrix: To evaluate the internal consistency of the pairwise comparison judgments, we computed the consistency ratio (CR) using Saaty's method. This process involved multiplying the original pairwise comparison matrix by the priority vector, followed by the calculation of λmax, the consistency index (CI), and the consistency ratio (CR). We multiplied each row of the original (non-normalized) matrix by the corresponding weights and summed across the row:

$$PT = (1)(0.543) + (4)(0.132) + (4)(0.132) + (3)(0.192) \approx 0.543 + 0.528 + 0.528 + 0.576 = 2.175$$

$$WD = (1/4)(0.543) + (1)(0.132) + (1)(0.132) + (0.67)(0.192) \approx 0.136 + 0.132 + 0.132 + 0.129 = 0.529$$

$$RS = (1/4)(0.543) + (1)(0.132) + (1)(0.132) + (0.67)(0.192) \approx 0.136 + 0.132 + 0.132 + 0.129 = 0.529$$

$$S = (1/3)(0.543) + (1.5)(0.132) + (1.5)(0.132) + (1)(0.192) \approx 0.181 + 0.198 + 0.198 + 0.192 = 0.769$$

Each element of the weighted sum vector (Aw) was divided by the corresponding priority weight, as shown in Table A3.

Table A3. Corresponding priority weight.

Attribute	A wi	wi	λi = (A·wi)/wi
PT	2.175	0.543	4.004
WD	0.529	0.132	4.008
RS	0.529	0.132	4.008
S	0.769	0.192	4.005

The average of the λi values gives λmax:

$$\lambda\text{max} = \frac{4.004 + 4.008 + 4.008 + 4.0054}{4} \approx 4.006$$

Then, the Consistency Index was computed as:

$$\text{CI} = \frac{\lambda\text{max} - n}{n-1} = \frac{4.006 - 4}{3} \approx 0.002$$

The Random Index (RI) for n = 4 is 0.90, therefore:

$$\text{CR} = \frac{0.002}{0.90} \approx 0.002$$

Since CR ≈ 0.002 < 0.1, the matrix was considered to be highly consistent, and the derived priority weights are reliable and logically coherent for use in decision-making.

Appendix A.1.2. Pairwise Comparison Matrix (B)—Scenario 2

The analysis was conducted for scenario 2, where the Sustainability (S) attribute was deemed the most important factor. Matrix B represents this revised scenario.

$$\text{B} = \begin{bmatrix} 1 & 2 & 2 & 1/3 \\ 1/2 & 1 & 1 & 1/6 \\ 1/2 & 1 & 1 & 1/6 \\ 3 & 6 & 6 & 1 \end{bmatrix}$$

This matrix demonstrates that S is three times more important than PT, and six times more important than both WD and RS. Additionally, PT is twice as important as WD and RS, which are considered equally important. In this scenario, the Consistency Ratio (CR ≈ 0.0037) is significantly below 0.10, indicating excellent consistency in the pairwise judgments. Therefore, matrix B is valid, and the weights can be confidently used for decision-making.

Appendix A.2. Information Regarding Chilean Standards

Table A4 summarizes the information regarding the classification of the main wood species in Chile according to the national standard NCh789:2023 [25].

Table A4. Wood species, expected life, and durability category according to NCh789:2023 [25].

Category	Classification	Expected Life	Chilean Wood Species
1	Very durable	≥20 years	*Nothofagus obliqua* (Roble) *Pilgerodendron uviferum* (Ciprés de las Guaitecas) *Fitzroya cupressoides* (Alerce)
2	Durable	≥15 years	*Nothofagus alpina* (Raulí) *Nothofagus pumilio* (Lenga) *Persea lingue* (Lingue)
3	Moderately durable	≥10 years	*Drimys winteri* (Canelo) *Nothofagus dombeyi* (Coigüe) *Weinmannia trichosperma* (Tineo) *Eucryphia cordifolia* (Ulmo)
4	Few durable	≥5 years	*Araucaria araucana* (Araucaria) *Eucalyptus globulus* (Eucalipto), *Laurelia sempervirens* (Laurel) *Podocarpus nubigenus* (Mañío)
5	Not durable	≤5 years	*Populus* sp. (Álamo) *Aextoxicon punctatum* (Olivillo) *Pinus radiata* (Pino radiata) *Laureliopsis philippiana* (Tepa)

Table A5 indicates the in-service risk classes of timber and wood elements according to the usage conditions as established in the national standard NCh819:2019 [9].

Table A5. In-service conditions according to NCh819:2019 [9].

In-Service Risk Level	Use Condition	Biological Degradation Agent
Risk 1 (R1)	Indoor use above ground, dry environments	Insects, including subterranean termites
Risk 2 (R2)	Indoor use, above ground, potentially humid, poorly ventilated environments	Rot fungi and insects, including subterranean termites
Risk 3 (R3)	Indoor or outdoor use, above ground, exposed to weather	Rot fungi and insects, including subterranean termites
Risk 4 (R4)	Indoor or outdoor use, in contact with soil, with possible exposure to fresh water	Rot fungi and insects, including subterranean termites
Risk 5 (R5)	Indoor or outdoor use, in contact with soil, for critical structural components, exposed to fresh water	Rot fungi and insects, including subterranean termites
Risk 6 (R6)	Use in contact with salt water	Marine borers, rot fungi, and insects

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