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Review

Actualized Scope of Forestry Biomass Valorization in Chile: Fostering the Bioeconomy

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Abstract

Chile is among the leading global exporters of pulp and paper, supported by extensive plantations of *Pinus radiata* and *Eucalyptus* spp. This review synthesizes recent progress in the valorization of forestry biomass in Chile, including both established practices and emerging bio-based applications. It highlights advances in lignin utilization, nanocellulose production, hemicellulose processing, and tannin extraction, as well as developments in thermochemical conversion technologies, including torrefaction, pyrolysis, and gasification. Special attention is given to non-timber forest products and essential oils due to their potential bioactivity. Sustainability perspectives, including Life Cycle Assessments, national policy instruments such as the Circular Economy Roadmap and Extended Producer Responsibility (REP) Law, are integrated to provide context. Barriers to technology transfer and industrial implementation are also discussed. This work contributes to understanding how forestry biomass can support Chile's transition toward a circular bioeconomy.

Keywords: eucalyptus and pine; fibers; tannins; hemicellulose; nanofibers; particleboard; byproducts; energy; pyrolysis; tree barks; circular economy

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1. Introduction

Forests and their derived industries play a central role in the global bioeconomy, contributing significantly to economic output, employment, and ecosystem services [1]. In

2022, global industrial roundwood production surpassed 2 billion cubic meters, with major producers including the United States, Brazil, Russia, China, and Canada [2]. Forecasts predict a substantial rise in demand for industrial wood products by 2050 [3].

Chile has positioned itself as a key actor in the international forest sector, with over 2.2 million hectares of plantations dominated by *Pinus radiata* and *Eucalyptus* spp. These plantations serve as the primary feedstock for pulp, paper, and wood panel exports. The country's forest sector is increasingly oriented toward sustainable resource use, emphasizing circular economy principles and innovation in byproduct valorization.

The forest sector requires more innovation to meet the rising demands and environmental challenges of this era. Key drivers include growing stressors like climate change, the transition to a wood-based bioeconomy, and the potential of non-wood forest products for billions of smallholders [3–5].

This review aims to present a comprehensive overview of the current state and prospects of forestry biomass valorization in Chile. It synthesizes research and industrial developments in the use of lignin, nanocellulose, hemicellulose, and bark-derived tannins. Also, it provides an evaluation of thermochemical conversion technologies and non-timber forest products. Furthermore, it contextualizes these advances within Chile's regulatory framework and national strategies aimed at promoting sustainability and resource efficiency.

2. Methodological Approach

This review synthesizes the current state of forestry biomass valorization in Chile through an integrative analysis of scientific articles, technical reports, and policy documents published between 2015 and 2024. No original experimental work was conducted. The methodology is based on a systematic analysis aligned with principles from established review protocols such as PRISMA [6]. The literature search was performed using major academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and SciELO, complemented by Google Scholar to identify relevant non-peer-reviewed sources. These sources included technical reports from research institutions like Unidad de Desarrollo Tecnológico (UDT, University of Concepción) and BIOREN (University of La Frontera, UFRO), as well as governmental bodies such as the Forest Institute (INFOR), the National Forestry Corporation (CONAF), and the National Statistics Institute (INE), as well as academic theses, dissertations, and conference proceedings. This dual approach was chosen to combine academic rigor with practical, country-specific data essential for policy and economic analysis. The search strategy applied Boolean operators with keywords in both English and Spanish. The complete search strategies, including Boolean operators, terms in both English and Spanish, and exclusion filters, are provided in the Supplementary Material (Table S1). The timeframe for included publications primarily ranged from 2015 to the present, a period chosen to cover the emergence and consolidation of the bioeconomy strategies in Chilean science and policy. The selection process followed a multi-stage screening protocol. Initially, approximately 550 records were identified. After title and abstract screening, 280 documents were retained for full-text review. A final selection of 181 documents was made, based on strict inclusion and exclusion criteria. The inclusion criteria required documents to directly address economic, technological, or policy aspects of forestry biomass valorization in Chile and to be published as peer-reviewed articles, technical reports, or policy documents. Topics had to focus on the valorization of byproducts such as lignin, nanocellulose, tannins, or bark. Exclusion criteria included studies focused solely on traditional forest commoditization, such as raw pulp or saw timber, without a clear valorization perspective, studies on non-forest biomass unless for comparative purposes, and global analyses lacking Chilean-specific data. Conference abstracts or documents without full-text availability were also excluded. This systematic approach ensures a comprehensive yet focused synthesis of the scientific progress, technological barriers, and knowledge gaps relevant to Chile's transition toward a circular bioeconomy.

3. The Chilean Forestry Industry Landscape

Chile's forestry sector comprises both plantation forests and native woodlands. As of 2022, commercial forest plantations cover approximately 2.28 million hectares, primarily composed of *P. radiata* (54.6%) and *E. globulus* and *E. nitens* (39.5%). Native forests account for over 14.7 million hectares, and wild protected areas span an additional 18.9 million hectares [7].

In 2023, industrial roundwood consumption in Chile reached approximately 39.95 million cubic meters (solid wood basis, without bark). These volumes were allocated across several industrial applications, including wood chips, sawn wood, pulp, panels and veneers, and posts and poles. Sawn wood and wood pulp constituted over 78% of total industrial roundwood use. Chile's installed sawmill capacity was reported to be over 8 million m^3 for single-shift operations [7].

Despite its strong pulp export orientation, Chile's forest industry has been criticized for an over-reliance on low-value-added products such as raw cellulose. However, recent trends show a growing interest in value-added segments, including panel manufacturing, veneer production, and specialty pulp derivatives [8]. Table 1 summarizes the distribution of industrial wood products and their respective market flows.

Table 1. Industrial roundwood consumption by wood products flow in Chile for 2023 (includes sawlogs and pulplogs) [7].

Wood Products	Consumption (m^3 swb)	Wood Products Flow (m^3 swb)		
		Primary Industry	Domestic Market	Foreign Market
Export Logs	62,524			62,524
Chips Logs	4,269,813	Wood Chips [(a)]	5,379,515 [(b)]	2,775,772
Sawlogs	13,491,275	Sawnwood [(a)]	4,863,916	2,022,935
Pulplogs	17,730,716	Wood pulp	898,837 ton	4,430,600 ton
Logs for Panels and Veneers	4,144,743	Panels and Veneers	1,604,956	1,295,644
Logs for Posts and Poles	249,276	Post and Poles	191,709	49,446
Total Industrial Roundwood Consumption	39,948,347			

[(a)] Sawmill wood residues of 4,234,675 m^3 swb. It refers to wood slabs and wood offcut volume that are chips in the sawmills. [(b)] Of the wood chips destined for the domestic market, 5,136,653 m^3 is used as raw material for pulp production and 363,088 m^3 for panel production. The rest is used as fuel and for other purposes.

Chile is also a major producer of chemical pulp via the Kraft process, with an installed capacity of 7.13 million tons as of 2023 [9,10]. Most products are destined for export, particularly bleached softwood and eucalyptus pulps. Key industrial actors include Celulosa Arauco, CMPC, and UNIPAPEL [7,11]. Growth in thermomechanical pulp (TMP) and diversification toward higher value-added wood products remain ongoing priorities for the sector.

4. Valorization of Forestry Byproducts

Forest biomass residues represent a strategic resource for the development of bio-based materials and compounds. This section details advances in lignocellulosic byproduct valorization, phenolic compound applications, and the integration of residual biomass into the wood panel industry in Chile.

4.1. Lignocellulosic

4.1.1. Lignin: Characteristics, Applications, Challenges, and Chilean Advances

Lignin is a heterogeneous, highly branched, three-dimensional biopolymer of phenolic units derived from phenylpropane, mainly linked by ether bonds. It contains various functional groups that provide active sites for chemical and biological interactions [12].

Lignin is a natural compound found in lignocellulosic plants, with a global production of approximately 300 billion tons and an annual growth rate of 7%. Of this amount, 100 million Mt/y comes from the pulp and paper industry, which produces technical lignin that varies considerably in its molecular structure and weight, affecting its applicability and valorization [13].

Technical lignins can be categorized into several types: Lignosulfonates, which are byproducts of the sulphite pulping process; Kraft lignin (KL), produced during the wood kraft pulping process as a byproduct known as black liquor. Soda lignin is obtained through the soda pulping process, primarily from the biomass of annual crops, and to some extent, hardwoods. Hydrolysis lignin (HL) is produced as a byproduct in cellulosic ethanol plants during the enzymatic hydrolysis processes. Organosolv lignin (OL) is derived from pulping processes that use organic solvents to separate lignin from cellulose, resulting in a lignin with low sulfur content and low molecular weight [14].

The global commercial production of technical lignin, excluding bioenergy, is approximately 1.65 million tons per year, with lignosulfonates accounting for nearly 80% of the market [13]. In Chile, the production of lignosulfonates is limited due to the predominance of the Kraft process in the pulp and paper industry. Although some mills using the sulfite process may generate lignosulfonates, the production volume is low compared to other regions.

Research on lignin and its potential high-value applications has been ongoing for decades. However, these applications have not yet been scaled to industrial levels.

Currently, most of the lignin produced from the paper industry is burned as a low-value fuel to generate electricity and heat, and only a small percentage is used to make specialty chemicals, such as dispersants, adhesives, surfactants, and other value-added products [15]. Different forms of integrating this biopolymer into the synthesis of sustainable materials include phenolic adhesive resins, formaldehyde-free resins, epoxy resins, polyurethane foams, carbon fibers, hydrogels, and 3D-printed composites [16].

From a bioeconomy perspective, lignin is a promising source of renewable phenols, with the potential for valorization as an alternative to petroleum-based polymers [13]. However, its industrial use has been a considerable challenge, primarily due to its low solubility, heterogeneous chemical structure, resistance to systematic depolymerization, and the production of a complex mixture of aromatic compounds during its degradation [17].

In Chile, the lignin obtained from the lignocellulosic biomass refining process is used for energy generation within the pulp mill itself. This is partly due to the lack of adequate infrastructure and the cost of the technological processes required to extract and purify lignin into forms that can be used in higher-value applications.

4.1.2. Nanocellulose (CNF): Production, Functionalization, and Applications

Nanofibrillated cellulose (CNF) is a renewable and biodegradable nanomaterial derived from cellulose, the main structural component of plant cell walls [18]. Through mechanical, chemical, or enzymatic disintegration processes, cellulose can be broken down into nanometric-scale structures, giving rise to materials with unique properties [19]. There are three main types of nanocellulose: nanofibrillated cellulose (CNF), characterized by networks of long and flexible fibrils; cellulose nanocrystals (CNC), formed by rigid and highly crystalline fragments; and bacterial cellulose (BC), biosynthesized by microorganisms in the form of pure fibril networks [20].

Chile is one of the world's leading exporters of cellulosic pulp, ranking second globally in export volume [21]. Its forestry production is mainly based on species such as *E. globulus*, *E. nitens*, and *P. radiata*, which have been widely investigated as raw materials for CNF production due to their abundance and favorable physicochemical properties [22].

4.1.3. CNF Production from *E. globulus*, *E. nitens*, and *P. radiata*

One of the first studies on CNF in Chile was conducted by Syverud et al. [23], who used mechanical methods to compare *E. globulus* and *P. radiata* fibers as raw materials for producing nanofibrillated cellulose. The study assessed structural and morphological parameters, including fibril diameter, suspension homogeneity, and process yield, concluding that both species have high potential for CNF production, though with significant differences in fibrillation behavior and surface properties. This pioneering work laid the groundwork for future research on bio-based materials in Chile, underscoring the importance of local forest resources in developing advanced biomaterials.

Subsequent studies evaluated the production of CNF using commercial Kraft pulps from *E. globulus* and *E. nitens*. Andrade et al. [22] investigated a combined enzymatic–mechanical process to enhance fibrillation, comparing these pulps with *P. radiata*. Differences in chemical composition, such as hemicellulose and residual lignin content, as well as fiber morphology, significantly influenced the fibrillation efficiency and the final properties of the nanofibers. Notably, *E. globulus* pulps produced nanofibers with higher aspect ratios (length/diameter) and intrinsic viscosity, which favors the formation of interconnected networks in aqueous suspension. Also, Henríquez-Gallegos et al. [24] studied the effect of different enzyme loads on CNF production from *E. globulus* and *E. nitens* pulps. Results indicated that a controlled reduction in the degree of polymerization (DP) facilitates the structural opening of cell walls, enhancing fibrillation efficiency. The resulting CNFs had average diameters ranging from 20 to 50 nm and exhibited high colloidal stability due to the generation of highly charged surfaces (see Figure 1).

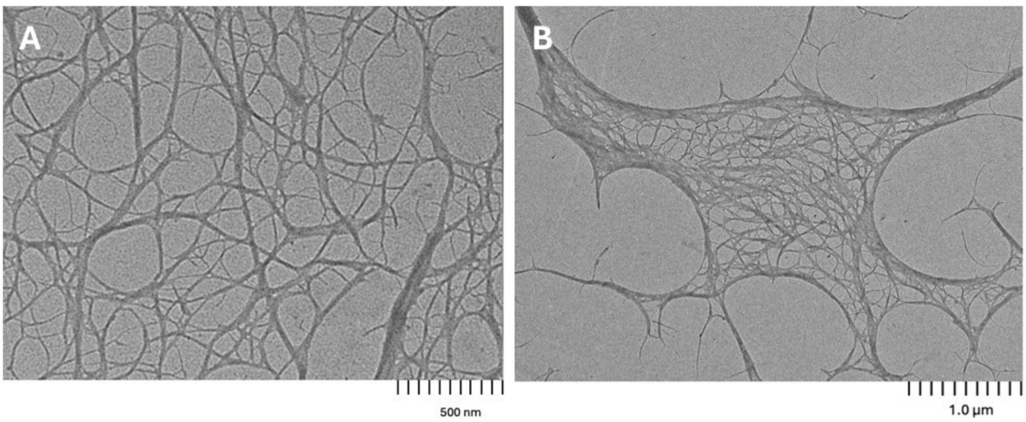

Figure 1. (**A**) Micrograph TEM *E. globulus* of 500 nm. (**B**) Micrograph TEM *E. globulus* of 1.0 µm.

Regarding material functionalization, Andrade et al. [25] evaluated the effect of incorporating lignin nanoparticles (LNPs) into CNF-based nanocomposites derived from *E. globulus* and *E. nitens*. The controlled addition of LNPs significantly enhanced the films' tensile strength and elastic modulus, thereby improving their thermal stability and increasing their thermal degradation temperatures. Furthermore, CNF-LNP nanocomposites exhibited increased resistance to moisture uptake, showing lower water absorption rates and swelling. These results suggest that LNPs act as reinforcing and barrier agents due to their hydrophobic aromatic nature, promoting interfacial compatibility with the CNF matrix and limiting water diffusion through the material. Moreover, Albornoz-Palma et al. [26] analyzed how hemicellulose and lignin content in *E. nitens* and *P. radiata* pulps affect fibrillation efficiency. Through oxidative and alkaline treatments, they altered pulp composition, improving the formation of nanofibril networks with diameters below 30 nm, enhancing suspension transparency, and producing films with high mechanical strength.

P. radiata, unlike eucalyptus species, is characterized by a higher residual lignin content and thicker cell walls, which affect its behavior during fibrillation. These structural features hinder the production of fine-diameter nanofibrils, negatively impacting the aspect ratio and suspension viscosity. Nevertheless, due to its high availability and favorable lignocellulosic composition, *P. radiata* has been widely explored as a raw material for CNF production [22,27]. In the same study of Andrade et al. [22], pine fibers were found to be deconstructed easily during mechanical processing. However, the resulting CNFs had larger fibril diameters (up to 100 nm) and lower aspect ratios than those derived from Eucalyptus, yielding suspensions with lower viscosity at the same concentration. Finally, Albornoz-Palma et al. [26] worked with chemically oxidized *P. radiata* pulps treated with sodium chlorite and acetic acid. As a result, they observed a significant reduction in fibril diameter and a substantial improvement in aqueous dispersion. Reducing the lignin content increased the exposure of cellulose hydroxyl groups, thereby enhancing water affinity and reducing nanofiber agglomeration during mechanical fibrillation.

4.1.4. CNF Applications

There is increasing interest in using CNF in various applications, including food packaging, biomedicine, and water purification. In addition, Aguayo et al. [28] demonstrated that rejected fibers from the industrial Kraft pulping process, traditionally considered waste, could be valorized as raw material for producing high-quality CNC with average dimensions of 5–10 nm in diameter and 100–200 nm in length. These findings underscore the importance of broadening the range of lignocellulosic sources, including both native species and industrial byproducts, in the development of CNF-based materials.

On the other hand, Vergara et al. [29] developed a nanocomposite biofilm using dual electro-spinning, combining cellulose nanofibers with natural zeolite exchanged with copper ions (Cu^{2+}). The resulting material exhibited effective antimicrobial properties and was proposed as an active barrier for food packaging. In another work, Cabrera-Barjas et al. [30] prepared and characterized a bio-nanocomposite film based on chitosan reinforced with *E. globulus* CNF for the release of vancomycin hydrochloride as an antibiotic. The drug release could be controlled by tuning the CNF content in the chitosan film.

Finally, a semi-industrial CNF production process was developed in the Technology Development Unit (UDT), at the University of Concepcion. This process served as the basis for preparing the CNF-acetylated derivative. Both products are now commercially available in Chile, used as bioplastic reinforcement, in the paint industry as a thickener, and in the wood particleboard industry as an adhesive replacement, to reduce formaldehyde emissions.

4.1.5. Hemicellulose: Extraction and Use in Food, Pharma, and Remediation

Hemicellulose is a structurally complex group of heteropolysaccharides found in plant cell walls. They comprise 20%–35% of the lignocellulosic biomass. These polysaccharides are amorphous, branched, and possess a lower degree of polymerization (DP 80–200). The low molecular weight makes their extraction and hydrolysis easy, essential for further industrial applications. Their sugar composition includes many monosaccharides like pentoses (xylose and arabinose), hexoses (glucose, mannose, galactose), and uronic acids [31].

All of them could exhibit variations in their content across different plant species and tissue types. The hemicelluloses are classified into four major structural classes: xylans, mannans, xyloglucans, and mixed-linkage β-glucans. Each type of polysaccharide shows different structural and functional properties in plant cell walls.

In the pulp and paper sector and forestry, hemicelluloses, particularly galactoglucosans (GGMs), represent up to 35% of the dry weight of softwoods such as *P. radiata*. One can recover these by mild acid hydrolysis or hot water. According to Reyes et al. [32], hemicellulose solubilization is highly influenced by temperature and time, but pH has no effect. The extraction yield of hemicellulose was 16%, and the molecular weights of the extracts ranged from 3720 to more than 50,000 g/mol, suggesting potential for additional processing into bio-based products. The primary application of hemicelluloses is in the paper and textile industries to enhance the interaction between fibers and improve print performance.

Hemicelluloses are important feedstocks in biorefineries. They generate xylose and mannose single sugars by hydrolysis, which can be fermented into ethanol, xylitol, furfural, 5-hydroxymethylfurfural (HMF), succinic acid, and lactic acid [33,34]. Moreover, solvents, biofuels, biodegradable polymers, and fine chemicals all start with these intermediates. Engineering microbial strains made it possible to transform pentoses into polyhydroxyalkanoates (PHAs), polylactic acid (PLA), and other building-block compounds [35].

Food companies use hemicellulose compounds as thickening agents, stabilizers, emulsifiers, and dietary fibers. Both arabinoxylans and β-glucans improve dough performance, the yogurt texture, and polyunsaturated fatty acid bioavailability [36]. GGMs also increase the bioavailability of polyunsaturated fatty acids and help stabilize emulsions. Xyloglucans possess additional gelling and stabilizing properties, making them suitable for use in dairy products, sauces, and jams.

On the other hand, hydrogels made from hemicellulose derivatives offer controlled drug release, tunable characteristics, and biocompatibility, making them attractive for pharmaceutical and therapeutic applications. For instance, the hydrogel of GGM–glycidyl methacrylate (GGM-GMA) has shown promise in producing responsive matrices for targeted drug delivery and wound healing, binding agents, or encapsulating active molecules.

Regarding environmental applications, hemicellulose-derived hydrogels have considerable potential for removing heavy metals from wastewater [37,38]. Cross-linkable macromonomers produced by functionalizing GGMs with methacrylate groups enable the synthesis of ion-exchange hydrogels. Using GGM-GMA-based hydrogels, Sánchez et al. [39] reported high adsorption capabilities for heavy metals, e.g., 90 mg/g for Cu(II), 60 to 70 mg/g for Cr(VI) and As(V). Using GGM-based hydrogels functionalized with sulfonic or quaternary ammonium groups, Encina et al. [40] effectively removed Cu(II), Cr(VI), Cd(II), Pb(II), and As(V). In the case of Pb(II), adsorption capacities up to 174.9 mg/g were achieved. All tested hydrogels maintained the removal capacity during several regeneration cycles, indicating the potential of these bioadsorbents for treating contaminated water.

4.2. Phenolic and Bioactive Compounds

4.2.1. Bark Tannins: Extraction and Industrial Applications

Bark from *P. radiata* and *Eucalyptus* ssp. trees is the most significant byproduct [41]. The bark is rich in phenolic compounds, primarily proanthocyanidins, also known as tannins. Tannins are large polyphenolic biomolecules found in gymnosperms and angiosperms. These biomolecules are classified as condensed or hydrolysable tannins. Hydrolysable tannins consist of glucose or other polyhydric alcohols that are esterified with gallic acid or hexahydroxydiphenic acid. They can be further classified as gallotannins or ellagitannins. The acid hydrolysis of these tannins yields gallic acid, ellagic acid, or similar compounds.

Conversely, condensed tannins comprise flavan-3-ols (catechins) and/or flavan-3,4-diols (leucoanthocyanidins). They have molecular weights ranging from 500 to over 20,000 and can react with aldehydes to form polymeric materials [42].

Tannins are found in various parts of plants, such as fruits, leaves, shoots, and bark. Tree bark, including pine, mimosa, quebracho, and chestnut trees, contains high concentrations of tannins. The tannin content of plants varies based on several factors, including the time of year, weather conditions, water availability, temperature, soil quality, and light intensity [43]. They can be extracted from tree bark using various solvents, including water, ethanol, and methanol [44–46]. Due to concerns about toxicity and environmental impact, ethanol and water are the more viable options. However, when considering the production costs associated with purchasing and recovering ethanol, water emerges as the optimal choice for extraction. Other variables, like pH, may also affect extraction efficiency [47].

Bark tannins from Chile, particularly those from *P. radiata* and *E. globulus*, have various potential applications. Studies have examined these tannins for their antioxidant properties and potential applications in biomedicine and cosmetics [48,49], food and feed [50,51], packaging, and related biomaterials [46,52,53], bio-adhesives [54–57], coating materials [58–60], growing media [41,61], wastewater treatment [62–64] and other nanobio-based products [45].

Chilean researchers have developed chitosan-based scaffolds loaded with *P. radiata* tannin-rich bark extract (PBE) and grape seed extract (GSE) for biomedical applications such as wound dressings. The addition of GSE and PBE enhances cell viability and inhibits bacterial activity. These non-toxic scaffolds improve blood absorption and release bioactive compounds. These properties make them promising materials for wound dressings [48]. Additionally, *P. radiata* bark wax is a sustainable alternative to petroleum-based cosmetic ingredients [49]. Recent studies suggest that PBE can mitigate the environmental impact of feed production and enhance the sustainability of aquaculture [50] and ruminant nutrition [51].

Bark tannins from *P. radiata* are promising additives for biodegradable plastics and food packaging. *P. radiata* bark polyflavonoids can be modified to improve compatibility with polymers such as polylactic acid (PLA), which enhances processability and miscibility [46,52,53]. Tannins in food biopackaging offer several advantages, including antioxidant and antimicrobial properties, UV protection, and improved mechanical and barrier characteristics [52,53]. Another application of bark tannins, from *P. radiata* and *E. globulus* trees in Chile, is for bio-adhesive preparation. When extracted on a pilot scale, a 50:50 ratio of these extracts was effective for particleboard adhesives [44]. Another study developed plywood adhesives using polyphenol extracts from *P. radiata* bark. The bio-based formulation, free of formaldehyde, phenol, and isocyanates, improved plywood quality and bond strength [54]. Other authors have discussed using pine tannin adhesives in Chile for particleboard and medium-density fiberboard (MDF), which have excellent quality and low formaldehyde content. Using paraformaldehyde or hexamethylenetetramine as a hardener improved the panels' emission class [55].

Tannins extracted from the waste bark of the *P. radiata* species show promise as coating materials. For instance, one study found that the coating achieved an eco-friendly FRR15 fire classification, equivalent to low-molecular-weight tannins. These coatings met commercial standards, offering increased abrasion resistance, adhesion, and decreased flexibility [58]. Another study used tannins as an inhibitor in epoxy resin and zinc oxide nanoparticles functionalized with 3-aminopropyltriethoxysilane to improve ASTM A36 steel's corrosion resistance [59]. Similarly, research on AISI 1010 steels treated with tannin primers formulated with natural tannins from Chilean radiata pine and Brazilian black acacia revealed that pine tannins are more reactive, more effective at inhibiting corrosion, and adhere better to metallic substrates [60].

Recent studies investigated how the tannin composition and the presence of phenolic and non-phenolic compounds in aqueous *P. radiata* bark extracts influence laccase-catalyzed polymerization and the resulting material's thermal and structural properties [57]. Tannin extracts rich in resorcinol and low in carbohydrates, with fewer polar compounds, produced highly cross-linked polymers with exceptional thermal stability. The same group is working on using tannin for the preparation of superabsorbent hydrogels for sustainable agriculture applications.

P. radiata bark and tannins modified with an acidified formaldehyde solution can effectively remove metal ions from water. The binding values of modified tannins were lower than those of modified bark [64]. Additionally, insoluble tannins from bark can drive Fenton reactions, providing a promising method for degrading wastewater through advanced oxidation processes [63]. Another study tested nine bioflocculants produced via the Mannich reaction using tannin extracts from Acacia, Quebracho, and Castanea, as well as amine derivatives, in wastewater samples. The most effective bioflocculants were Acacia-ammonium chloride and quebracho-diethanolamine [62].

The industrial production of tannins from forestry residues, particularly pine bark, is a well-established technology currently operating at Technology Readiness Level (TRL) 9. Companies such as TANAC S.A. in Brazil [65] and Silvateam S.p.A. in Italy [66] have successfully scaled up the extraction of condensed tannins, primarily proanthocyanidins, from the bark of *Pinus* and *Acacia mearnsii* trees using aqueous and hydroalcoholic processes. These extracts have a variety of applications, including leather tanning, wood adhesive production, and animal nutrition. They are also valued for their natural antioxidant properties [67]. While companies have explored eucalyptus-derived polyphenols, to our knowledge, no eucalyptus tannin extract is currently commercially available. In Chile, UDT/CENAMAD has scaled up its extraction protocols for eucalyptus and pine bark to the pilot stage (TRL 6–7) [44]. This demonstrates the potential of eucalyptus bark as a source of tannins within the circular bioeconomy of forests.

4.2.2. Bio-Based Adhesives Replacing Synthetic Resins

Most industrial panels rely on thermosetting synthetic resins such as urea–formaldehyde (UF), melamine–urea–formaldehyde (MUF), and phenol–formaldehyde (PF). MUF and PF are favored for OSB and exterior-grade boards due to their better water resistance [54]. However, concerns about emissions, especially formaldehyde, have led to tighter regulations and a search for safer alternatives. To meet emission limits, strategies have included incorporating formaldehyde scavengers during curing [68], reducing formaldehyde content during resin synthesis [69], or replacing formaldehyde resins altogether with polyurethanes or isocyanates like methylene diphenyl diisocyanate (MDI) [70]. Yet, despite emission reductions, synthetic resins remain problematic due to their fossil origin, toxicity, and health risks during manufacturing and handling.

Consequently, interest has shifted to bio-based adhesives derived from renewable feedstocks. These include formulations using carbohydrates (e.g., starch and chitosan), proteins (e.g., soy derivatives and animal collagen), and polyphenols such as lignin and tannins extracted from lignocellulosic biomass [71]. Among these, tannin-rich bark extracts, particularly from *P. radiata* and *Eucalyptus* ssp., stand out due to their abundance in Chilean forestry and high phenolic content.

Since the late 1980s, Chile has been at the forefront of research into bio-adhesives based on pine bark extracts. E. von Leyser and collaborators demonstrated the viability of using these extracts as partial phenol replacements in phenol–formaldehyde (PF) resins for exterior-grade panels [72–76]. Initial methods involved the sodium sulfite-assisted aqueous extraction of bark, followed by resin formulation with PF or polymeric MDI as a hardener (5%–10% of extract dry weight). These adhesives were adopted industrially at the Masisa particleboard factory in Chiguayante, Chile, between 1993 and 2002 [55]. In 2012, trials at the Masisa-Mapal MDF plant in Coronel confirmed the feasibility of producing MDF using bark extract adhesives combined with pMDI.

The growing work on bark-based adhesives in Chile spurred the creation of the Technological Development Unit (UDT) at the University of Concepción in 1996. UDT houses a state-of-the-art pilot plant for lignocellulosic extraction, allowing for the optimization and scale-up of extraction processes and the formulation of wood adhesives [77]. For instance, they conducted extensive studies on extraction conditions, chemical characterization, and the curing behavior of pine bark adhesives. One innovation was replacing paraformaldehyde with glyoxal (10%–15% on an extract basis), a less toxic alternative, resulting in particleboards with formaldehyde emissions comparable to natural wood [78,79]. These bio-adhesives also showed acceptable mechanical properties and processing behavior under standard panel manufacturing conditions.

Further advances were reported by Santos et al. [54], successfully producing plywood using pine bark extract adhesives cured with hexamine (5% on an extract basis), using extracts obtained at pilot scale. These efforts reinforced the industrial potential of bark-derived adhesives as replacements for synthetic formulations in wood-based product manufacturing. Despite their promise, several limitations prevent the complete substitution of synthetic adhesives. One challenge is the variability in the chemical composition of bark extracts, which depends on species, growing conditions, and extraction methods. Another is the limited availability of extracts on an industrial scale. Additionally, many bio-adhesive formulations require longer pressing times than conventional adhesives, which can impact production efficiency.

The European wood processing industry has increasingly turned to incorporating recycled particles and byproducts from other sectors as partial substitutes for fresh wood chips [80] to reduce demand for fresh wood and the process's carbon footprint. Stringent regulations concerning formaldehyde and, more recently, VOC (volatile organic compound) emissions from wood-based panels [81] have also led to the development of formaldehyde scavenger agents and low-formaldehyde amine resins [68], as well as bio-adhesives based mainly on wood industry byproducts such as pine bark and lignosulfonates. Companies such as the multinational FINSA have developed wood fiberboard (MDF) made with bio-based adhesives obtained from pine bark, which has a natural component content of over 99% [82].

Pine bark-based adhesives remain one of the most advanced bio-resin alternatives. High-phenolic content extracts are already marketed for adhesive applications, and their partial incorporation into industrial products in Chile is a growing trend. Ongoing research is focused on enhancing reproducibility, improving performance, and shortening pressing cycles. Optimizing extraction parameters to standardize the polyphenol content and curing response is critical for broader application [44].

Chile's strong forestry sector, coupled with academic expertise in biomass chemistry, extraction technologies, and process engineering, provides a solid foundation for expanding the use of bio-adhesives. Continued innovation in the valorization of forestry byproducts, particularly bark, will be crucial to developing low-toxicity, high-performance wood adhesives that align with global bioeconomy and sustainability goals.

4.2.3. Essential Oils and Hydrolates from Eucalyptus and Pinus

E. globulus essential oils (EOs) primarily contain eucalyptol (1,8-cineole, 42%–62%), globulol, α-pinene, and limonene, with the composition depending on the extraction methods and environmental conditions such as altitude [83,84]. In *P. radiata*, essential oils predominantly feature α and β-pinene, monoterpenes renowned for antimicrobial, antioxidant, and anti-inflammatory properties (see Table 2) [85,86].

Table 2. Main chemical compounds identified in the essential oils of *E. globulus* and *E. nitens* extracts, their biological effects, and mechanisms of action.

Plant Species	Main Compound	Biological Effect	Action Mechanism	Ref.
E. globulus	1,8-cineol (eucaliptol)	Antimicrobial (Gram-positive bacteria and fungi)	Inhibition of Gram-positive bacteria and fungi growth by altering cell membrane permeability	[87]
		Antioxidant (presence of flavonoids and tannins)	Neutralization of free radicals due to the presence of flavonoids and tannins	[88]
		Antimicrobial (*Staphylococcus aureus*)	Inhibition of bacterial cell wall synthesis	[89]
		Antifungal (*Candida albicans*)	Alteration of fungal cell membrane integrity	[90]
		Antimicrobial (*Escherichia coli* and *Staphylococcus aureus*)	Disruption of bacterial cell membrane	[91]
		Antimicrobial (periodontal pathogens)	Inhibition of bacterial virulence factors	[92]
		Antiviral (molecular modeling)	Potential inhibition of SARS-CoV-2 by blocking viral proteins	[93]
		Antiviral	Inhibition of viral replication	[94]
		Multiple (antimicrobial, antioxidant, anti-inflammatory)	Various mechanisms including cell membrane alteration	[95]
	1,8-cineol (eucaliptol), α-pineno α-terpineol, γ-terpineno Globulol and epiglobulol	Antibacterial	Disruption of bacterial cell membrane	[83]
		Anti-inflammatory	Inhibition of pro-inflammatory cytokine production	[96]
		Antifungal (dermatophytes)	Inhibition of ergosterol synthesis	[97]
E. nitens	1,8-cineol (eucaliptol) (59.85%), α-pineno (18.36%)	Insecticide (fumigant and repellent against *Sitophilus zeamais*)	Neurotoxicity in insects	[98]

Traditional extraction methods like hydrodistillation and steam distillation remain relevant, although emerging technologies such as ultrasound and microwave-assisted extraction significantly enhance yields and efficiency [99]. Supercritical fluid extraction, particularly with CO_2, also stands out for preserving thermosensitive compounds and is an environmentally friendly process [100].

These oils find diverse applications in cosmetic, pharmaceutical, and agro-industrial sectors, noted for their proven antimicrobial, antioxidant, and anti-inflammatory activities in both in vitro and in vivo studies [93,101]. Additionally, their capability to reduce methane emissions in ruminants represents another significant opportunity, contributing to environmental management in livestock production [102]. Not only EO but also other types of extracts from pine show interesting biological activity with potential industrial applications (see Table 3).

Table 3. Main chemical components and biological effects of different Pinus extract types, with associated mechanisms of action.

Extract Type	Main Compounds	Biological Effect	Action Mechanism	Ref.
Wax	Methyl 4-ketohex-5-enoate; 1-naphthanol; dioctyl adipate; eicosanebiotic acid dimethyl ester	Toxicity evaluation for cosmetic application	Non-toxic up to 2% concentration	[49]
EO	α-pinene, β-pinene, δ-3-carene, β-caryophyllene, limonene/β-phellandrene, and germacrene D	Multiple effects: antiviral, antibacterial, antifungal, herbicidal	Biological activity dependent on dominant terpene components	[103]
EO	1,8-cineole (63.1%), p-cymene (7.7%), α-pinene (7.3%), and α-limonene (6.9%)	Antimicrobial against *S. aureus* and *E. coli*	Disruption of bacterial cell membrane integrity	[104]
Hydrolate	Phenolic compounds, organic acids, and water-soluble terpenes	Antimicrobial against *E. coli*, *S. aureus*, and *C. albicans*	Inhibition of microbial growth through multiple mechanisms	[105]
Oleoresin	Volatile fraction (essential oil), solid fraction (rosin) containing abietic and pimaric acids	Anti-inflammatory and antimicrobial	Inhibition of inflammatory mediators; disruption of microbial membranes	[106]

The Chilean essential oils and hydrolates market from Eucalyptus and Pinus presents critical structural weaknesses that prevent the exploitation of its forestry potential. The severely underdeveloped structured industry is evident in the lack of dedicated infrastructure for extraction and processing. At the same time, a massive import dependence generates a significant trade deficit, reflecting the country's inability to meet its domestic demand. The sector maintains an outdated extractive model, where 95% of the forestry industry focuses on traditional commodities (pulp, paper, and sawn timber), wasting forestry byproducts such as bark, leaves, and branches that have high potential for essential oils. This situation is aggravated by insufficient technology transfer from R&D to the productive sector, which manifests in the limited application of existing research on the chemical potential of local species, the absence of yield and quality characterization by geographical region, and restricted commercial use limited primarily to cosmetics and environmental fragrances rather than diversified industrial applications. Finally, the non-existent regulatory framework lacks specific regulations for forestry essential oil production, quality and origin certifications, and incentives for diversification toward higher value-added products, perpetuating a vicious cycle that maintains Chile as a net importer in a sector where it should be a regional leader.

5. Bark Fiber

Trees, the largest and longest-living organisms, have evolved a tough outer layer called bark to protect themselves. The visible part of the bark, known as the rhytidome, is dead tissue rich in a fatty substance called suberin. Beneath it lies the inner bark, or phloem, comprising living cells responsible for storing and transporting carbohydrates [107]. In general, bark represents a minimum of 10% of the weight of the biomass processed in sawmills and pulp mills.

Based on the total global roundwood in 2022 [108], the estimated bark volume would range between 300 and 600 million m^3, with about 33.3% from coniferous trees and 66.7% from non-coniferous trees. It is, therefore, of interest to identify potential applications that could enhance their value beyond their current use as fuel [109].

Bark, in addition to the typical lignocellulosic polymers in cell walls (cellulose, hemicellulose, and lignin), can also contain significant levels of the structural polymer suberin and an abundant concentration of non-structural polymers such as tannins, stilbenes, and triterpenes [109–111].

Mainly, in some tree species, such as *Eucalyptus* ssp., the bark is presented as a fibrous morphology due to their high cellulose content compared with pine species [112–114]. This characteristic makes it difficult to manage sawmills, even if used as fuel [115]. Figure 2 shows a comparative picture of its different morphologies.

Figure 2. (**A**) *P. radiata* D. Don bark and (**B**) *E. globulus* bark.

Eucalyptus bark is characterized by its high availability [116], which renders it a potentially attractive source for utilization. In this sense, it can be considered to cover the current need to find new natural fiber sources to reduce plastic and increase bio-based materials development. Also, Mustapha et al. [117], through modified pyrolysis, produced a biochar to remove Cr(VI) and Pb(II) in industrial effluent with an excellent performance. Another application is using bark to produce pellets as renewable energy [118]. In addition, Rodriguez et al. [119] studied the preliminary suitability of eucalyptus bark's enzymatic hydrolysate as a feedstock for polyhydroxyalkanoate. Tamayo-Peña et al. [120] provided new insights into effectively generating xylo-oligosaccharides under relatively mild conditions using eucalyptus branches and bark.

In this context, Fuentealba et al. [112,115] have used eucalyptus fiber bark to produce thermal insulation panels for construction, offering environmental and social benefits while maintaining cost-effectiveness and efficiency in thermal conductivity (See Figure 3, Table 4). In this manner, the problematic residue is transformed into a valuable resource, thereby reducing the negative environmental impact of synthetic thermal insulation materials such as mineral wool and extruded polystyrene. This cost-effective alternative increases the use of renewable raw materials, enhances construction affordability, and supports social sustainability. The Life Cycle Assessment (LCA) results of the environmental impact of the stages of producing eucalyptus bark panels showed that it could be a promising feedstock for producing thermal insulation panels with potential applications in the building sector [121]. Additionally, Bakatovich et al. [122] showed high resistance to fungal growth when wet in this same application, suggesting good durability for thermal insulation applications. Different mechanical conversion technologies can be implemented for eucalyptus bark. The versatility of this raw material made it possible to control the density, which affects the thermal properties [112].

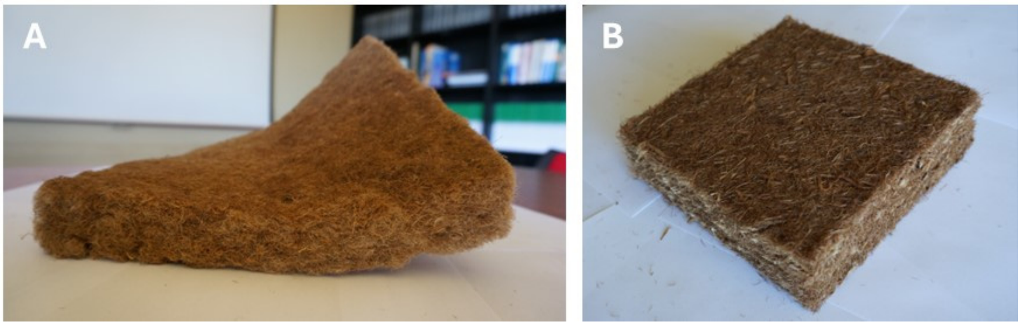

Figure 3. Eucalyptus bark fiber mat with 30 kg/m^3 density (**A**) and wood fiber insulation board with 100 kg/m^3 density (**B**) [123].

Table 4. Comparison of the thermal conductivity of eucalyptus bark panel and other alternative insulation materials [115].

Material	Density (kg/m^3)	Thermal Conductivity (W/mK)	Reference
Eucalyptus bark	97.8 ± 6.5	0.0379 ± 0.00052	[115]
Eucalyptus bark	80–300	0.064–0.077	[112]
Eucalyptus bark	140–160	0.042	[122]
Kenaf	30–180	0.034–0.043	[124]
Jute	26.1	0.0458	
Flax	32.1	0.0429	[125]
Hemp	79.6	0.0475	
Hemp	40.2	0.0393	
Rock wool	40–200	0.0330–0.040	[124]
EPS *	15–35	0.0310–0.0380	
Polyurethane	24	0.0240	[126]

* EPS: Expanded polystyrene.

Eucalyptus bark is an abundant byproduct whose commercial potential has not yet been fully realized on a global scale. However, in Chile, a recent successful transfer of the technology related to the fabrication of fiber thermal insulation boards using eucalyptus bark as a raw material was made from the academy to the industry [127], representing a significant step forward in the commercial valorization of forest residues and the promotion of circular economy practices.

Taking advantage of its fibrous and water-retaining properties, eucalyptus bark has been tested as a growing medium in the search for ecological alternatives to traditional substrates such as peat, pine bark, and coconut fiber. Growing environmental awareness about conserving peatlands has driven extensive research to develop alternative materials to replace peat. Chemetova et al. have reported that hydrothermal treatments effectively removed phytotoxicity from fresh *E. globulus* bark [128–130]. Mixing 25% treated bark with peat improved aeration while maintaining water content. With additional nitrogen fertilization, plant growth (*Chinese cabbage*) matched or exceeded commercial substrates, supporting its use in substrate formulations.

Other investigations have demonstrated that excellent results can be obtained using a mix of 75% eucalyptus and 25% commercial substrates, such as peat, coconut fiber, moss, and composted pine. In addition, it is possible to enhance the growth of radish and Chinese cabbage by incorporating encapsulated fulvic acid at a concentration of 0.1% [41]. The same substrates, such as *P. radiata* and *Quillaja saponaria*, were tested for the growth of forest species [61]. An optimal mixture of 75% eucalyptus bark and 25% peat was obtained for the growth of pine seeds. In contrast, for *Q. saponaria* seeds, the optimal ratio was 50% eucalyptus bark−50% coconut fiber. These results demonstrate that eucalyptus bark can be used as a growth substrate in both horticulture and for the cultivation of forest species, an area of interest for promoting circularity in the forestry sector. Globally, there is no industrial production of eucalyptus bark-based growth substrates, presenting an opportunity to create a commercial product that replaces coconut fiber and peat. Figure 4 shows substrates containing eucalyptus bark fiber mixed with moss, peat, coconut fiber, and composted *P. radiata* bark used for *Q. saponaria* seed growth.

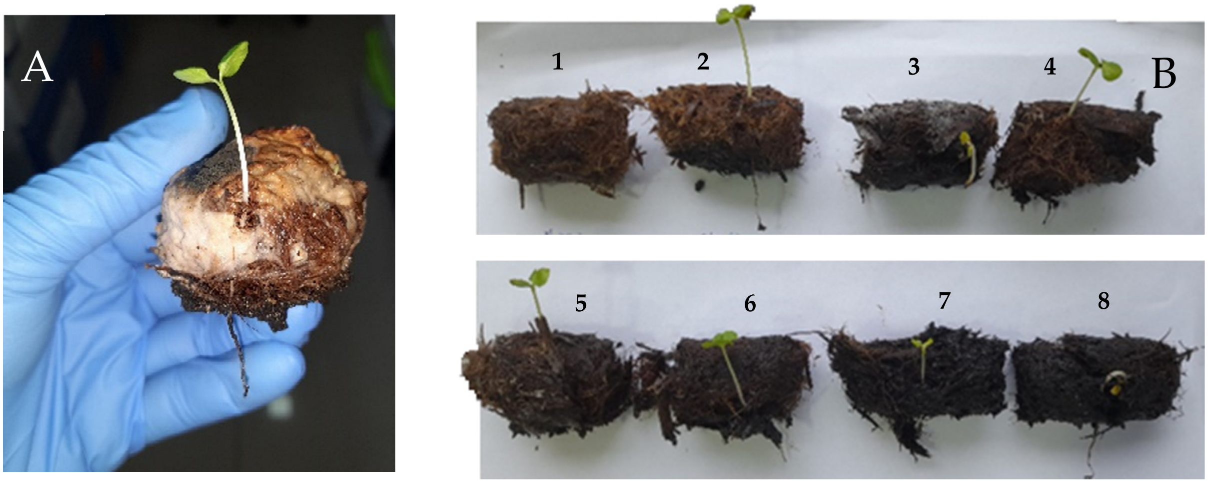

Figure 4. Substrates used in *Quillaja saponaria* (quillay) seed growth. (**A**) Eucalyptus bark fiber–peat–phytostimulant mixture. (**B**) Eucalyptus bark fiber–musk mixture without (1) and with Eucalyptus extract (2). Eucalyptus bark fiber–peat mixture without (3) and with Eucalyptus extract (4). Eucalyptus bark fiber–coconut mixture without (5) and with Eucalyptus extract (6). Composted Eucalyptus–Pine bark fiber mixture without (7) and with Eucalyptus extract (8).

6. Thermochemical Transformation of Forest Byproducts in Chile

Lignocellulosic biomass has roughly 80% volatile matter and 20% fixed carbon; it is biodegradable, hygroscopic, and exhibits a low bulk density of 200–250 kg/m^3. These characteristics complicate management, transport, and preparation for several applications. Chile produces approximately 4.3 million cubic meters of forest biomass byproducts annually, primarily from industrial forestry activities. The valorization of these residues via thermochemical processes—such as torrefaction, pyrolysis, and gasification—presents a promising opportunity for the development of bioenergy and bioproducts. Nevertheless, in comparison to global progress, Chile is still in the early stages of development, with efforts limited to pilot projects and research initiatives. This section contextualizes Chile's position in the global advancement of torrefaction, pyrolysis, and gasification for the valorization of forestry biomass.

6.1. Torrefaction

Torrefaction is a thermochemical pre-treatment that decomposes hemicellulose and partially degrades cellulose and lignin, resulting in a solid fuel with enhanced grindability, hydrophobicity, and heating value (19–23 MJ/kg). This technique enhances energy densification, yielding energy levels ranging from 50% to 90%, depending on operating conditions [131].

Torrefaction achieved commercial maturity on a global scale. Companies like Blackwood Technology (Hoofddorp, The Netherlands) manage facilities that produce over 50,000 tons of torrefied biomass annually, providing it for co-firing in coal power stations and cement kilns. These facilities combine torrefaction with pelletization to enhance fuel transportation, storage, and combustion efficiency [132].

Torrefaction research in Chile commenced in 2013 with preliminary screening studies and kinetic modeling [133]. In 2014, a notable endeavor was undertaken by UDT (Universidad de Concepción), Engie Energía, and Forestal Calle-Calle to establish a pilot-scale facility for the torrefaction and pelletization of eucalyptus residues (bark and leftovers). The 70 kg/h facility, integrated with a 300 kg/h pelletization system, employs a multiple-hearth reactor utilizing superheated steam and has oxygen-free storage and condensate recovery (Figure 5a) [134].

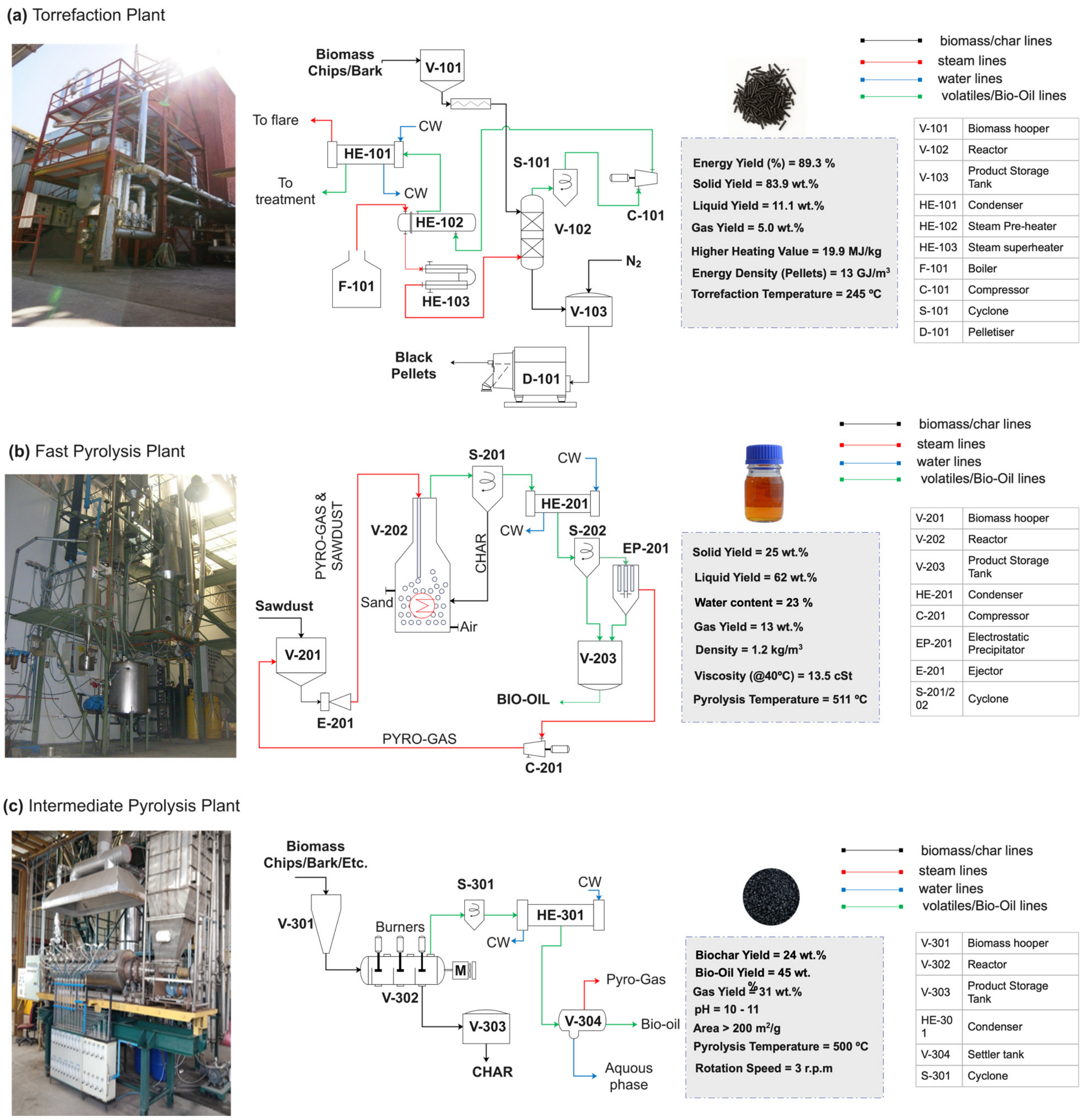

Figure 5. Photographs, process flow diagrams, and performance indicators of pilot plants established within UDT facilities. (**a**) Torrefaction plant, (**b**) fast pyrolysis plant, and (**c**) intermediate pyrolysis plant.

Despite these advancements, no industrial-scale torrefaction facilities are present in Chile. Research entities like BIOREN at Universidad de la Frontera and UDT have successfully conducted the torrefaction of *P. radiata* residues, attaining calorific values comparable to international standards (20–22 MJ/kg). Nonetheless, combustion experiments are confined to laboratory-scale and small boiler configurations [135]. The limited information on techno-economic evaluations and their integration with current pellet industries constitutes an important barrier to commercial implementation.

6.2. Pyrolysis

Pyrolysis breaks down biomass in oxygen-restricted environments at temperatures between 400 °C and 700 °C, yielding three primary products: bio-oil, permanent gases (such as CO, CO_2, and H_2), and charcoal. The yields and composition of the pyrolytic products depend on the characteristics of the feedstock, the heating rate, and the reactor configuration.

Fast pyrolysis has been marketed globally by businesses, including Ensyn [136] and BTG-BTL [137]. Their technologies transform forest and agricultural residues into bio-oils, which are utilized as fuels or chemical feedstocks. Biochar is used in agriculture, water purification, and carbon sequestration [138].

In Chile, pyrolysis initiatives concentrate on research and pilot demonstrations. BIOREN and UDT are the principal entities advancing this technology. UDT functions as a 25 kg/h flash pyrolysis unit that can yield around 60 wt% bio-oil, utilizing a three-stage fluidized bed reactor with integrated heat recovery. Bio-oils generated from forestry have elevated water content (>45 wt%), necessitating further condensation separation (Figure 5b) [139].

Another unit at UDT—a 12 kg/h intermediate pyrolysis plant—incorporates a rotating kiln and ten axial gas burners, operating within a broad temperature range (450–950 °C). This technology has generated biochar and bio-oil from various biomass sources for application in fuels and fertilizers (Figure 5c).

Despite these technical capabilities, no commercial pyrolysis facilities are currently operational in Chile for biomass conversion. There are no regulatory frameworks for the utilization of bio-oil as fuel, nor are there national certification standards for biochar. This regulatory gap hinders commercialization and restricts investor interest in biorefinery-scale applications. Conversely, foreign entities gain advantages from more defined policy frameworks and developed markets.

6.3. Gasification

Gasification involves the partial oxidation of carbonaceous materials (e.g., biomass and coal) to generate a producer gas mixture containing H_2, CO, CO_2, C_xH_y, particulates, and tars. The gasification gas can be utilized in combined heat and power systems, internal combustion engines, or refined into fuels and chemicals.

Europe and Asia are at the forefront of biomass gasification implementation. However, the installation and operation of industrial gasification systems have reduced their relevance over the past decade.

In Chile, gasification is limited to academic institutions. UDT manages a bench-scale facility (1–5 g/min) for the catalytic elimination of tar from syngas, incorporating a downdraft reactor, real-time gas analysis, and catalyst evaluation for tar reduction to <100 ppm [140,141]. Moreover, researchers from the Mechanical Engineering Department at the Universidad de Concepción have implemented a gasification system for producing syngas in a modified updraft reactor, which is being tested for flexi-fuel gasification [142]. In addition, the Center for Study of Energy Resources (CERE-Universidad de Magallanes) evaluated a 10 kW All Power Labs unit using Lenga wood chips, achieving gas yields of approximately 2 m^3/kg in laboratory conditions and 1.84 m^3/kg during field experiments at sub-zero temperatures.

The Universidad Técnica Federico Santa María (UTFSM) also operates modest downdraft gasifiers (5–100 kWth) primarily for educational and prototyping purposes. Syngas has been assessed for use in internal combustion engines and thermal provision in off-grid rural and agro-industrial environments.

Although the technical viability of biomass gasification has been established, Chile lacks the necessary industrial-scale infrastructure and integration within energy systems. In contrast to nations with robust rural electrification initiatives, Chile's policy framework for decentralized bioenergy is fragmented. Closing the gap between research and commercialization requires focused demonstration programs and targeted government incentives.

7. Sustainability and Regulatory Framework

The valorization of forestry biomass in Chile is closely tied to national sustainability strategies, legal frameworks, and environmental metrics. Incorporating life cycle thinking and promoting circular economy practices are critical for guiding innovation and industrial adoption.

7.1. Circular Economy Roadmap and Extended Producer Responsibility (REP) Law

The concept of the bioeconomy has recently become a strategic tool for balancing environmental sustainability with economic growth [143]. The concept of bioeconomy has been defined and interpreted in various ways [144]. For instance, the European Commission defined it as "*the production and extraction of renewable biological resources (termed 'biomass') and their transformation into food and feed; bio-based products (including timber, fibre, chemicals, or bioplastics) and bioenergy (such as firewood, biofuels, or biogas)*" [145]. Conversely, the Biomass Research and Development Board [146] characterizes the bioeconomy as the worldwide industrial shift towards the sustainable utilization of renewable aquatic and terrestrial biomass resources for energy, intermediates, and final products, aimed at economic, environmental, social, and national security objectives. Consequently, the bioeconomy refers to the transition to renewable biological processes to produce bioenergy and bioproducts, which promotes economic growth while also providing environmental and social benefits. In this context, Chile has undertaken various international commitments that necessitate integrating the bioeconomy into its governmental agenda. In its 2020 update of the Nationally Determined Contributions (NDCs) [147], Chile identified the circular economy as a fundamental pillar of its adherence to the Paris Agreement. Chile has made three specific promises: (i) a Roadmap to the Circular Economy 2040 [148], (ii) a National Organic Waste Strategy [149], and (iii) the development and implementation of circularity metrics and indicators to evaluate the nation's progress in this area. Furthermore, Chile reiterates its commitment to the Sustainable Development Goals (SDGs) of the 2030 Agenda, positioning the bioeconomy as a strategic approach to aligning policies necessary for the implementation of the 2030 Agenda [143]. The bioeconomy specifically advocates for innovative production models (e.g., biorefineries and bio-industry) that facilitate the creation of novel products utilized as inputs in various sectors (e.g., biomaterials for construction and biochemicals for agriculture, among others) [143].

The Roadmap to the Circular Economy 2040, launched by the Ministry of Environment [148], seeks to help the shift to a circular economy. The aim is to achieve the country's sustainable and fair participatory development, promoting the responsible use of natural resources and supporting sustainable production and consumption patterns.

Holistically, evaluating the entire life cycle of goods, services, and processes helps to create more environmentally friendly manufacturing and resource management systems. Moreover, the Law on Extended Producer Responsibility (Ley REP), passed in 2016 [150], is now in force. Its goals are to reduce national waste generation and promote reuse inside the country. The Chilean government aims to alter general consumer behavior and promote the concept of continuous material recycling. The polluter pays principle holds that a company generating waste is responsible for it and must absorb the related expenses and adverse effects of waste management. Apart from that, Chile boasts a forested area of more than 16 million hectares; natural forests account for 86% while plantations make up the remaining 14% [151]. Chile is also one of the top twenty exporters of forest products globally. Furthermore, regarded as pollution and problematic in the linear perspective of the economy are the availability of significant volumes of waste biomass produced in biologically based primary sectors, especially in forestry waste. From a circular bioeconomy perspective, these components are resources nevertheless, valuable for new value chains (energy, bioplastics and other biomaterials, the recovery of proteins and enzymes for industrial use, and others).

7.2. Life Cycle Assessment (LCA) of Bioproducts

Emphasizing the bioenergy route through thermochemical processes, numerous national studies have established the technical viability of various bioeconomic pathways, including bio-based chemicals such as bio-adhesives and bio-based panels, as previously described. Many studies support the sustainability of the already mentioned paths; yet, depending on renewable resources does not automatically make the bioeconomy sustainable [144]. Therefore, the need to evaluate sustainability performance calls for applying Life Cycle Assessment (LCA), the main approach for analyzing environmental performance by spotting and assessing the possible environmental effects connected with every level of a bioeconomy life cycle [152].

From an environmental standpoint, greenhouse gas emissions are the most interesting impact category reported in the literature, particularly for biomass energy pathways compared to fossil energy routes. The biomass–energy pathway (0.17–0.25 kg CO_{2eq}/kWh) is recognized as producing significantly lower greenhouse gas emissions than hard coal (1.13 kg CO_{2eq}/kWh), lignite (1.06 kg CO_{2eq}/kWh), and natural gas (0.49 kg CO_{2eq}/kWh) [153]. Nonetheless, when comparing different bioenergy routes, total carbon emissions per kWhe vary significantly between technologies and feedstocks, ranging from 0.049 to 2.58 kg CO_{2eq}/kWhe, as shown in Table 5. It is crucial to acknowledge that the environmental performance of the circular bioeconomy is highly contingent upon the bioeconomy system boundaries, technology type and efficiency, biomass productivity, the completeness and representativeness of input data, and methodological assumptions, including burden allocation procedures and functional units. For instance, carbon emissions from sawmill residue processing are estimated to be 0.17 kg CO_{2eq}/kWhe, which is three to four times higher than those reported by [154] (0.049 kg CO_{2eq}/kWhe for forest residues) and [155] (0.038 kg CO_{2eq}/kWhe for wood chips) under similar power generation schemes. Weldu et al. [154] found that excluding silviculture and road construction activities from their system boundaries contributed to lower emissions. Furthermore, transportation distances played a significant role in the differences. Those considered in the reference studies were approximately 48% shorter than the sawmill residue supply chain, resulting in noticeably lower associated emissions.

Table 5. Comparative analysis of different bioenergy routes and bio-based materials.

Bioeconomy Routes	Raw Materials	$kgCO_{2eq}$/kWh	References
Bioenergy Pathway			
Combustion	Forest residues (FRs)	0.063	[154]
	Pellets from FR	0.615	[156]
	Pellets from SRa	0.731	[156]
Co-firing CHP	Coal and raw pellets	2.32	[157]
Co-firing CHP	Coal and torrefied pellets	2.58	[157]
Co-firing CHP	Peat and biomass	0.72	[158]
Gasification–ICE	FR [a]	0.049	[154]
Gasification–ICE	Wood chip	0.038	[155]
Gasification–ICE	SR [b]	0.17–0.20	[153]
Bio-Based Materials	**Embodied Energy MJ/f.ub [c]**	**$kgCO_{2eq}$/f.ub**	**References**
Expanded polyurethane	125	5.1	[159]
Expanded polystyrene	130	5.0	[159]
Glass wool	229	9.8	[159]
Rice husk	45	1.9	[160]
Kenaf fibers	42.3	1.1	[161]
Eucalyptus bark fibers	16–72	1.4–5.9	[121]

[a] FRs: forest residues. [b] SRa: sawmill residues. [c] f.u: the mass (kg) of insulation material delivering 1 m^2K/W of thermal resistance.

When analyzing total carbon emissions and embodied energy per functional unit (f.u) for bio-based materials, a wide variation is observed across different insulation materials, with carbon emissions ranging from 1.1 to 10 kg CO_2eq/f.u and embodied energy spanning 16.2 to 229 MJ/f.u. Overall, thermal insulation materials derived from natural fibers—such as kenaf, rice husk, and eucalyptus bark—tend to exhibit significantly better environmental performance than conventional synthetic materials. Specifically, natural fiber-based insulations typically require less energy (16.2–72.3 MJ/f.u) and result in lower carbon emissions (1.1–5.9 kg CO_{2eq}/f.u). In contrast, traditional materials such as glass wool, expanded polyurethane, and expanded polystyrene demonstrate considerably higher environmental impacts.

However, while bioeconomy pathways exhibit environmental benefits in specific impact categories, such as global warming and energy demand, they do not consistently provide advantages across all environmental impact categories. In this sense, Casas-Ledón et al. [153] demonstrated that silviculture significantly contributed to the eutrophication category (>42%) due to phosphate and NO_3 emissions during forest management for gasification–ICE systems integrated into sawmills in Chile. Similarly, Arteaga-Perez [157] discovered that co-firing coal with forest biomass for electricity generation in Chile could diminish greenhouse gas emissions yet exhibited a greater eutrophication potential than fossil fuel systems (coal). These results align with comparable international studies, confirming that the biomass energy pathway may have a greater impact on eutrophication than fossil fuels [162–164].

Bio-based materials also demonstrated environmental benefits [165]. Most studies agree that using bio-based panels, whether from forestry or agriculture, can reduce the impact on climate change and abiotic resources [121,165,166] compared to conventional materials; however, it may hurt eutrophication and land use. Furthermore, forestry management has been implicated in several negative environmental impacts [167]. For instance, Braun et al. [167] discovered that the presence of forestry plantations harmed plant biodiversity. They observed a significant decrease in species richness, native species, and endemic species in the central zone of Chile. Additionally, Echeverria et al. [168] reported a reduction in native forest and its fragmentation, with the largest patch of native forest decreasing from 6.91% in 1975 to 0.16% in 2000 due to the proliferation of exotic trees, thereby diminishing the core habitat. Moreover, exotic tree plantations have contributed to heightened land erosion [169] and reduced the morpho-sedimentary regulation capacity of the Biobío River basin [170]. Moreover, the current forest model has precipitated various socio-environmental conflicts in the regions hosting the plantations, including rural exodus [171,172] and community displacement [173,174], and has even resulted in violent confrontations in certain rural areas of the Araucanía Region [175].

Chile has promoted sustainable forest management through PEFC-endorsed Chilean CERTFOR and Forest Stewardship Council (FSC) schemes, which have been implemented for both native and plantation forestry [176]. This certification involves impacts, including the cessation of deforestation for plantation establishment, the rehabilitation of natural ecosystems, greater benefits to local communities, and the development of a positive dialog between forestry businesses and their stakeholders. In this context, Tricallotis et al. [177] have reported the beneficial effects of certification in mitigating unsustainable forest management, which may facilitate a more sustainable bioeconomy pathway through a cradle-to-cradle approach.

The switch to a sustainable bioeconomy requires substituting renewable biological resources for fossil fuels and establishing a sustainable supply chain that encompasses sustainable biomass feedstock manufacturing and logistics, as well as sustainable biomass conversion techniques and the production of sustainable products. The integration of several essential elements will determine the ongoing success of the bioeconomy. This includes developing effective and sustainable logistics systems to support biomass supply chains; formulating standardized regulatory frameworks guaranteeing safety, quality, and environmental compliance across areas; and encouraging economic innovation to produce competitive bio-based products and services [178,179]. Stimulating market demand also depends critically on raising public awareness and fostering customer acceptance. All bioeconomic policies must still be based primarily on an intense focus on sustainability, encompassing social, economic, and environmental aspects.

8. Barriers to Technology Transfer and Industrial Adoption

Despite scientific progress, several barriers hinder the industrial implementation of biomass valorization technologies in Chile.

Regarding the technical and scale-up limitations, many pilot studies remain limited to laboratory or semi-industrial scale due to challenges in consistency, process integration, and capital investment. For instance, producing nanocellulose with controlled properties at an industrial scale requires high energy input and robust quality control. Adhesive systems using lignin or tannins often require formulation optimization to achieve a suitable balance of curing time, viscosity, and bond strength under industrial pressing conditions.

On the other side, another significant constraint is the lack of specific Chilean standards for bio-based adhesives, biodegradable composites, and non-timber forest product (NTFP) extracts. Without clear performance criteria, manufacturers are reluctant to substitute conventional inputs. Additionally, the absence of harmonized safety evaluations (e.g., for food contact materials or agricultural inputs) delays commercialization.

All these barriers impact the market and overall competitiveness, creating a challenging environment in which bio-based alternatives often face resistance due to higher costs, a lack of awareness, or market inertia. Educational campaigns, public procurement incentives, and eco-labeling could help create demand. Strategic alliances among academia, government, and industry are essential for mitigating risks associated with early adoption phases.

9. Research Gaps and Future Directions

Although progress has been made in forestry biomass valorization in Chile, several scientific, technical, and policy-related gaps remain. Addressing these challenges is crucial for scaling up innovations and establishing a robust forest-based bioeconomy.

9.1. Pilot-Scale Validation and Industrial Scaling

A key limitation is the scarcity of pilot-scale demonstrations (TRL 5–7) for bioproducts based on lignin, tannins, nanocellulose, and hemicellulose. Most studies remain at laboratory scale, limiting the generation of reliable techno-economic and environmental data. There is a need to establish shared pilot plants, such as modular biorefineries, where SMEs and researchers can test scale-up processes and material performance in real industrial conditions.

9.2. Functionalization and Performance Optimization

Further research is needed on the chemical modification of lignin and hemicelluloses to improve solubility, thermal stability, and compatibility with polymers. For nanocellulose, surface functionalization to control hydrophobicity and dispersion remains underdeveloped in Chile. Cross-disciplinary work with polymer chemists and materials engineers is needed to enable tailored applications such as barrier coatings, hydrocolloids, and innovative packaging.

9.3. Standardization and Regulatory Framework

Chile lacks standardized protocols for testing and certifying bio-based adhesives, packaging, and NTFPs. This absence limits industrial trust and market entry. Future work should focus on developing national standards that are aligned with EU and ISO frameworks, particularly for food-grade materials and biodegradable composites.

9.4. Integration of Biodiversity and Native Species

Current valorization strategies focus mainly on *P. radiata* and *Eucalyptus* spp. Future directions should explore underutilized native species such as Drimys winteri, Laurelia sempervirens, and *Nothofagus* spp. for their unique polyphenolic, aromatic, or extractive profiles. Genomic tools and phytochemical libraries could guide selective valorization strategies while preserving biodiversity.

9.5. Policy Instruments and Demand Creation

Research should evaluate how public procurement, green labeling, and carbon markets can incentivize the adoption of bio-based products. Integrating forestry valorization into national decarbonization plans (e.g., NDCs) could leverage climate finance and accelerate deployment.

9.6. LCA and Techno-Economic Models for New Products

Very few studies have conducted full cradle-to-grave LCA or techno-economic assessment (TEA) of new Chilean bio-based products. Developing open-access models and LCA databases tailored to Chilean forestry contexts is necessary for informed investment decisions and adequate policy support.

9.7. Socioeconomic and Regional Development Impacts

Future research should also investigate how biomass valorization can contribute to regional development, particularly in forest-rich but economically underdeveloped areas, such as Araucanía and Los Ríos. This includes rural entrepreneurship, job creation, and the preservation of ecosystem services under a just transition lens.

10. Conclusions

Chile's forestry sector is undergoing a paradigm shift from a resource extraction model to one grounded in value-added bioproducts and sustainable circular economy principles. This review identified technical advances, institutional support, and knowledge gaps in the valorization of biomass. Chilean forest developments reflect a growing institutional and industrial commitment to innovation in bioprocessing and materials science.

Despite these advances, the full-scale deployment of bio-based technologies remains constrained by biomass variability, gaps in process standardization, limited regulatory incentives, and a lack of established high-value markets. We also recognize limitations in the scope of this review, including the need for broader benchmarking with international experiences and more comprehensive life cycle data for each valorization pathway.

To address these issues, future priorities should include the following roadmap: strengthening research and development in green biorefinery technologies, scaling up pilot processes with public–private partnerships, standardizing bio-based product quality and certification, expanding education and innovation incentives for SMEs, and enhancing LCA and policy frameworks.

Ultimately, Chile's biodiversity, forestry infrastructure, and scientific capacity provide a robust foundation for becoming a leader in the forest-based bioeconomy in Latin America. However, achieving this will require sustained institutional coordination, industrial transformation, and science-based environmental stewardship.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f16081208/s1, Table S1. Search strategies used in database search.

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References

1. Nepal, P.; Prestemon, J.P.; Joyce, L.A.; Skog, K.E. Global Forest Products Markets and Forest Sector Carbon Impacts of Projected Sea Level Rise. *Glob. Environ. Change* **2022**, *77*, 102611. [CrossRef]
2. FAO. *Global Forest Products. Facts and Figures 2023*; FAO: Rome, Italy, 2024; ISBN 978-92-5-139445-8.
3. FAO. *The State of the World's Forests 2024*; FAO: Rome, Italy, 2024; ISBN 978-92-5-138867-9.

4. Weiss, G.; Ludvig, A.; Živojinović, I. Embracing the Non-Wood Forest Products Potential for Bioeconomy—Analysis of Innovation Cases across Europe. *Land* **2023**, *12*, 305. [CrossRef]
5. Slavec, A.; Hoeben, A.D.; Moreno-Torres, M.; Primožič, L.; Stern, T. When Intentions Do Not Matter: Climate Change Mitigation and Adaptation Innovations in the Forest-Based Sector. *For. Policy Econ.* **2023**, *157*, 103074. [CrossRef]
6. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
7. Poblete, P.; Kahler, C.; Bañados, J.; Gysling, J.; Pardo, E.; Soto, D.; Baeza, D.; Catelicán, L.; Hernández, J.; Troncoso, H. *Anuario Forestal de Chile 2024, Boletín Estadístico N° 199*; Instituto Forestal: Santiago, Chile, 2024.
8. Cardemil, M. *Industria Forestal En Chile. Serie Minutas N° 68-21*; Biblioteca del Congreso Nacional de Chile, Departamento de Estudios, Extensión y Publicaciones: Santiago, Chile, 2021; pp. 1–14.
9. Klein, H.S.; Luna, F.V. Chapter 10: Cellulose. In *Brazilian Crops in the Global Market*; Springer Nature: Cham, Switzerland, 2023; pp. 269–293.
10. Barrera, D. *Celulosa Chilena: Avances y Perspectivas de Su Comercio Exterior. Oficina de Estudios y Políticas Agrarias (ODEPA)*; Biblioteca Digital ODEPA: Santiago, Chile, 2018.
11. González, M.; Morin, V.; Labra, N.; Castro, A. The Cellulose Industry and Its Impact on the Population: From the Social to the Biochemical. *Rev. Interam. Ambient. Tur.* **2021**, *17*, 179–188. [CrossRef]
12. Ralph, J.; Lundquist, K.; Brunow, G.; Lu, F.; Kim, H.; Schatz, P.F.; Marita, J.M.; Hatfield, R.D.; Ralph, S.A.; Christensen, J.H.; et al. Lignins: Natural Polymers from Oxidative Coupling of 4-Hydroxyphenyl-Propanoids. *Phytochem. Rev.* **2004**, *3*, 29–60. [CrossRef]
13. Dessbesell, L.; Paleologou, M.; Leitch, M.; Pulkki, R.; Xu, C. (Charles) Global Lignin Supply Overview and Kraft Lignin Potential as an Alternative for Petroleum-Based Polymers. *Renew. Sustain. Energy Rev.* **2020**, *123*, 109768. [CrossRef]
14. Ekielski, A.; Mishra, P.K. Lignin for Bioeconomy: The Present and Future Role of Technical Lignin. *Int. J. Mol. Sci.* **2021**, *22*, 63. [CrossRef]
15. Bajwa, D.S.; Pourhashem, G.; Ullah, A.H.; Bajwa, S.G. A Concise Review of Current Lignin Production, Applications, Products and Their Environment Impact. *Ind. Crops Prod.* **2019**, *139*, 111526. [CrossRef]
16. Vásquez-Garay, F.; Carrillo-Varela, I.; Vidal, C.; Reyes-Contreras, P.; Faccini, M.; Mendonça, R.T. A Review on the Lignin Biopolymer and Its Integration in the Elaboration of Sustainable Materials. *Sustainability* **2021**, *13*, 2697. [CrossRef]
17. Sethupathy, S.; Murillo Morales, G.; Gao, L.; Wang, H.; Yang, B.; Jiang, J.; Sun, J.; Zhu, D. Lignin Valorization: Status, Challenges and Opportunities. *Bioresour. Technol.* **2022**, *347*, 126696. [CrossRef]
18. Moon, R.J.; Martini, A.; Nairn, J.; Simonsen, J.; Youngblood, J. Cellulose Nanomaterials Review: Structure, Properties and Nanocomposites. *Chem. Soc. Rev.* **2011**, *40*, 3941–3994. [CrossRef]
19. Klemm, D.; Kramer, F.; Moritz, S.; Lindström, T.; Ankerfors, M.; Gray, D.; Dorris, A. Nanocelluloses: A New Family of Nature-Based Materials. *Angew. Chem. Int. Ed.* **2011**, *50*, 5438–5466. [CrossRef] [PubMed]
20. Abitbol, T.; Rivkin, A.; Cao, Y.; Nevo, Y.; Abraham, E.; Ben-Shalom, T.; Lapidot, S.; Shoseyov, O. Nanocellulose, a Tiny Fiber with Huge Applications. *Curr. Opin. Biotechnol.* **2016**, *39*, 76–88. [CrossRef] [PubMed]
21. Volza Grow Global "Exportaciones de Pulpa de Madera Desde Chile". Available online: https://www.volza.com/p/wood-pulp/export/export-from-chile/ (accessed on 29 April 2025).
22. Andrade, A.; Henríquez-Gallegos, S.; Albornoz-Palma, G.; Pereira, M. Effect of the Chemical and Structural Characteristics of Pulps of Eucalyptus and Pinus on the Deconstruction of the Cell Wall during the Production of Cellulose Nanofibrils. *Cellulose* **2021**, *28*, 5387–5399. [CrossRef]
23. Syverud, K.; Chinga-Carrasco, G.; Toledo, J.; Toledo, P.G. A Comparative Study of Eucalyptus and Pinus Radiata Pulp Fibres as Raw Materials for Production of Cellulose Nanofibrils. *Carbohydr. Polym.* **2011**, *84*, 1033–1038. [CrossRef]
24. Henríquez-Gallegos, S.; Albornoz-Palma, G.; Andrade, A.; Soto, C.; Pereira, M. Impact of the Enzyme Charge on the Production and Morphological Features of Cellulose Nanofibrils. *Polymers* **2021**, *13*, 3238. [CrossRef]
25. Andrade, A.; Nuñez, J.; Henríquez-Gallegos, S.; Torres, C.; Mendez-Miranda, A.; Valenzuela-García, E.; Albornoz-Palma, G.; Ortega-Sanhueza, I.; Valerio, O.; Montoya, L.F.; et al. Interaction of Nanofibrillated Cellulose with Lignin Nanoparticles: Effects on CNF-LNP Composite Properties. *Carbohydr. Polym. Technol. Appl.* **2025**, *9*, 100651. [CrossRef]
26. Albornoz-Palma, G.; Henríquez-Gallegos, S.; Ortega-Sanhueza, I.; Teruel-Juanes, R.; Ribes-Greus, A.; Pereira, M. Influence of Hemicellulose and Lignin on the Fibrillation Efficiency and Properties of Cellulose Nanofibrils from Native and Oxidized Eucalyptus Nitens and Pinus Radiata Pulps. *Cellulose* **2025**, *32*, 2629–2648. [CrossRef]
27. Hoeger, I.C.; Nair, S.S.; Ragauskas, A.J.; Deng, Y.; Rojas, O.J.; Zhu, J.Y. Mechanical Deconstruction of Lignocellulose Cell Walls and Their Enzymatic Saccharification. *Cellulose* **2013**, *20*, 807–818. [CrossRef]

28. Aguayo, M.G.; Pérez, A.F.; Reyes, G.; Oviedo, C.; Gacitúa, W.; Gonzalez, R.; Uyarte, O. Isolation and Characterization of Cellulose Nanocrystals from Rejected Fibers Originated in the Kraft Pulping Process. *Polymers* **2018**, *10*, 1145. [CrossRef] [PubMed]
29. Vergara-Figueroa, J.; Alejandro-Martin, S.; Cerda-Leal, F.; Gacitúa, W. Dual Electrospinning of a Nanocomposites Biofilm: Potential Use as an Antimicrobial Barrier. *Mater. Today Commun.* **2020**, *25*, 101671. [CrossRef]
30. Cabrera-Barjas, G.; Becherán, L.; Valdés, O.; Giordano, A.; Segura-del Río, R.; Bravo-Arrepol, G.; Durán-Lara, E.F.; Cea, J.; Berg, A.; Castaños, J.; et al. Effect of Cellulose Nanofibrils on Vancomycin Drug Release from Chitosan Nanocomposite Films. *Eur. Polymer. J.* **2023**, *197*, 112371. [CrossRef]
31. Qaseem, M.F.; Shaheen, H.; Wu, A.M. Cell Wall Hemicellulose for Sustainable Industrial Utilization. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110996. [CrossRef]
32. Reyes, P.; Teixeira Mendonça, R.; Rodríguez, J.; Fardim, P.; Vega, B. Characterization of the Hemicellulosic Fraction Obtained After Pre-Hydrolysis of Pinus Radiata Wood Chips with Hot-Water at Different Initial Ph. *J. Chil. Chem. Soc.* **2013**, *58*, 1614–1618. [CrossRef]
33. Olivares, Y.; Herrera, C.; Seguel, J.; Sepúlveda, C.; Parra, C.; Pecchi, G. Stable Sulfonic MCM-41 Catalyst for Furfural Production from Renewable Resources in a Biphasic System. *Catalysts* **2023**, *13*, 1024. [CrossRef]
34. Valenzuela, R.; Priebe, X.; Troncoso, E.; Ortega, I.; Parra, C.; Freer, J. Fiber Modifications by Organosolv Catalyzed with H_2SO_4 Improves the SSF of Pinus Radiata. *Ind. Crops Prod.* **2016**, *86*, 79–86. [CrossRef]
35. Singh, A.K.; Upadhyay, S.K.; Singh, S.P. Microbial Bioreactors for Industrial Molecules. In *Microbial Bioreactors: An Introduction*; Singh, S.P., Upadhyay, S.K., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2023; pp. 1–16.
36. Mathura, S.R.; Landázuri, A.C.; Mathura, F.; Andrade Sosa, A.G.; Orejuela-Escobar, L.M. Hemicelluloses from Bioresidues and Their Applications in the Food Industry-towards an Advanced Bioeconomy and a Sustainable Global Value Chain of Chemicals and Materials. *Sustain. Food Technol.* **2024**, *2*, 183. [CrossRef]
37. Dax, D.; Chávez, M.S.; Xu, C.; Willför, S.; Mendonça, R.T.; Sánchez, J. Cationic Hemicellulose-Based Hydrogels for Arsenic and Chromium Removal from Aqueous Solutions. *Carbohydr. Polym.* **2014**, *111*, 797–805. [CrossRef] [PubMed]
38. Dax, D.; Soledad Chávez Bastidas, M.; Honorato, C.; Liu, J.; Spoljaric, S.; Seppälä, J.; Mendonça, R.T.; Xu, C.; Willför, S.; Sánchez, J.; et al. Tailor-Made Hemicellulose-Based Hydrogels Reinforced with Nanofibrillated Cellulose. *Nord. Pulp Pap. Res. J.* **2015**, *30*, 373–384. [CrossRef]
39. Sánchez, J.; Dax, D.; Tapiero, Y.; Xu, C.; Willför, S. Bio-Based Hydrogels with Ion Exchange Properties Applied to Remove Cu(II), Cr(VI), and As(V) Ions from Water. *Front. Bioeng. Biotechnol.* **2021**, *9*, 656472. [CrossRef] [PubMed]
40. Encina, L.; Elgueta, E.; Rivas, B.L.; Pereira, M.; Sanhueza, F. Hydrogels Derived from Galactoglucomannan Hemicellulose with Inorganic Contaminant Removal Properties. *RSC Adv.* **2021**, *11*, 35960–35972. [CrossRef]
41. Escobar-Avello, D.; Ferrer, V.; Bravo-Arrepol, G.; Reyes-Contreras, P.; Elissetche, J.P.; Santos, J.; Fuentealba, C.; Cabrera-Barjas, G. Pretreated Eucalyptus Globulus and Pinus Radiata Barks: Potential Substrates to Improve Seed Germination for a Sustainable Horticulture. *Forests* **2023**, *14*, 991. [CrossRef]
42. Das, A.K.; Islam, M.N.; Faruk, M.O.; Ashaduzzaman, M.; Dungani, R. Review on Tannins: Extraction Processes, Applications and Possibilities. *S. Afr. J. Bot.* **2020**, *135*, 58–70. [CrossRef]
43. Shirmohammadli, Y.; Efhamisisi, D.; Pizzi, A. Tannins as a Sustainable Raw Material for Green Chemistry: A Review. *Ind. Crops Prod.* **2018**, *126*, 316–332. [CrossRef]
44. Santos, J.; Escobar-Avello, D.; Fuentealba, C.; Cabrera-Barjas, G.; González-Álvarez, J.; Martins, J.M.; Carvalho, L.H. Forest By-Product Valorization: Pilot-Scale Pinus Radiata and Eucalyptus Globulus Bark Mixture Extraction. *Forests* **2023**, *14*, 895. [CrossRef]
45. Cabrera-Barjas, G.; Butto-Miranda, N.; Nesic, A.; Moncada-Basualto, M.; Segura, R.; Bravo-Arrepol, G.; Escobar-Avello, D.; Moeini, A.; Riquelme, S.; Neira-Carrillo, A. Condensed Tannins from Pinus Radiata Bark: Extraction and Their Nanoparticles Preparation in Water by Green Method. *Int. J. Biol. Macromol.* **2024**, *278*, 134598. [CrossRef]
46. García, D.E.; Gavino, J.; Escobar, D.; Cancino, R.A. Maleinated Polyflavonoids and Lignin as Functional Additives for Three Kinds of Thermoplastics. *Iran. Polym. J. (Engl. Ed.)* **2017**, *26*, 295–304. [CrossRef]
47. Fraga-Corral, M.; García-Oliveira, P.; Pereira, A.G.; Lourenço-Lopes, C.; Jimenez-Lopez, C.; Prieto, M.A.; Simal-Gandara, J. Technological Application of Tannin-Based Extracts. *Molecules* **2020**, *25*, 614. [CrossRef] [PubMed]
48. Borges-Vilches, J.; Unalan, I.; Aguayo, C.R.; Fernández, K.; Boccaccini, A.R. Multifunctional Chitosan Scaffold Platforms Loaded with Natural Polyphenolic Extracts for Wound Dressing Applications. *Biomacromolecules* **2023**, *24*, 5183–5193. [CrossRef] [PubMed]
49. Sandoval-Rivas, D.; Morales, D.V.; Hepp, M.I. Toxicity Evaluation of Pinus Radiata D.Don Bark Wax for Potential Cosmetic Application. *Food Chem. Toxicol.* **2023**, *178*, 113896. [CrossRef] [PubMed]
50. Astuya, A.; Ziehe, J.; Rivera, A.; Ortiz, S.; Ulloa, V.; Roeckel, M.; Aspé, E.; Fernández, K. Antioxidant and Anti-Inflammatory Activities of Pinus Radiata Bark Extract in Salmonid Cell Lines. *Aquac. Res.* **2017**, *48*, 3568–3578. [CrossRef]

51. Vera, N.; Gutiérrez, C.; Williams, P.; Fuentealba, C.; Allende, R.; Ávila–Stagno, J. Low Concentrations of a Polyphenolic Extract from Pine Bark in High–Concentrate Diets Decrease in Vitro Rumen Ammonia Nitrogen but Not Methane Production. *J. Appl. Anim. Res.* **2021**, *49*, 413–422. [CrossRef]
52. García, D.E.; Medina, P.A.; Zúñiga, V.I. Toxicological Features of Maleilated Polyflavonoids from Pinus Radiata (D. Don.) as Potential Functional Additives for Biomaterials Design. *Food Chem. Toxicol.* **2017**, *109*, 1069–1078. [CrossRef] [PubMed]
53. Vera, M.; Mella, C.; García, Y.; Jiménez, V.A.; Urbano, B.F. Recent Advances in Tannin-Containing Food Biopackaging. *Trends Food Sci. Technol.* **2023**, *133*, 28–36. [CrossRef]
54. Santos, J.; Delgado, N.; Fuentes, J.; Fuentealba, C.; Vega-Lara, J.; García, D.E. Exterior Grade Plywood Adhesives Based on Pine Bark Polyphenols and Hexamine. *Ind. Crops Prod.* **2018**, *122*, 340–348. [CrossRef]
55. Valenzuela, J.; von Leyser, E.; Pizzi, A.; Westermeyer, C.; Gorrini, B. Industrial Production of Pine Tannin-Bonded Particleboard and MDF. *Eur. J. Wood Wood Prod.* **2012**, *70*, 735–740. [CrossRef]
56. Soto, R.; Freer, J.; Baeza, J. Evidence of Chemical Reactions between Di- and Poly-Glycidyl Ether Resins and Tannins Isolated from Pinus Radiata D. Don Bark. *Bioresour. Technol.* **2005**, *96*, 95–101. [CrossRef]
57. Vera, M.; Silva, C.; Li, N.; García, Y.; Jiménez, V.A.; Urbano, B.F. Laccase-mediated Polymerization of Tannins from a Pine Bark Extract: Toward an Eco-friendly Valorization of Forest Wastes. *J. Appl. Polym. Sci.* **2024**, *141*, 55437. [CrossRef]
58. Montoya, L.F.; Flores, J.; Ramírez, J.; Rojas, D.; Oñate, Á.; Fernández, K.; Jaramillo, A.F.; Miranda, C.; Melendrez, M.F. New Sustainable Intumescent Coating Based on Polyphenols Obtained from Wood Industry Waste. *Coatings* **2024**, *14*, 1004. [CrossRef]
59. Jaramillo, A.F.; Montoya, L.F.; Prabhakar, J.M.; Sanhueza, J.P.; Fernández, K.; Rohwerder, M.; Rojas, D.; Montalba, C.; Melendrez, M.F. Formulation of a Multifunctional Coating Based on Polyphenols Extracted from the Pine Radiata Bark and Functionalized Zinc Oxide Nanoparticles: Evaluation of Hydrophobic and Anticorrosive Properties. *Prog. Org. Coat.* **2019**, *135*, 191–204. [CrossRef]
60. Matamala, G.; Smeltzer, W.; Droguett, G. Comparison of Steel Anticorrosive Protection Formulated with Natural Tannins Extracted from Acacia and from Pine Bark. *Corros. Sci.* **2000**, *42*, 1351–1362. [CrossRef]
61. Ferrer-Villasmil, V.; Fuentealba, C.; Reyes-Contreras, P.; Rubilar, R.; Cabrera-Barjas, G.; Bravo-Arrepol, G.; Escobar-Avello, D. Extracted Eucalyptus Globulus Bark Fiber as a Potential Substrate for Pinus Radiata and Quillaja Saponaria Germination. *Plants* **2024**, *13*, 789. [CrossRef] [PubMed]
62. Arismendi, W.A.; Ortiz-Ardila, A.E.; Delgado, C.V.; Lugo, L.; Sequeda-Castañeda, L.G.; Celis-Zambrano, C.A. Modified Tannins and Their Application in Wastewater Treatment. *Water Sci. Technol.* **2018**, *78*, 1115–1128. [CrossRef]
63. Romero, R.; Contreras, D.; Segura, C.; Schwederski, B.; Kaim, W. Hydroxyl Radical Production by a Heterogeneous Fenton Reaction Supported in Insoluble Tannin from Bark of Pinus Radiata. *Environ. Sci. Pollut. Res.* **2017**, *24*, 6135–6142. [CrossRef]
64. Palma, G.; Freer, J.; Baeza, J. Removal of Metal Ions by Modified Pinus Radiata Bark and Tannins from Water Solutions. *Water Res.* **2003**, *37*, 4974–4980. [CrossRef]
65. TANAC S.A. Available online: www.tanac.com.br (accessed on 29 June 2025).
66. SILVATEAM. Available online: www.silvateam.com (accessed on 29 June 2025).
67. Pizzi, A. Tannins: Prospectives and Actual Industrial Applications. *Biomolecules* **2019**, *9*, 344. [CrossRef]
68. Costa, N.A.; Pereira, J.; Ferra, J.; Cruz, P.; Martins, J.; Magalhães, F.D.; Mendes, A.; Carvalho, L.H. Scavengers for Achieving Zero Formaldehyde Emission of Wood-Based Panels. *Wood Sci. Technol.* **2013**, *47*, 1261–1272. [CrossRef]
69. Santos, J.; Pereira, J.; Paiva, N.; Ferra, J.; Magalhães, F.D.; Martins, J.M.; de Carvalho, L.H. Water Resistance Evaluation of a MFU Resins with Different Molar Ratio Catalyzed with Citric Acid. *Int. J. Adhes. Adhes.* **2022**, *117*, 103020. [CrossRef]
70. Fernandes, R.A.; Ferreira, N.; Lopes, S.; Santos, J.; Bento Pereira, N.; Ferreira, N.O.; Nunes, L.; Martins, J.M.; Carvalho, L.H. Development of an Innovative Lightweight Composite Material with Thermal Insulation Properties Based on Cardoon and Polyurethane. *Polymers* **2024**, *16*, 137. [CrossRef]
71. Arias, A.; González-Rodríguez, S.; Vetroni Barros, M.; Salvador, R.; de Francisco, A.C.; Moro Piekarski, C.; Moreira, M.T. Recent Developments in Bio-Based Adhesives from Renewable Natural Resources. *J. Clean. Prod.* **2021**, *314*, 127892. [CrossRef]
72. Pizzi, A. Pine Tannin Adhesives for Particleboard. *Holz Als Roh-Und Werkst.* **1982**, *40*, 293–301. [CrossRef]
73. von Leyser, E.; Pizzi, A. The Formulation and Commercialization of Glulam Pine Tannin Adhesives in Chile. *Holz Als Roh Werkst.* **1990**, *48*, 25–29. [CrossRef]
74. Pizzi, A.; von Leyser, E.R.; Valenzuela, J.; Clark, J.G. The Chemistry and Development of Pine Tannin Adhesives for Exterior Particleboard. *Holzforschung* **1993**, *47*, 168–174. [CrossRef]
75. Pizzi, A.; Valenzuela, J.; Westermeyer, C. Non-Emulsifiable, Water-Based, Mixed Diisocyanate Adhesive Systems for Exterior Plywood Part II. Theory Application and Industrial Results. *Holzforschung* **1993**, *47*, 68–71. [CrossRef]
76. Pizzi, A.; Valenzuela, J.; Westermeyer, C. Low Formaldehyde Emission, Fast Pressing, Pine and Pecan Tannin Adhesives for Exterior Particleboard. *Holz Als Roh Werkst.* **1994**, *52*, 311–315. [CrossRef]

77. Bocalandro, C.; Sanhueza, V.; Gómez-Caravaca, A.M.; González-Álvarez, J.; Fernández, K.; Roeckel, M.; Rodríguez-Estrada, M.T. Comparison of the Composition of Pinus Radiata Bark Extracts Obtained at Bench- and Pilot-Scales. *Ind. Crops Prod.* **2012**, *38*, 21–26. [CrossRef]
78. Navarrete, P.; Mansouri, H.R.; Pizzi, A.; Tapin-Lingua, S.; Benjelloun-Mlayah, B.; Pasch, H.; Rigolet, S. Wood Panel Adhesives from Low Molecular Mass Lignin and Tannin without Synthetic Resins. *J. Adhes. Sci. Technol.* **2010**, *24*, 1597–1610. [CrossRef]
79. Mansouri, H.R.; Navarrete, P.; Pizzi, A.; Tapin-Lingua, S.; Benjelloun-Mlayah, B.; Pasch, H.; Rigolet, S. Synthetic-Resin-Free Wood Panel Adhesives from Mixed Low Molecular Mass Lignin and Tannin. *Eur. J. Wood Wood Prod.* **2011**, *69*, 221–229. [CrossRef]
80. Iždinský, J.; Vidholdová, Z.; Reinprecht, L. Particleboards from Recycled Wood. *Forests* **2020**, *11*, 1166. [CrossRef]
81. Gonçalves, S.; Curling, S.F.; Ormondroyd, G.; Paiva, N.T.; Martins, J.; Magalhães, F.D.; Carvalho, L.H. Volatile Organic Compound (VOC) Emissions from No-Added-Formaldehyde Lignosulphonate/PMDI Particleboards and Their Effect on Indoor Air Quality. *Wood Mater. Sci. Eng.* **2024**, 1–9. [CrossRef]
82. Finsa: Fibrapan Bio. Available online: https://www.finsa.com/en/fp/fibrapan-fibrapan_bio/fibrapan/fibrapan-bio (accessed on 30 June 2025).
83. El Guerrouj, B.; Taibi, M.; Elbouzidi, A.; Bouhassoun, S.; Loukili, E.H.; Moubchir, T.; Haddou, M.; Hammouti, Y.; Khoulati, A.; Addi, M.; et al. The Effect of Altitude on the Chemical Composition, Antioxidant and Antimicrobial Activities of Eucalyptus Globulus Labill. Essential Oils. *Trop. J. Nat. Prod. Res.* **2023**, *7*, 5279–5285. [CrossRef]
84. Čmiková, N.; Galovičová, L.; Schwarzová, M.; Vukic, M.D.; Vukovic, N.L.; Kowalczewski, P.Ł.; Bakay, L.; Kluz, M.I.; Puchalski, C.; Kačániová, M. Chemical Composition and Biological Activities of Eucalyptus Globulus Essential Oil. *Plants* **2023**, *12*, 1076. [CrossRef] [PubMed]
85. Hernández, F.; Cordano, G.; Medina, J.; Rivera, E. Pino Radiata y Eucaliptus Citriodora: Fuente de Materias Primas Para La Industria Cosmética. *Rev. Col. Químico Farm.* **1979**, *35*, 30–36.
86. Sisubalan, N.; Sivamaruthi, B.S.; Kesika, P.; Chaiyasut, C. Composition, Bioactivities, Safety Concerns, and Impact of Essential Oil on Pets' and Animals' Health. *Preprints* **2023**, 1–25. [CrossRef]
87. Chariguamán Coello, A.; Montero Mora, M.C.; Velastegui Freire, C.A.; Guerrero Naranjo, L.E. Evaluación de los Compuestos Bioactivos y Aplicaciones Terapéuticas del Aceite Esencial de Eucalyptus Globulus. *Sapiens Int. Multidiscip. J.* **2025**, *2*, 1–11. [CrossRef]
88. González-Burgos, E.; Liaudanskas, M.; Viškelis, J.; Žvikas, V.; Janulis, V.; Gómez-Serranillos, M.P. Antioxidant Activity, Neuroprotective Properties and Bioactive Constituents Analysis of Varying Polarity Extracts from Eucalyptus Globulus Leaves. *J. Food Drug Anal.* **2018**, *26*, 1293–1302. [CrossRef]
89. Nadjib, B.M.; Amine, F.M.; Abdelkrim, K.; Fairouz, S.; Maamar, M. Liquid and Vapour Phase Antibacterial Activity of Eucalyptus Globulus Essential Oil = Susceptibility of Selected Respiratory Tract Pathogens. *Am. J. Infect. Dis.* **2014**, *10*, 105–117. [CrossRef]
90. Macedo-Ramírez, Y.; Mejía-Delgado, E. Antifungal Efficacy of Eucalyptus Globulus Ethanolic Extract on In Vitro Candida Albicans. *Rev. Méd. Trujillo* **2019**, *14*, 79–91. [CrossRef]
91. Shiekh, R.A.E.; Atwa, A.M.; Elgindy, A.M.; Mustafa, A.M.; Senna, M.M.; Alkabbani, M.A.; Ibrahim, K.M. Therapeutic Applications of Eucalyptus Essential Oils. *Inflammopharmacology* **2025**, *33*, 163–182. [CrossRef]
92. Müller-Heupt, L.K.; Vierengel, N.; Groß, J.; Opatz, T.; Deschner, J.; von Loewenich, F.D. Antimicrobial Activity of Eucalyptus Globulus, Azadirachta Indica, Glycyrrhiza Glabra, Rheum Palmatum Extracts and Rhein against Porphyromonas Gingivalis. *Antibiotics* **2022**, *11*, 186. [CrossRef] [PubMed]
93. Fernandez, S.A.; Pelaez-Prestel, H.F.; Ras-Carmona, A.; Mozas-Gutierrez, J.; Reyes-Manzanas, R.; Reche, P.A. Eucalyptus Essential Oil Inhibits Cell Infection by SARS-CoV-2 Spike Pseudotyped Lentivirus. *Biomedicines* **2024**, *12*, 1885. [CrossRef]
94. Mieres-Castro, D.; Ahmar, S.; Shabbir, R.; Mora-Poblete, F. Antiviral Activities of Eucalyptus Essential Oils: Their Effectiveness as Therapeutic Targets against Human Viruses. *Pharmaceuticals* **2021**, *14*, 1210. [CrossRef]
95. Dhakad, A.K.; Pandey, V.V.; Beg, S.; Rawat, J.M.; Singh, A. Biological, Medicinal and Toxicological Significance of *Eucalyptus* Leaf Essential Oil: A Review. *J. Sci. Food Agric.* **2018**, *98*, 833–848. [CrossRef]
96. Lin, W.; Jianbo, S.; Wanzhong, L.; Yanna, L.; Weiwei, S.; Gang, W.; Chunzhen, Z. Protective Effect of Eucalyptus Oil on Pulmonary Destruction and Inflammation in Chronic Obstructive Pulmonary Disease (COPD) in Rats. *J. Med. Plants Res.* **2017**, *11*, 129–136. [CrossRef]
97. Baptista, E.B.; Zimmermann-Franco, D.C.; Lataliza, A.A.B.; Raposo, N.R.B. Chemical Composition and Antifungal Activity of Essential Oil from Eucalyptus Smithii against Dermatophytes. *Rev. Soc. Bras. Med. Trop.* **2015**, *48*, 746–752. [CrossRef]
98. González-Guiñez, R.; Silva-Aguayo, G.; Urbina-Parra, A.; Gerding-González, M. Aceite Esencial de *Eucalyptus globulus* Labill Y *Eucalyptus nitens* H. Deane & Maiden (MYRTACEAE) Para El Control de *Sitophilus zeamais* Motschulsky. *Chil. J. Agric. Anim. Sci.* **2016**, *32*, 204–216.

99. Pheko-Ofitlhile, T.; Phiri, N.; Serame, E.; Lepodise, L.M. Chemical Profiling and Spectroscopic Studies of Leaf Volatile Oil of *Eucalyptus globulus* from Botswana Isolated by Conventional Hydrodistillation and Ultrasound Assisted Hydrodistillation. *Nat. Prod. Res.* **2024**, 1–8. [CrossRef]
100. Hasni, S.; Riguene, H.; Mendiola, J.A.; Ibáñez, E.; Montero, L.; Domínguez-Rodríguez, G.; Ghazghazi, H.; Rigane, G.; Salem, R. Ben Optimization of a Pressurized Extraction Process Based on a Ternary Solvent System for the Recovery of Neuroprotective Compounds from Eucalyptus Marginata Leaves. *Int. J. Mol. Sci.* **2025**, *26*, 94. [CrossRef]
101. Xu, G.; Guo, J.; Sun, C. Eucalyptol Ameliorates Early Brain Injury after Subarachnoid Haemorrhage via Antioxidant and Anti-Inflammatory Effects in a Rat Model. *Pharm. Biol.* **2021**, *59*, 112–118. [CrossRef] [PubMed]
102. Kurniawati, A.; Al Anas, M.M. The Effect of a Candidate Feed Additive Derived from the Essential Oils of *Pinus merkusii* (Jungh & de vriese) and *Melaleuca leucadendra* (l.) on the Kinetics of Gas Production and Methane Emitted during In-Vitro Ruminal Fermentation. In Proceedings of the BIO Web of Conferences, Yogyakarta, Indonesia, 23 August 2021; EDP Sciences: Les Ulis, France, 2021; Volume 33, p. 04009.
103. Nikolić, B.M.; Ballian, D.; Mitić, Z.S. Diversity of Needle Terpenes Among Pinus Taxa. *Forests* **2025**, *16*, 623. [CrossRef]
104. Mirković, S.; Tadić, V.; Milenković, M.T.; Ušjak, D.; Racić, G.; Bojović, D.; Žugić, A. Antimicrobial Activities of Essential Oils of Different Pinus Species from Bosnia and Herzegovina. *Pharmaceutics* **2024**, *16*, 1331. [CrossRef] [PubMed]
105. Ancuceanu, R.; Anghel, A.I.; Hovaneț, M.V.; Ciobanu, A.M.; Lascu, B.E.; Dinu, M. Antioxidant Activity of Essential Oils from Pinaceae Species. *Antioxidants* **2024**, *13*, 286. [CrossRef] [PubMed]
106. Semerdjieva, I.; Cantrell, C.L.; Zheljazkov, V.D.; Radoukova, T.; Koleva-Valkova, L.H.; Astatkie, T.; Kačániová, M.; Borisova, D. Chemical Profile, Antioxidant and Antimicrobial Activity of Pinus Heldreichii Christ. Distributed in Bulgaria. *Heliyon* **2024**, *10*, e22967. [CrossRef]
107. Morris, H.; Jansen, S. Bark: Its Anatomy, Function and Diversity. *Int. Dendrol. Soc.* **2017**, 51–61.
108. FAOSTAT—Forestry Production and Trade. Available online: https://www.fao.org/faostat/en/#data/FO (accessed on 11 November 2024).
109. Neiva, D.M.; Ek, M.; Sels, B.F.; Samec, J.S.M. Toward Sustainable Upgrading of Bark. *Chem. Catal.* **2024**, *4*, 101022. [CrossRef]
110. Domingues, R.M.A.; Oliveira, E.L.G.; Freire, C.S.R.; Couto, R.M.; Simões, P.C.; Neto, C.P.; Silvestre, A.J.D.; Silva, C.M. Supercritical Fluid Extraction of Eucalyptus Globulus Bark—A Promising Approach for Triterpenoid Production. *Int. J. Mol. Sci.* **2012**, *13*, 7648–7662. [CrossRef]
111. Neiva, D.M.; Araújo, S.; Gominho, J.; de Cássia Carneiro, A.; Pereira, H. Potential of Eucalyptus Globulus Industrial Bark as a Biorefinery Feedstock: Chemical and Fuel Characterization. *Ind. Crops Prod.* **2018**, *123*, 262–270. [CrossRef]
112. Fuentealba, C.; Segovia, C.; Pradena-Miquel, M.; César, A.G. Efficient Bio-Based Insulation Panels Produced from Eucalyptus Bark Waste. *Forests* **2024**, *15*, 1628. [CrossRef]
113. Feng, S.; Cheng, S.; Yuan, Z.; Leitch, M.; Xu, C. Valorization of Bark for Chemicals and Materials: A Review. *Renew. Sustain. Energy Rev.* **2013**, *26*, 560–578. [CrossRef]
114. Xiao, M.Z.; Chen, W.J.; Cao, X.F.; Chen, Y.Y.; Zhao, B.C.; Jiang, Z.H.; Yuan, T.Q.; Sun, R.C. Unmasking the Heterogeneity of Carbohydrates in Heartwood, Sapwood, and Bark of Eucalyptus. *Carboh. Polym.* **2020**, *238*, 116212. [CrossRef]
115. Fuentealba, C.; Segovia, C.; Vibert, C.; Brosse, N. Eucalyptus Globulus Bark as Valuable Raw Material to the Development of Bio-Based Material. In *Springer Proceedings in Materials*; Springer: Berlin/Heidelberg, Germany, 2024; Volume 43, pp. 76–87.
116. Quilhó, T.; Pereira, H. Within and Between-Tree Variation of Bark Content and Wood Density of Eucalyptus Globulus in Commercial Plantations. *IAWA J.* **2001**, *22*, 255–265. [CrossRef]
117. Mustapha, L.S.; Obayomi, O.V.; Yahya, M.D.; Lau, S.Y.; Obayomi, K.S. Exploring the Synergistic Effects of Calcium Chloride Modification on Stem Bark Eucalyptus Biochar for Cr(VI) and Pb(II) Ions Removal: Kinetics, Isotherm, Thermodynamic and Optimization Studies. *Bioresour. Technol. Rep.* **2024**, *25*, 101699. [CrossRef]
118. Laloon, K.; Junsiri, C.; Sanchumpu, P.; Ansuree, P. Factors Affecting the Biomass Pellet Using Industrial Eucalyptus Bark Residue. *Biomass Conver. Biorefin.* **2024**, *14*, 10101–10113. [CrossRef]
119. Rodrigues, T.; Torres, C.A.V.; Marques, S.; Gírio, F.; Freitas, F.; Reis, M.A.M. Polyhydroxyalkanoate Production from Eucalyptus Bark's Enzymatic Hydrolysate. *Materials* **2024**, *17*, 1773. [CrossRef]
120. Tamayo-Peña, J.A.; Tovar, L.P.; Pacheco, L.C.A.; Gonçalves, A.R.; Franco, T.T. Eucalyptus Grandis Forestry Residue Valorization: Distinct and Integrated Pretreatment Methods for Enhanced Xylooligosaccharide Production. *Bioenergy Res.* **2024**, *17*, 1503–1521. [CrossRef]
121. Casas-Ledón, Y.; Daza Salgado, K.; Cea, J.; Arteaga-Pérez, L.E.; Fuentealba, C. Life Cycle Assessment of Innovative Insulation Panels Based on Eucalyptus Bark Fibers. *J. Clean. Prod.* **2020**, *249*, 119356. [CrossRef]
122. Bakatovich, A.; Bakatovich, N.; Silva, A.; Gaspar, F. Thermal Insulation Materials Based on Eucalyptus Bark Fibres. *Constr. Build. Mater.* **2024**, *449*, 138559. [CrossRef]

123. Fuentealba, C.; Berg, A.; Salazar, J.; Vega, J.; Michanickl, A. Un Proceso de Obtención de Un Material Fibroso a Partir de Corteza Útil Para Fabricar Materiales Aislantes. CL2016003408A1, 2 June 2017. Available online: https://www.patentguru.com/CL2016003408A1 (accessed on 23 April 2025).
124. Asdrubali, F.; D'Alessandro, F.; Schiavoni, S. A Review of Unconventional Sustainable Building Insulation Materials. *Sustain. Mater. Technol.* **2015**, *4*, 1–17. [CrossRef]
125. Korjenic, A.; Petránek, V.; Zach, J.; Hroudová, J. Development and Performance Evaluation of Natural Thermal-Insulation Materials Composed of Renewable Resources. *Energy Build.* **2011**, *43*, 2518–2523. [CrossRef]
126. Ardente, F.; Beccali, M.; Cellura, M.; Mistretta, M. Building Energy Performance: A LCA Case Study of Kenaf-Fibres Insulation Board. *Energy Build.* **2008**, *40*, 1–10. [CrossRef]
127. AISLACOR: Aislante Sustentable. Available online: https://aislacor.cl/ (accessed on 26 June 2025).
128. Chemetova, C.; Mota, D.; Fabião, A.; Gomimho, J.; Ribeiro, H. Valorization of Eucalyptus Globulus Bark as a Growing-Media Component for Potted Plants. In Proceedings of the 15th International Conference on Environmental Science and Technology (CEST) 2017, Rhodes, Greece, 31 August–2 September 2017; pp. 1–5.
129. Chemetova, C.; Fabião, A.; Gominho, J.; Ribeiro, H. Range Analysis of Eucalyptus Globulus Bark Low-Temperature Hydrothermal Treatment to Produce a New Component for Growing Media Industry. *Waste Manag.* **2018**, *79*, 1–7. [CrossRef] [PubMed]
130. Chemetova, C.; Mota, D.; Fabião, A.; Gominho, J.; Ribeiro, H. Low-Temperature Hydrothermally Treated Eucalyptus Globulus Bark: From By-Product to Horticultural Fiber-Based Growing Media Viability. *J. Clean. Prod.* **2021**, *319*, 128805. [CrossRef]
131. Gizaw, D.G.; Periyasamy, S.; Baylie, H.; Tassew Redda, Z.; Asaithambi, P.; Jayakumar, M.; Baskar, G.; Pugazhendhi, A. Advances in Solid Biofuels Production through Torrefaction: Potential Biomass, Types of Torrefaction and Reactors, Influencing Process Parameters and Future Opportunities—A Review. *Process Saf. Environ. Prot.* **2024**, *186*, 1307–1319. [CrossRef]
132. Blackwood Technology. Available online: https://www.blackwood-technology.com/ (accessed on 25 June 2025).
133. Arteaga-Pérez, L.E.; Segura, C.; Espinoza, D.; Radovic, L.R.; Jiménez, R. Torrefaction of *Pinus radiata* and *Eucalyptus globulus*: A Combined Experimental and Modeling Approach to Process Synthesis. *Energy Sustain. Dev.* **2015**, *29*, 13–23. [CrossRef]
134. Arteaga-Pérez, L.E.; Grandón, H.; Flores, M.; Segura, C.; Kelley, S.S. Steam Torrefaction of *Eucalyptus globulus* for Producing Black Pellets: A Pilot-Scale Experience. *Bioresour. Technol.* **2017**, *238*, 194–204. [CrossRef]
135. Pérez-Jeldres, R.; Cornejo, P.; Flores, M.; Gordon, A.; García, X. A Modeling Approach to Co-Firing Biomass/Coal Blends in Pulverized Coal Utility Boilers: Synergistic Effects and Emissions Profiles. *Energy* **2017**, *120*, 663–674. [CrossRef]
136. Ensyn Technology. Available online: https://www.ensyn.com/ (accessed on 25 June 2025).
137. BTG Bioliquids. Available online: https://www.btg-bioliquids.com/plants/ (accessed on 25 June 2025).
138. Vandana, T.U.; Tripathy, B.K.; Mishra, R.K.; Sharma, A.; Mohanty, K. A Review on Waste Biomass-Derived Biochar: Production, Characterisation, and Advanced Analytical Techniques for Pollutants Assessment in Water and Wastewater. *Process Saf. Environ. Prot.* **2025**, *201*, 107505. [CrossRef]
139. Wilkomirsky, I.; Moreno, E.; Berg, A. Bio-Oil Production from Biomass by Flash Pyrolysis in a Three-Stage Fluidized Bed Reactors System. *J. Mat. Sci. Chem. Eng.* **2014**, *2*, 6–10. [CrossRef]
140. Gómez Cápiro, O.; Aravena Riquelme, K.A.; Jiménez, R.; Arteaga-Pérez, L.E. Carbothermic Reduction of Carbon Aerogel-Supported Fe during the Catalytic Decomposition of Toluene. *Catal. Today* **2021**, *372*, 82–88. [CrossRef]
141. Gómez-Cápiro, O.; Matschuk, K.; Schulzke, T.; Concepción, R.J.; Arteaga-Pérez, L.E. Carbon Aerogel-Supported Iron for Gasification Gas Cleaning: Tars Decomposition. *Catalysts* **2022**, *12*, 391. [CrossRef]
142. Domínguez, J.I.; Blanco Machín, E.; Travieso Pedroso, D.; Wagemman Herrera, E.; Cuevas Barraza, C. Advanced Thermoconversion Technology for Municipal Solid Waste Energetic Valorization. *Renew. Energy* **2024**, *228*, 120604. [CrossRef]
143. Rodríguez, A.G.; Rodrigues, M.; Sotomayor, O. Towards a Sustainable Bioeconomy in Latin America and the Caribbean: Elements for a Regional Vision. *Nat. Resour. Dev. Ser.* **2019**, *191*, 1–49.
144. Tan, E.C.D.; Lamers, P. Circular Bioeconomy Concepts—A Perspective. *Front. Sustain.* **2021**, *2*, 701509. [CrossRef]
145. European Commission. *Communication on Innovating for Sustainable Growth: A Bioeconomy for Europe*; European Commission: Brussels, Belgium, 2012.
146. Biomass Research and Development Board. *The Bioeconomy Initiative: Implementation Framework*; Biomass Research and Development Board: Washington, DC, USA, 2018.
147. Gobierno de Chile. *Contribución Determinada a Nivel Nacional (NDC) de Chile*; Gobierno de Chile: Santiago, Chile, 2020.
148. Ministerio del Medio Ambiente (MMA). *Hoja de Ruta Para Un Chile Circular al 2040*; Ministerio del Medio Ambiente (MMA): Santiago, Chile, 2021; pp. 1–67.
149. Gobierno de Chile. *Estrategia Nacional de Residuos Orgánicos Chile 2040*; Gobierno de Chile: Santiago, Chile, 2020.
150. Ministerio del Medio Ambiente (MMA). *Ley 20920. Ley 20920. Establece Marco para la Gestión de Residuos, la Responsabilidad Extendida del Productor y Fomento al Reciclaje*; Ministerio del Medio Ambiente (MMA): Santiago, Chile, 2016; pp. 17–20.

151. Papageorgiou, S.; Massai, C. *Chile's Forests: A Pillar for Inclusive and Sustainable Development-Country Forest Note*; World Bank: Washington, DC, USA, 2020; pp. 1–106.
152. Espinosa Gutiérrez, G.; Casas Ledón, Y. Life Cycle Thinking: An Essential Framework for Eco-Industrial Development. In *Eco-Industrial Development as an Industrial Strategy from a German-Chilean Research Partnership*; Braun, A., Espinoza, G., Tröger, D., Hirth, T., Eds.; Springer Nature: Cham, Switzerland, 2025; pp. 69–92.
153. Casas-Ledón, Y.; Flores, M.; Jiménez, R.; Ronsse, F.; Dewulf, J.; Arteaga-Pérez, L.E. On the Environmental and Economic Issues Associated with the Forestry Residues-to-Heat and Electricity Route in Chile: Sawdust Gasification as a Case Study. *Energy* **2019**, *170*, 763–776. [CrossRef]
154. Weldu, Y.W. Life Cycle Human Health and Ecosystem Quality Implication of Biomass-Based Strategies to Climate Change Mitigation. *Renew. Energy* **2017**, *108*, 11–18. [CrossRef]
155. Cleary, J.; Caspersen, J.P. Comparing the Life Cycle Impacts of Using Harvest Residue as Feedstock for Small- and Large-Scale Bioenergy Systems (Part I). *Energy* **2015**, *88*, 917–926. [CrossRef]
156. Röder, M.; Whittaker, C.; Thornley, P. How Certain Are Greenhouse Gas Reductions from Bioenergy? Life Cycle Assessment and Uncertainty Analysis of Wood Pellet-to-Electricity Supply Chains from Forest Residues. *Biomass Bioenergy* **2015**, *79*, 50–63. [CrossRef]
157. Arteaga-Pérez, L.E.; Vega, M.; Rodríguez, L.C.; Flores, M.; Zaror, C.A.; Casas Ledón, Y. Life-Cycle Assessment of Coal-Biomass Based Electricity in Chile: Focus on Using Raw vs Torrefied Wood. *Energy Sustain. Dev.* **2015**, *29*, 81–90. [CrossRef]
158. Murphy, F.; Sosa, A.; McDonnell, K.; Devlin, G. Life Cycle Assessment of Biomass-to-Energy Systems in Ireland Modelled with Biomass Supply Chain Optimisation Based on Greenhouse Gas Emission Reduction. *Energy* **2016**, *109*, 1040–1055. [CrossRef]
159. Ricciardi, P.; Belloni, E.; Cotana, F. Innovative Panels with Recycled Materials: Thermal and Acoustic Performance and Life Cycle Assessment. *Appl. Energy* **2014**, *134*, 150–162. [CrossRef]
160. Buratti, C.; Belloni, E.; Lascaro, E.; Merli, F.; Ricciardi, P. Rice Husk Panels for Building Applications: Thermal, Acoustic and Environmental Characterization and Comparison with Other Innovative Recycled Waste Materials. *Constr. Build. Mater.* **2018**, *171*, 338–349. [CrossRef]
161. Schiavoni, S.; D'Alessandro, F.; Bianchi, F.; Asdrubali, F. Insulation Materials for the Building Sector: A Review and Comparative Analysis. *Renew. Sustain. Energy Rev.* **2016**, *62*, 988–1011. [CrossRef]
162. Atilgan, B.; Azapagic, A. Life Cycle Environmental Impacts of Electricity from Fossil Fuels in Turkey. *J. Clean. Prod.* **2015**, *106*, 555–564. [CrossRef]
163. Cherubini, F.; Bird, N.D.; Cowie, A.; Jungmeier, G.; Schlamadinger, B.; Woess-Gallasch, S. Energy- and Greenhouse Gas-Based LCA of Biofuel and Bioenergy Systems: Key Issues, Ranges and Recommendations. *Resour. Conserv. Recycl.* **2009**, *53*, 434–447. [CrossRef]
164. Huang, Y.F.; Syu, F.S.; Chiueh, P.-T.; Lo, S.L. Life Cycle Assessment of Biochar Cofiring with Coal. *Bioresour. Technol.* **2013**, *131*, 166–171. [CrossRef]
165. Barrio, A.; Francisco, F.B.; Leoncini, A.; Wietschel, L.; Thorenz, A. Life Cycle Sustainability Assessment of a Novel Bio-Based Multilayer Panel for Construction Applications. *Resources* **2021**, *10*, 98. [CrossRef]
166. Le, D.L.; Salomone, R.; Nguyen, Q.T. Circular Bio-Based Building Materials: A Literature Review of Case Studies and Sustainability Assessment Methods. *Build. Environ.* **2023**, *244*, 110774. [CrossRef]
167. Braun, A.C.; Troeger, D.; Garcia, R.; Aguayo, M.; Barra, R.; Vogt, J. Assessing the Impact of Plantation Forestry on Plant Biodiversity: A Comparison of Sites in Central Chile and Chilean Patagonia. *Glob. Ecol. Conserv.* **2017**, *10*, 159–172. [CrossRef]
168. Echeverria, C.; Coomes, D.; Salas, J.; Rey-Benayas, J.M.; Lara, A.; Newton, A. Rapid Deforestation and Fragmentation of Chilean Temperate Forests. *Biol. Conserv.* **2006**, *130*, 481–494. [CrossRef]
169. Banfield, C.C.; Braun, A.C.; Barra, R.; Castillo, A.; Vogt, J. Erosion Proxies in an Exotic Tree Plantation Question the Appropriate Land Use in Central Chile. *CATENA* **2018**, *161*, 77–84. [CrossRef]
170. Díaz, M.E.; Figueroa, R.; Alonso, M.L.S.; Vidal-Abarca, M.R. Exploring the Complex Relations between Water Resources and Social Indicators: The Biobío Basin (Chile). *Ecosyst. Serv.* **2018**, *31*, 84–92. [CrossRef]
171. Cerda, R.; Gallardo-Cobos, R.; Sánchez-Zamora, P. An Analysis of the Impact of Forest Policy on Rural Areas of Chile. *Forests* **2020**, *11*, 1105. [CrossRef]
172. Berasaluce, M.; Díaz-Siefer, P.; Rodríguez-Díaz, P.; Mena-Carrasco, M.; Ibarra, J.T.; Celis-Diez, J.L.; Mondaca, P. Social-Environmental Conflicts in Chile: Is There Any Potential for an Ecological Constitution? *Sustainability* **2021**, *13*, 12701. [CrossRef]
173. Carte, L.; Hofflinger, Á.; Polk, M.H. Expanding Exotic Forest Plantations and Declining Rural Populations in La Araucanía, Chile. *Land* **2021**, *10*, 283. [CrossRef]
174. Carranza, D.M.; Varas-Belemmi, K.; De Veer, D.; Iglesias-Müller, C.; Coral-Santacruz, D.; Méndez, F.A.; Torres-Lagos, E.; Squeo, F.A.; Gaymer, C.F. Socio-Environmental Conflicts: An Underestimated Threat to Biodiversity Conservation in Chile. *Environ. Sci. Policy* **2020**, *110*, 46–59. [CrossRef]

175. Reyes, R.; Nelson, H. A Tale of Two Forests: Why Forests and Forest Conflicts Are Both Growing in Chile. *Int. For. Rev.* **2014**, *16*, 379–388. [CrossRef]
176. Obtén La Certificación FSC. Available online: https://cl.fsc.org/cl-es/obten-la-certificacion (accessed on 8 July 2025).
177. Tricallotis, M.; Gunningham, N.; Kanowski, P. The Impacts of Forest Certification for Chilean Forestry Businesses. *For. Policy Econ.* **2018**, *92*, 82–91. [CrossRef]
178. Barañano, L.; Unamunzaga, O.; Garbisu, N.; Briers, S.; Orfanidou, T.; Schmid, B.; de Arano, I.M.; Araujo, A.; Garbisu, C. Assessment of the Development of Forest-Based Bioeconomy in European Regions. *Sustainability* **2022**, *14*, 4747. [CrossRef]
179. Emmanuel Miassi, Y.; Fabrice Dossa, K. Circular Economy Initiatives for Forest-Based Bioeconomy: Harnessing the Potential of Non-Wood Biomaterials. *Waste Manag. Bull.* **2024**, *2*, 270–278. [CrossRef]