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Forest Management Residues for Engineered Wood-Based Composites and Bio-Adhesive Systems: A Critical Review on Material Valorization and Circular Biomass Integration

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Abstract: Forest residues generated from logging operations, forest maintenance, and wood-processing activities represent an increasingly important secondary biomass resource for sustainable material engineering. The heterogeneous composition of these residues, together with their high lignocellulosic content, creates significant opportunities for their integration into wood-based composites and bio-derived adhesive systems. However, variability in species, morphology, moisture sensitivity, and chemical composition still limits their large-scale and standardized industrial utilization. This review investigates the valorization pathways of forest management residues within engineered wood-based material systems, with particular emphasis on wood–plastic composites, fiberboards, veneer-based products, and bio-adhesives derived from lignin and tannin fractions. The reviewed studies were identified through a structured survey of recent scientific literature focusing on the processing, classification, physicochemical characteristics, and engineering applications of forest biomass residues. Different utilization strategies were examined according to the geometrical form of the biomass, including fibers, particles, powders, and chemically extracted constituents used for adhesive formulation. The reviewed literature showed that forest residues were successfully incorporated into thermoplastic and thermosetting composite systems, where they contributed to stiffness enhancement, material lightweighting, and partial substitution of petroleum-derived constituents. Lignin- and tannin-based bio-adhesives also demonstrated promising potential for reducing formaldehyde dependence in wood panel manufacturing, although challenges related to reactivity, water resistance, and compositional variability remained significant. The findings further indicated that hybrid biomass systems, adhesive-free densified boards, and integrated biorefinery approaches have progressively expanded the technological possibilities for circular biomass utilization. The study demonstrates that forest residues can serve as multifunctional feedstocks for sustainable wood-based engineering materials when supported by appropriate material selection, traceability, and process integration strategies. The review also provides critical insights into the current limitations, scalability challenges, and future research directions associated with the transition toward low-emission and circular lignocellulosic material systems.

Keywords: Forest management residues; Wood-based composite systems; Lignocellulosic biomass valorization; Bio-adhesives; Circular bioeconomy; Wood-plastic composites; Sustainable material engineering; Ligni-based adhesives

1 Introduction

1.1 Sources and Characteristics of Forest Residues

The increasing demand for forest products, such as wood and paper, together with agricultural activities and forest management, generates an important amount of forest residues [1]. These are wood materials, hence containing a

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significant amount of lignin, therefore with limited hydrophilicity, in various forms, from powders to larger pieces, or even chunks, which are generated by several different activities [2].

To cover, at least partially, this need, the concept of “wood cascading” has been proposed, in the sense of application to different products till this is possible, therefore delaying as much as possible the final incineration of the material [3]. The lignin content comparable, if not superior to cellulose, does set these materials apart from the larger sector of agroforest waste, which is increasingly being of interest as regards the production of natural fiber composites [4, 5] or even as a substitute for wood in some cases, though with some criticalities, among which in the first place is seasonality [6]. In the case of waste from wood industry, a typology classification is reported in Figure 1.


HARDWOOD WASTE

OFFCUTS

SOFT WOOD OFFCUTS

WOOD SHAVINGS

MIXED WASTE

SAW DUST

Figure 1. Typical geometries of wood industrial waste

Wood waste may generally include [7]:

- Logging and wood processing, including sawmilling [8], and particleboard and plywood production [9];
- Perennial crop plantation management, including tree pruning and replanting, especially for large extension crops (rubber, coconut, palm oil, etc.) [10];
- Crops planted for agricultural purposes, eradicated after harvesting, yet with significant amounts of biomass left. These can be perceived, due to their continued presence, as “carbon storage” sources [11].

1.2 Environmental Management and Disposal of Forest Residues

Novel plywood structures, such as mass plywood or prefabricated computerized numerical control (CNC) structures [12], are specifically designed to minimize the amount of waste produced during production and normally manufactured with wood from the same tree species, namely Douglas fir [13]. These materials would, in the long run, drastically reduce secondary raw materials available in this sector, which would result in an advantage for sustainability. Yet also other types of wood biomass, hence generating residues, exist, not specifically linked to any specific production activity, in particular these include:

- Biomass from clearing of forest lands destined for agricultural purposes, cutting or logging trees [14];
- Eradication of trees growing from lands with different destinations, agricultural, communal gardens or generally urban green, or private land, etc. [15].

All over the world, incineration is used as a method of disposing of forest residues to reduce the risk of forest fires while trying to reduce resource depletion, avoiding critical changes in climate [16]. However, this still does not solve the problem of dangerous emissions into the environment. Some forest biomass contains heavy metals, and when they are burnt, ashes may contain e.g., chromium, nickel, lead, copper, cadmium, zinc, etc., hence affecting the composition of the soil, yet able to be recovered in some cases [17]. The presence of heavy and alkali metals may also impede the application of forest residues in wood composites, albeit not the extraction of suitable chemicals from them. In particular, a higher alkali metal content would more likely suggest their use as a source of thermal energy. To reduce the variability of their composition, a proposal could be for forest residues to be segregated at the source [18]. Additionally, the burning of heaps increases soil temperature and moisture, triggering a range of reactions, including seed mortality, nutrient leaching, disturbances in microbial activity, and the development of water-repellent properties [19]. On the other hand, incineration tends to increase soil properties such as electrical conductivity, releasing nutrients like nitrogen, phosphorus, potassium, calcium, and magnesium into it and normally increasing soil pH [20]. The value of pH also depends on the intensity of burning, which may lead to limited tree colonization [21]. If the ashes are produced in a porous and chemically active form, referred to as “biochar”, also the quality of the soil can be finally improved [22]. Biochar, as a product of forest biomass, can coexist in the processing system with biofuels [23], which involve a delignification process [24], renewable chemical components [25], and bioenergy [26, 27]. The latter option is widely practiced, though with significant differences across the world [28–30] (Figure 2). Recent considerations suggest that implications of climate change aspects need to be integrated into pyrolysis for biochar production, so to possibly obtain a fairer balance over the realistic effects. This is especially required whenever the net calorific value is low and hence more material is needed for combustion, which is the case e.g., for wet or marine biomass [31], or the production of hardly manageable waste, such as carbonaceous soot, is abundant, such as it occurs on pines needles and cones [32].

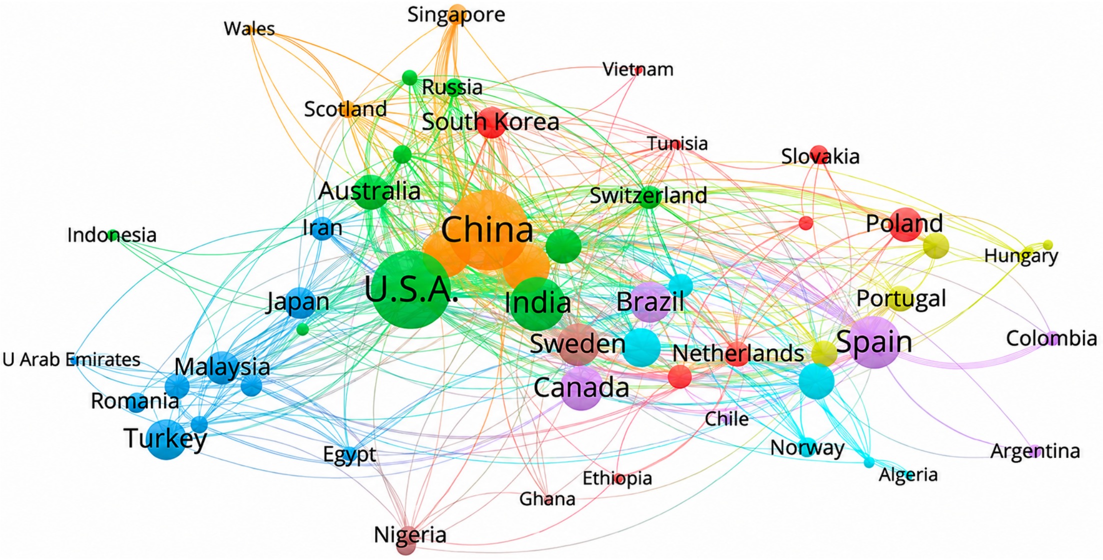

Figure 2. Studies on bioenergy from forest biomass in the world [27]

1.3 Valorization of Forest Residues in a Circular Bioeconomy

The progress towards the reduction of carbon footprint as a rule-of-the-thumb asks to normally prioritize material recycling over energy recovery, such as indicated by EU Directive 98/2008. This can be considered together with the growing need for timber raw materials and generally the depletion of resources created an increasing interest towards forest residues as alternative wood materials, which is necessarily used to address brought on by the large volume of timber production without further aggravation on the environmental situation [33]. Compliance on what the Directive asks is linked to a few biomass-related characteristics, namely chemical composition, moisture content and potential absorption, calorific value and ultimately price. This is particularly significant in the case of most diffuse wood species for industrial use, such as poplar [34]. While the wood panel industry increasingly demands sustainable and cost-effective materials, on the other hand, a considerable fraction, such as over 40% of waste in the form of wood biomass, is left in the cutting area as a result of the mechanical processing of wood [35]. Moreover, the decrease of agricultural land did lead to a lower need for biomass as an erosion controlling material, though this might represent a debatable consideration, to be approached only with a "case by case" philosophy [36]. In contrast, the process of transforming forest residues into high added-value products, such as materials for plywood, would generate further interest and possibly result in justifying transportation costs when a "zero km" exploitation is not possible. Trying sounder economic considerations, forest residues have a variable possibility to be exploitation provided a sufficiently strong and strictly bound value chain is created, including resource procurement, transport and handling, transformation and processing, valorization and market, and leading at end-use of products [37]. This involves further experimentation: For example, extracting chemicals from forest biomass, this needs to be characterized from the physical, thermal, and chemical point of view, e.g., measuring the amount of holocellulose, lignin, and ultimately extractives present in it [38].

Despite the growing number of studies on forest biomass utilization, the available literature remains highly fragmented with respect to material classification, engineering performance evaluation, and industrial scalability. A comprehensive critical assessment connecting biomass variability, processing strategies, and multifunctional composite applications is still limited.

The main sources of forest residues and their potential applications are summarized in Table 1.

Table 1. Main sources of forest residues and potential applications

Source of Residues	Typical Biomass Components	Physical Form	Potential Applications
Logging operations	Branches, tops, bark	Chips, chunks	Particleboards, wood-plastic composites (WPC), bioenergy
Tree pruning	Branches, foliage	Fibers, particles	Fiberboards, fillers for composites
Wood processing industries	Sawdust, shavings	Powder, particles	Particleboard, fillers, adhesives
Plantation management	Stems, bark, pruning residues	Fibers, flour	WPC, veneer products, bio-based chemicals
Urban tree maintenance	Mixed woody biomass	Heterogeneous particles	Composite fillers, recycled wood materials

1.4 Scope of the Review

This review critically examines the integration of forest management residues into engineered wood-based composite systems, with particular emphasis on sustainable material valorization, bio-adhesive development, and circular biomass utilization strategies. Particular attention is given to their use either as fillers of different sizes and geometries (such as fibers, particles, and powders) or as sources of binders and resins derived from lignocellulosic components. The latter option is especially relevant due to its higher added value and the growing need to replace conventional petroleum-based adhesives used in wood products.

The valorization of forest residues is becoming increasingly important due to rising demand for timber-based materials, the limited availability of primary resources, and the need to promote circular economy strategies in the forest and wood sectors. Large amounts of secondary woody biomass generated during forest management, logging, and industrial processing represent a potentially valuable secondary resource capable of supporting the transition toward low-emission and circular lignocellulosic engineering materials.

This review discusses the principal technological pathways for incorporating forest residues into wood-based composite systems while critically analyzing the limitations associated with biomass heterogeneity, interfacial compatibility, process scalability, and material performance variability.

1.5 Methodology

The present review was developed through a structured survey of scientific literature focusing on the valorization of forest management residues in engineered wood-based composite systems and bio-adhesive applications. Relevant publications were systematically identified through major scientific databases, including Scopus, Web of Science, and Google Scholar, with particular attention given to recent studies addressing sustainable composite engineering, lignocellulosic biomass processing, and bio-based adhesive technologies. The search focused on keyword combinations, including forest residues, wood-based composites, lignocellulosic biomass, wood-plastic composites (WPC), and bio-adhesives. The selected literature includes research articles, review papers, and technical reports addressing the availability, properties, processing, and applications of forest residues. Particular attention was given to studies discussing the use of these materials either as fillers (fibres, particles, or powders) or as sources of binders and resins. The collected studies were analysed to identify the main technological approaches, opportunities, and limitations associated with the valorisation of forest residues in wood-based composites. The main parameter for selection is the evidence of effective application of traceable and characterised forest waste, giving some preference, yet not exclusively, to studies issued in the last decade. The combined discussion of wood-based composites and bio-adhesive systems was intended to provide an integrated perspective on fully valorized lignocellulosic material platforms within a circular bioeconomy framework.

2 Woody Residues from Tree Management

2.1 Characteristics and Availability of Woody Residues

The large amount of biomass generated from the forest management operations described in the Introduction requires a more systematic classification according to species, physicochemical characteristics, and potential engineering applications. Some types of wood waste are more abundant for technical reasons, in that they are subjected to frequent pruning or replanting operations. Exploitation of pruning waste is not a novel issue, and it is mainly regulated by the need to keep healthy soil, while in some cases the excess of this waste is disposed of as a cheap form of energy with no land consumption [39]. In this respect, it is also suggested that forest maintenance operations need to occur at regular intervals for the residues to be of interest in a possible marketability process, in other words, subjecting forest housekeeping to management considerations [40]. For this reason, for pruning residues, energy production, or else disposal in the soil for agricultural purposes appear still the first considered options [41], also due to the difficulty of proposing contemporary design objects from wood waste [42]. This aspect highlights the need for more sustainable and higher-value engineering applications for pruning-derived biomass, as reflected in recent literature that also focused on parts of the tree that are generally poorly exploited, such as bark [43], though recent studies also proposed the use of bark flour as an additive in plywood [44]. Potential use of bark would depend on the climate, though. In subtropical climates, especially in the Mediterranean region, bark samples are left in forested areas to prevent the spread of bark beetles [45]. Bark is also valued in landscaping for its recognized ability to increase soil water retention in a mulching-like use [46]. It is also possible to perform an operation of energy recovery by burning the dead ground cover layer from biomass in forest areas, namely, with bark. However, the gaseous emissions are significant, so that the process is not always viable [47], together with nitrogen, which can act as fertilizer [48], and chlorine. More recently, a biorefinery approach for bark residue has also been proposed, due to the variety of products obtainable [49]. In other climates, however, the extraction of bark in the form of short fibers for their introduction in polymer composites, such as, for example, in the case of Acacia Caesia, a tree diffused in the Indian sub-continent, whose bark is normally used for scrubbing and the production of cosmetics [50]. The concept has progressively expanded toward the broader integration of bark-derived fibers into composite material systems [51]. Furthermore, if not intended for domestic use, the ashes from these products are not disposed of in an environmentally beneficial way: The most suitable solution appears to be their application in cement factories [52], where even the tree bark, e.g., of willow and eucalyptus, was proposed for use [53].

Going beyond industrial operations, a balanced report needs to observe that the reluctance to use pruning residues in materials can be related to its potential in maintaining soil health.

2.2 Agricultural and Plantation Residues

Specific studies exist on plants with very variable amounts of lignin, such as cocoa [54], or where transportation of residue would be much less profitable than improving the product yield e.g., for tea [55]. Improving soil sustainability by enhancing water retention capabilities has been demonstrated for cactus pear pruning waste, even for low amounts of this refuse in the soil (10%) [56]. In another sense, the use of various green waste as a source of nutrients, such as garden pruning has been compared with subtropical (avocado, cherimoya, mango) leaves, the latter offering higher release of potassium and phosphorus [57]. These findings also indicate the potential for integrating agricultural and forest-derived residues into multifunctional bio-based material systems.

2.3 Applications in Composite Materials

Despite the challenges associated with species heterogeneity and material inconsistency, pruning-derived biomass has progressively entered engineering sectors such as sustainable construction materials and polymer-based composite systems. This is the case for example of Merida (Mexico), where a mixture with recovered plastic was proposed for it, to obtain WPC prototype, though with resistance not comparable with acrylic or polyurethane sheets [58].

The question of difficulty in separating pruning residue from the different species is important for application in materials, though. Moreover, in view of guaranteeing a continuous supply, many species have been considered alongside [59] as for effectiveness in the production of wood-cement composites, namely willow wattle (Acacia salicina), buttonwood (Conocarpus erectus), lofty fig (Ficus altissima), lead tree (Leucaena glauca), Manila tamarind (Pithecellobium dulce) and Athel tree (Tamarix aphylla). The study indicated an increase of properties when the bulk density was brought from 1100 to 1300 kg/m^3, as it suggested the need for 3% calcium chloride ($CaCl_2$), aluminum sulphate $Al_2(SO_4)_3$ or magnesium chloride ($MgCl_2$) treatment to enhance compatibility with cement. Obviously, the range of species for WPCs production, when obtained from pruning/replanting, is much wider than that obtained from the wood/paper system. In this way, also fast-growing plants from orchards were considered, such as the case for pecan flour, which proved effective in combination with HDPE, at contents of up to 60 wt.% with mesh sizes from 10 to 60 [60]. In the circular economy, this process integrates into a much broader production system based on nut tree waste, including groundnut wood replacement panels [61]. It is also worth noting that, in the most common case, the use of these materials is advisable as part of a complex production system, such as for perennial crop plantation management. This is also applied, other than in temperate climates, in tropical contexts, e.g., for rubber trees in Malaysia [62], and, with regard to coconut coir [63], oil palm [64], pineapple leaves [65], etc. In the last case, wood-plastic composites produced with pineapple leaves showed a modulus of rupture (1353 MPa) largely exceeding those measured on those including coir (353 MPa) and sugarcane bagasse (423 MPa). The diversification of biomass feedstocks further demonstrates the adaptability of engineered composite systems to heterogeneous lignocellulosic resources.

3 Wood-Based Composites

Wood-based composites (WBCs) comprise engineered material systems containing ligneous matter in different formats, from veneers to fibers and fillers (Table 2) structurally joined by adhesives, or else self-bonded e.g., by a thermoforming process [66]. These changes in approach further indicate the versatility of this material concept [67].

Table 2. Main wood-based composites and their characteristics

Composite Type	Raw Material Geometry	Typical Binders/Matrix	Main Applications
Plywood	Veneers	Urea-formaldehyde (UF), phenol-formaldehyde (PF)	Construction panels, furniture
Laminated veneer lumber (LVL)	Veneers	Phenolic or structural adhesives	Beams, structural elements
Parallel strand lumber (PSL)	Veneer strands	Structural adhesives	Load-bearing members
Fiberboards	Fibers	UF, melamine-urea-formaldehyde (MUF) resins	Interior panels, furniture
Wood fiber composites	Short fibers	Thermoplastics polypropylene (PP), high density polyethylene (HDPE), poly(lactic acid) (PLA)	Automotive components, panels
Wood flour composites	Powder / flour	Thermoplastics, compatibilizers	Decking, furniture parts

Among the materials mentioned for completeness in Table 2, the latter, namely wood fiber composites and wood flour composites can be produced using forest residues, as exposed here below.

3.1 Wood Fiber Composites

Typical use of short wood fibers, normally around a few millimeters long, involves their injection molding/extrusion with thermoplastic matrices [68]. A flow chart of the process is presented in Figure 3 [69]. For the production of composites, polyolefin matrices, such as polypropylene (PP) and high-density polyethylene (HDPE), have a long history with wood fibers, typically obtained from spruce and pine, so that concerns over flammability have been experimentally addressed [70]. HDPE has also been used in combination with waste from birch plywood production, namely sanding dust, which markedly decreased ultimate deformation [71]. Their behavior is advantageous in terms of impact strength and stiffness, allowing fiber contents of up to 50 wt.% to be introduced using fabrication methods such as twin-screw extrusion [72]. Gradual modifications intended to improve the sustainability of these materials led to the substitution of traditional polyolefin matrices with bio-based polymers, such as poly(lactic acid) (PLA) and poly(hydroxyalkanoate) (PHA), although some limitations in mechanical performance and durability remained evident [73]. In particular, the introduction of 50 wt.% wood flour into PHA led to tensile strain at break dropping from 12% to 1.5%.

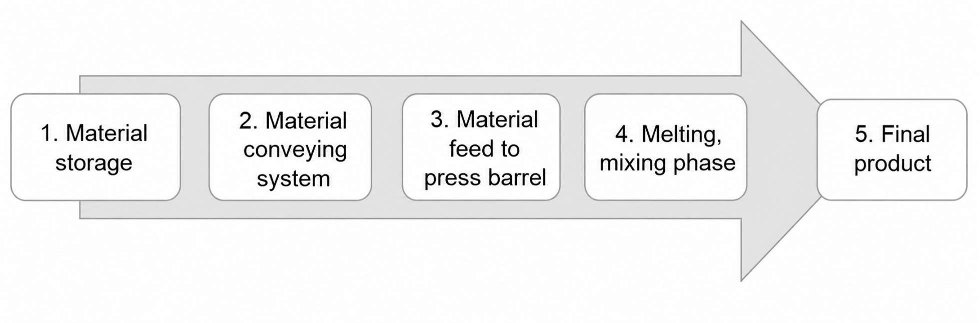

Figure 3. Flowchart of the production phases for a particleboards, wood–plastic composites (WPC) [69]

3.2 Wood Flour and Particle-Based Composites

To improve interfacial compatibility between wood flour and thermoplastic matrices, such as polypropylene, treatments typical of natural fibers can be used, such as mercerization with NaOH, silanization [74], or non-chemical modifications, such as plasma treatment [75]. A particularly effective surface modification is maleic anhydride grafting of polypropylene (MAPP), which can lead either to esterification or to its addition of compatibilizer, improving tensile, flexural and impact strength of the composite [76] (the addition of only 10% filler brought Izod impact energy from 0.87 to 1.5 kJ/m^2), though with limited (if any) effect on toughness [77]. Normally, wood flour is obtained from grinding spruce or pine; more recently, it has also been blended using biopolymers, such as PLA, which allowed investigations in terms of cost and sustainability [78]. PLA and poly(vinyl alcohol) (PVA) are typical examples of bio-based formaldehyde-free adhesives, which can be synthesized and not necessarily obtained from waste biomass [79, 80].

3.3 Adhesives and Binders in Wood Composites

The adhesive serves as a binding component that ensures the strength and integrity of the structure. The main families of bio-adhesives derived from biomass are summarized in Table 3.

Table 3. Main families of bio-adhesives derived from biomass

Bio-Adhesive Source	Raw Material	Advantages	Limitations
Lignin	Wood residues	Renewable, aromatic structure	Low reactivity
Tannins	Bark extracts	High reactivity	Limited water resistance
Starch	Plant biomass	Low cost	Moisture sensitivity
Proteins	oilseed meals	Biodegradable	Lower durability

The combination of two essential elements (wood species and adhesive) thus dictates the mechanical and physical characteristics of plywood [81–85]. Comparative studies are available differently combining both the aforementioned elements. In particular, on 150 g/m^2 parica (Anadenanthera peregrina) and pine wood veneers pressed at 150 °C and 0.98 MPa for 10 minutes two urea-formaldehyde and phenol-formaldehyde adhesives, the lower performance of parica was attributed to adhesive penetration due to porosity, with limited difference between the two formulations [82]. For other species, such as the comparison between southern yellow pine and red maple plywood, regardless of wood species, plywood manufactured with polyurethane and phenol-formaldehyde showed higher shear strength than those manufactured with polymeric diphenylmethane diisocyanate (pMDI) and phenol-resorcinol-formaldehyde (PRF) [84].

Among these properties, the most sought after in wood products and inevitably connected with adhesives are flexural strength [86], then tensile strength, which heavily depends on the lay-up of plywood [87], elastic behavior, hence stiffness [88]. Some other properties are more related to the actual service use of plywood and other related products: These are impact [89] or indentation resistance [90], fatigue performance [91], creep behavior [92] and screw-withdrawal resistance of self-tapping screws (STS) [93]. This is an essential test for wood-based products, which is illustrated in Figure 4 [94].

Plywood binders in LVPs production need to function as structural adhesives, so that their strength and rigidity will match that of solid wood or even exceed it [95, 96]. Often, wood adhesives are also added with other types of ligneous biomass, including various nutshells or e.g., coconut husk, to improve shear resistance and hardness while modifying rheology [97]. The effects on LVP strength of different types of well-known adhesives, such as urea-formaldehyde (UF) [98], melamine-urea-formaldehyde (MUF) [99], phenol-formaldehyde (PF) [100], emulsion polymer isocyanates (EPI) [101], PVA, sometimes in combination with melamine [102], and PRF [103], were investigated, specifically in terms of water resistance, as indicated by the appearance of cracks. Among these, a wider attention has been paid to a a more sustainable approach to phenol-formaldehyde, by using biomass and/or reducing formaldehyde emission during service, or ensuring a more facile transformation of phenol into carbon products at end-of-life [104].

Among alternative adhesives, the results of adhesive as a whole indicated that PVA showed the highest compressive strength, which the additional flexibility of linear molecular chain segments can explain. In terms of durability, PVA did also outperform most other adhesives [105]. In recent years, there has also been an increase in interest in the use of PVC resin as a binding agent with improved adhesion properties due to chlorine atoms to try to introduce wood flour with poplar veneer. The interface was effectively modified by the introduction of four different agents, such as silane-based, aluminate-based, MAPP, and maleic anhydride polyethylene (MAPE) [106]. The latter proved very suitable also for application in the production of chipboards [107]. Moreover, to minimize the environmental impact by recycling both wood and polymer waste, there is a growing interest in manufacturing polyethylene-based laminated wood veneer-polymer composites, such as in study [108], from post-consuming plastic bags. The substitution of formaldehyde with alternative petroleum-based, yet secondary, hence waste-derived, bonding agents, such as epoxy-based ink adhesive, was also attempted with some success, though representing a niche refuse in terms of quantity [109]. This indicates that the formaldehyde-replacement theme is much larger than the bio-adhesives-based approach, though it can promote their use by facilitating easier procurement.

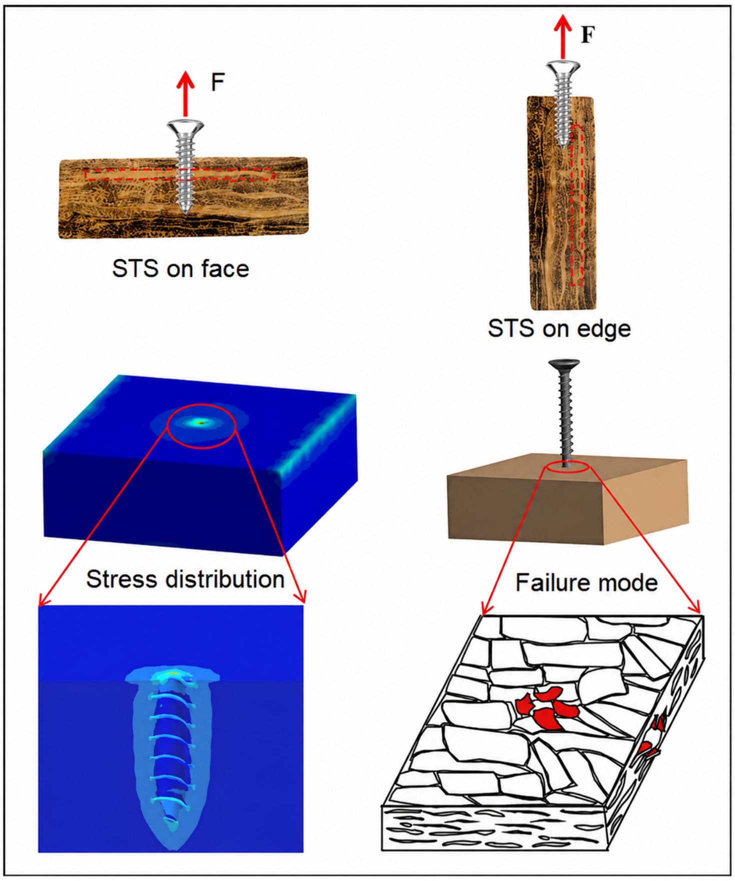

Figure 4. Screw withdrawal tests on self-tapping screws [95]

3.4 Emerging Technologies and Adhesive-Free Systems

It is noteworthy that forest residues can also be used to produce self-bonding wood boards, which are adhesive-free and in which wood powder serves as a structural material through the application of pressure typically in the order of a few tens of MPa, to result in plant cell collapse and therefore densification [110]. It is fair to say that initial attempts have concerned the most common industrial woods, such as poplar [111], though some experiments have also been performed using steam-exploded wood biomass [112]. As a contrasting concept, a natural lignification process has also been considered, which treats the a cross-linking means to supply the cell wall with the needed hardness as a bark-like material, increasing the cell wall thickness and with a final infiltration of phenol formaldehyde resin [113]. This is a kind of process easily applicable to mixed forest residues. These emerging approaches further demonstrate the transition from conventional wood utilization toward integrated and low-emission lignocellulosic engineering systems.

4 Valorization of Forest Residues

4.1 Characteristics and Classification of Forest Biomass

As previously discussed, lignocellulosic biomass is primarily composed of three major constituents: Lignin, cellulose, and hemicellulose, which further determine its physical and chemical properties. An abundant presence of lignin, in particular forming the xylem, is important for the structural properties of wood, as well as resistance to water stress [114]. Moreover, varieties and subgroups are defined depending on biological diversity, source, and origin, such as coniferous or deciduous; angiospermous or gymnospermous; soft or hard; stems, branches, foliage, bark, chips, lumps, pellets [115], briquettes, sawdust, sawmill [116], and others, from various tree species [117]. In the case of sawdust, which is a material of considerable interest for the production of particleboards, the factors involved for their effective use are numerous, more linked to the technology adopted than to botanical characteristics. These include methods of sawing (frame, band, etc.), cutting speed, feed, and ultimately the fineness of the fraction obtained [118]. It is reasonable to assume that, especially in terms of circular economy and due to the mentioned variability, forest residues will be applied in the production of wood composites alongside post-consumer waste from e.g., end-of-life plywood [119] or even more structured furniture waste, which equally have received attention [120].

The utilization of this biomass generally enables the development of engineered biocomposite systems, in the understanding that these would in some way compete with traditional wood composites [121]. These are obtained from a polymer matrix reinforced with bio-reinforcements from wood [122]. A global and articulated classification of a very large number of biomass species is offered in study [123], though this is specifically aimed at its application as fuel. Forest residues can be more generally employed for a large variety of products, which can be illustrated based on the stakeholders' perception [124], albeit some terms, such as "bioplastics", may appear of controversial meaning (Figure 5).

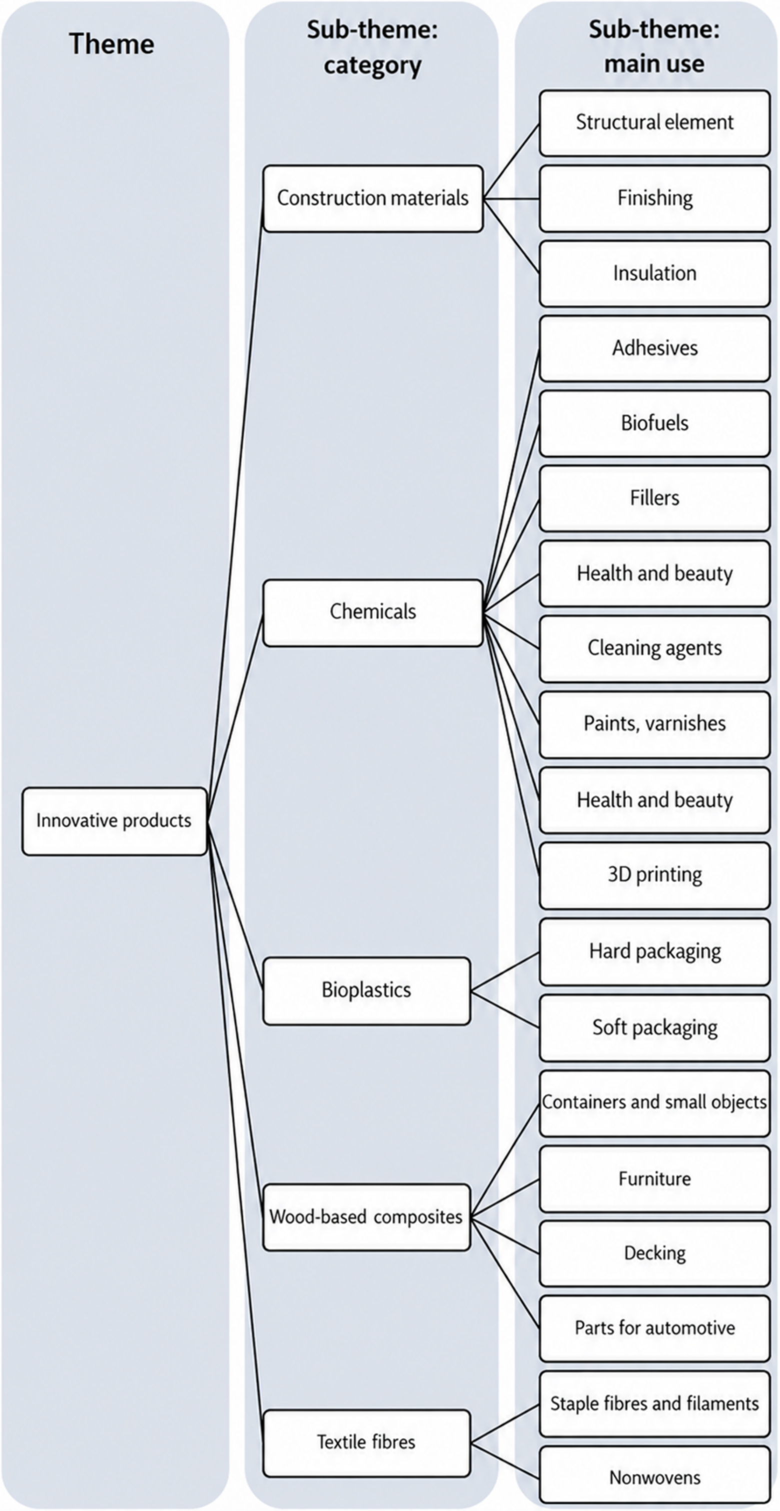

Figure 5. Potential products from forest residues [125]

A comprehensive approach to forest residue valorization should consider the entire material lifecycle, from feedstock selection to end-use engineering applications, therefore trying to match the nature of the raw material, including the species in the case of biomass, with its potential application [125–127]. In particular, a classification of composites from forest biomass [128], divided according to the construction or non-construction application, is offered in Figure 6.

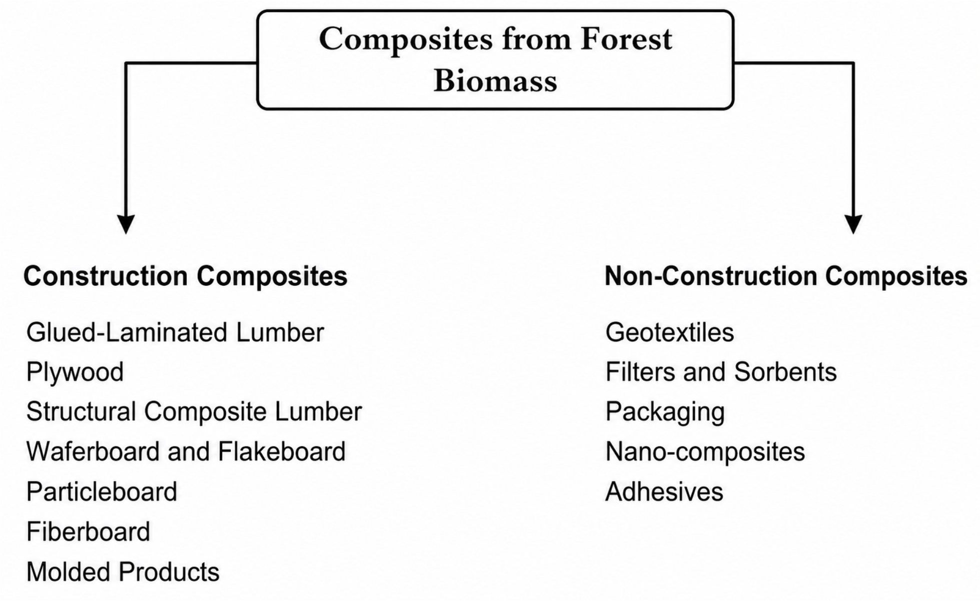

Figure 6. Classification of composites from forest biomass

4.2 Applications for Structural Wood Products

4.2.1 Veneer-based products

Though the main focus of forest residues does not go to dimensions larger than small chips, as it is the case for birch in Finland [129], the potential use of forest residues as core chips rather than powder in veneer products introduces an important variable in these materials, which is the use of different species. This yielded in some cases very promising results, even comparable with solid wood, such as it has been the case for *Gmelina arborea* [130] or patula pine [131]. Whenever possible, it is suggested to correlate with typical sources of raw matter, such as poplar, where the fast-growing characteristics does ultimately apply also to the generation of residues. However, the choice is very wide, as indicated in study [132], where examples from rubber wood, Paulownia, rubber tree, willow, are offered, including also more exotic species. In this respect, for veneers, for the high volume needed, the correlation with local industry is more evident and exploitable, a number of studies exist in this respect, related e.g., to the Philippines [133], or Nigeria [134]. The use for production of veneers is always in competition by its possible revalorization in terms of cellulose products, even at high added value, such as it is the case for nanocrystalline cellulose (NCC) [135–140]. Alongside this, from forest residues, cellulose can be obtained in macroscopic form, such as for paper products [141], while it is also possible to derive the biological feed source for bacterial biopolymers PHA [142]. More specifically, it is noteworthy that this approach can be suggested as a biorefinery route, which includes all possible and prospected products e.g., in particular energy (electricity, syngas and transportation fuels), chemical feedstock, and nanocrystalline cellulose, ideally leaving no waste [143]. In this respect, hydrothermal processes can represent a very effective way to maximize the yield of high-value secondary chemicals [144]. However, the least energy-consuming products, i.e., those centered on wood replacement and the large industry focusing on it, are largely neglected in this context. This highlights the need for more integrated biomass valorization frameworks capable of balancing energy recovery, chemical extraction, and structural material applications. To address this kind of issue, the structure of bio-refinery has been articulated into various sectors, namely those of true commodities, pseudo-commodities (high-volume and low value, such as fuels, woodchips, etc.), fine chemicals and specialty chemicals' production [145].

4.2.2 Hybrid panels and engineered boards

A classical approach to optimize the use of biomass from the same production system is hybridization in the production of oriented strand boards (OSB) of different residues (Figure 7). This proved very suitable in the case of oil palm, where oil palm trunk (OPT) and oil palm empty fruit bunches (OPEFB) were employed alongside each other, which resulted in their effective application, though with a typical large-use unsustainable adhesive, such as urea-formaldehyde [146]. The large variety of by-products obtainable from oil palm residues suggests their use in a biorefinery concept [147], also indicating that due to potential adaptability of the ligneous matter of all possible geometries to the adhesive, passing to more sustainable solutions is only a matter of time [148]. As always, local availability appears a significant factor, such as was the case for *Azadirachta excelsa* (Sentang) palm residues in Indonesia [149]. The local character is able to significantly enhance the preparation of hybrids, though the simplest solution appears always the application of urea-formaldehyde adhesives, though smoothened by its blending e.g., by cassava starch, such as in study [150], where the different biomasses uses are specifically plantain (*Musa paradisiaca*) pseudostem, *Theobroma cacao* stem and pod, and sawdust of kapok (*Ceiba pentandra*). It is interesting to note for example of these raw matters, that they have all been used in the field of biodegradable composites (plantain in study [150], cocoa pods in study [151], and more generally kapok, which is at the center of a multifaceted production system [152]).

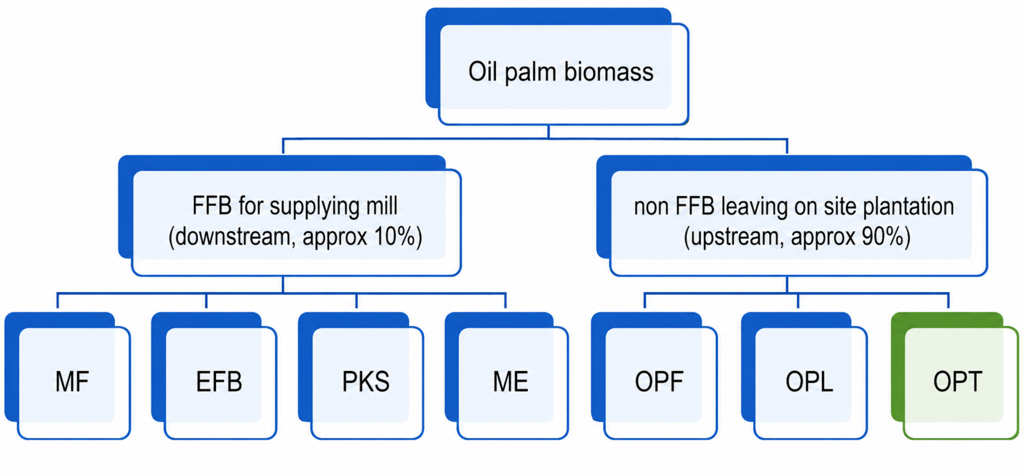

Figure 7. Various by-products from oil palm system for wood panels: Empty fruit bunches (EFB), mesocarp fibers (MF), mill effluents (ME), oil palm frond (OPF), oil palm leaves (OPL), oil palm trunk (OPT), palm kernel shells (PKS) [147]

In practical terms, the substitution of traditional materials for wood panels with forest residues does not always result in comparable properties, e.g., application of Scots pine biomass offered a higher thickness swelling, limiting therefore their use in interior dry conditions [153]. This may impose significant limitations on the large-scale engineering applicability of these materials, and once again, suggests the opportunity of a hybrid approach with materials of different measures.

4.3 Fiber- and Particle-Based Composites

4.3.1 Fiberboards and thermoplastic composites

The idea to use forest residues to produce fiberboards is by no means absolutely new: The initial approach involved formaldehyde-based adhesives, obviously not considering the sustainability concept; some proposals concerned back in the 70s Douglas fir waste [154] or, once again, based on local needs, such as in Nigeria [155]. In the most common case, a thermosetting resin [156] thus traditionally formed adhesives for wood. However, over the years also thermoplastic polymers proved suitable for the purpose, which do obviously require hot pressing, such as it is the case for low-density polyethylene (HDPE): Bekhta et al. [157] did compare a number of different wood species, namely beech, birch, hornbeam and poplar, using various thicknesses of adhesive, 50, 100 and 150 µm. In another study, birch, beech and spruce veneer were also compared for adhesion, finally recommending a co-polyamide (CoPA) adhesive for the first two woods, and a co-polyester (CoPE) one for the third one [158].

Generally, the characteristic that enables the effective manufacturing of veneer-based products is their glueability, intended as the velocity and strength of adhesive junction, which can be opportunely enhanced by an adapted level of pre-pressing [159]. More recently, wood fibers have been typically blended with recycled thermoplastics, mainly various types of polyolefin, in composites. This offers a suitable environment for the introduction of forest residues.

4.3.2 Wood flour and recycled wood waste

The typical distinction between fibers, which offer some additional tensile or flexural strength, and powders, mainly intended as hardeners, is given by the respective aspect ratio (length/diameter). In practice, fibers have also been compounded into composites with polypropylene using different raw materials, such as pellets, heat-treated fibers, and wood flour, of course with some variation in properties depending on the source [160]. One of the critical factors for application is the cycle linked to absorption-desorption of humidity, namely when fine wood flour is involved in the material [161]. In terms of sustainability, potential has been indicated by the management of wood derived from municipal waste, which is normally hardly suitable for recycling [162], due to specific difficulties especially linked to the fact that any type of post-consumer wood can be included, from packaging to furniture waste. Despite this, up to 30 wt.% of wood waste has been introduced once ground between 50 and 100 mesh into a MAPP matrix, and allowed the production of various furniture components, such as crates and chair legs [163]. In other cases, also wood/phenolic flour from furniture waste was able to be bonded with polypropylene in form of WPC, demonstrated an acceptable rheology for molding [164]. This suggests that mixed forest-derived wood waste in short-fiber or powder form may provide a more adaptable pathway for scalable composite manufacturing.

4.3.3 Alternative functional materials

The variety of components in forest waste do sometimes suggests their application in materials with different objectives than wood replacement. For example, fungicidal films have been developed from various treatments of different pine tree waste, such as needles and bark meal, bonded using PVA. Here, the disadvantages with biodegradability were compensated and the mechanical properties were enhanced by treatment with oleic acid and glycerol [165].

4.4 Bio-Adhesives and Bio-Based Binders

4.4.1 Formaldehyde-based adhesives and environmental concerns

Valorization of forest industry residues can produce not only materials for wood-plastic composites, but also bio-adhesives and resins [166]. The growing concern regarding formaldehyde emissions from wood-based products has become a major driving force for the development of bio-adhesive systems in the building materials used [167]. Currently, the use of synthetic adhesives in the wood industry with a high content of free formaldehyde, based on urea-formaldehyde [168], is growing due to concerns about both human health and the environment. This trend also includes melamine-formaldehyde [169] and phenol-formaldehyde resins [170]. Furthermore, urea-formaldehyde resin is the most commonly used of them, due to the low price of raw materials and ease of processing [171]. Possibility to add lignocellulosic fibers to urea-formaldehyde resin has also been explored [172]. Methods to reduce free formaldehyde in the polymer structure of the resin are based primarily on the use of formaldehyde traps (urea, polyvinyl alcohol, and melamine) that bind free formaldehyde. To this a careful control of the conditions of the resin synthesis process, such as pH, temperature, and reaction time needs to be added. Yet, the most effective method of all is the reduction of the molar ratio of formaldehyde/urea, as it has a lower formaldehyde emission [173, 174]. Attempts were also performed to try to evaluate whether for wood biomass from some species, such as oil palm, the use of bio-adhesives based e.g., on resorcinol, could offer a comparable performance to formaldehyde-based ones, though the results were not conclusive [175]. In conclusion, methods to limit toxic emissions do not completely solve the problem; therefore, in the age of environmental responsibility, the priority is to create bio-adhesives from renewable resources, such as biomass from various sources. Four families of bio-adhesives can be obtained from biomass, namely from lignin, tannins, protein (oil pressed meal from plants), and starch [176]. Forest residues can definitely provide the first two categories, though in the more general agroforest system, also the other categories are available. A further detailed picture is presented in Figure 8 [177].

4.4.2 Lignin-based bio-adhesives

Forest biomass contains lignin, tannin, and carbohydrate-based (cellulose, hemicellulose) compounds that make it suitable for use in the production of bio-adhesives. These bio-adhesives may compete with those that contain formaldehyde [178]. Lignin gives the plant support and rigidity, which enables mechanical resistance to environmental influences. Although the average lignin content varies up to 30%, it depends on the type of plant. Furthermore, the chemical characteristics of a heterogeneous structure of lignin can be a cause of resistance to fractionation, depolymerization, and valorization. Therefore, this makes the process of recycling more difficult, requiring higher amounts of energy, which is costly and environmentally problematic. The structure of lignin consists of three monolignol links: P-coumaric alcohol, coniferyl alcohol, and sinapyl alcohol [179, 180]. Lignins are divided according to their way of separation: Possibilities are kraft lignin, mostly used for paper production, sulfur-free alkali/soda lignin, lignosulfonates, where the bond to polysaccharides is broken down, organosolv lignin, and steam explosion lignin [181]. However, this disadvantage, namely their low reactivity with aldehydes, has developed interest in the research and development of new formulations of modern bio-adhesives through the use of alternative reactions such as demethylation [182], oxidation, crosslinking of pre-glyoxalated lignandialdehyde starch with urea, non-isocyanate polyurethane (NIPU) based on lignin, etc., also possibly with hybridization with further lignin [183–186]. Another possibility is offered by in-situ lignin bonding, which enables the production of formaldehyde-free fiberboards [187]. Other methods have also been proposed for an improved selection, such as microwave liquefaction, which offers at the same time liquid products and the development of solid biopolymers, an example being the development of polyurethane foams from microwave processing of sugarcane bagasse [188], which is depicted in Figure 9. These developments demonstrate the growing transition from conventional adhesive technologies toward multifunctional and low-emission lignocellulosic binder systems.

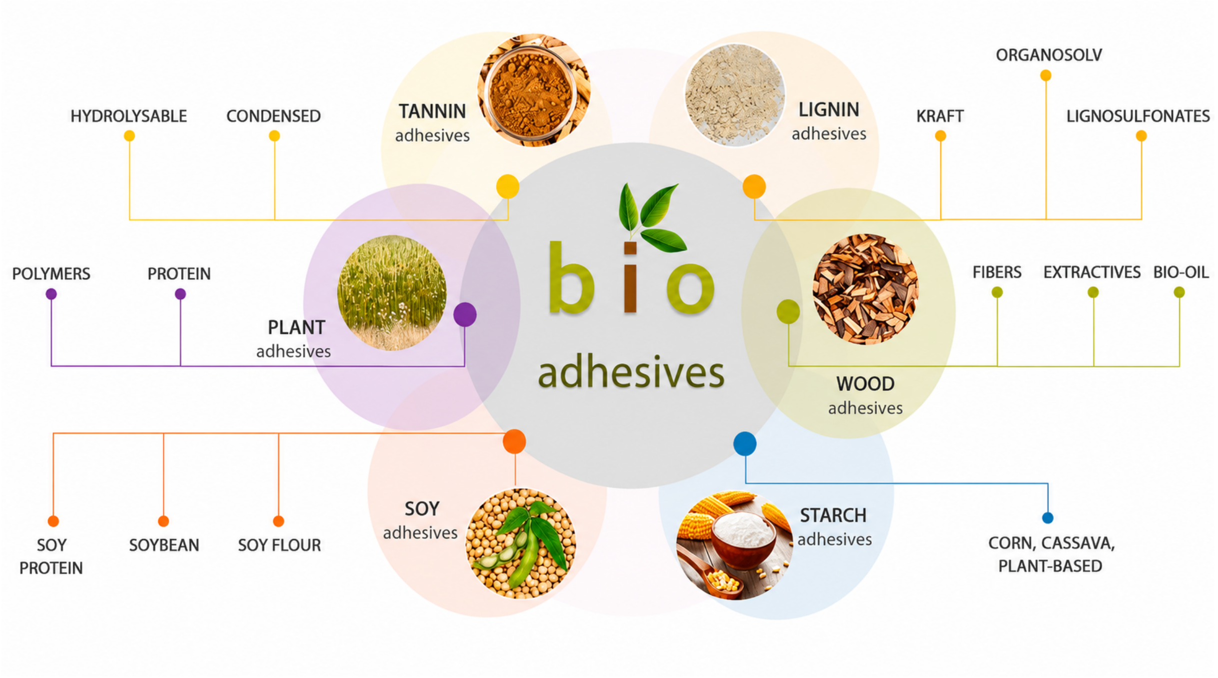

Figure 8. Bio-alternatives for the production of wood bio-adhesives [177]

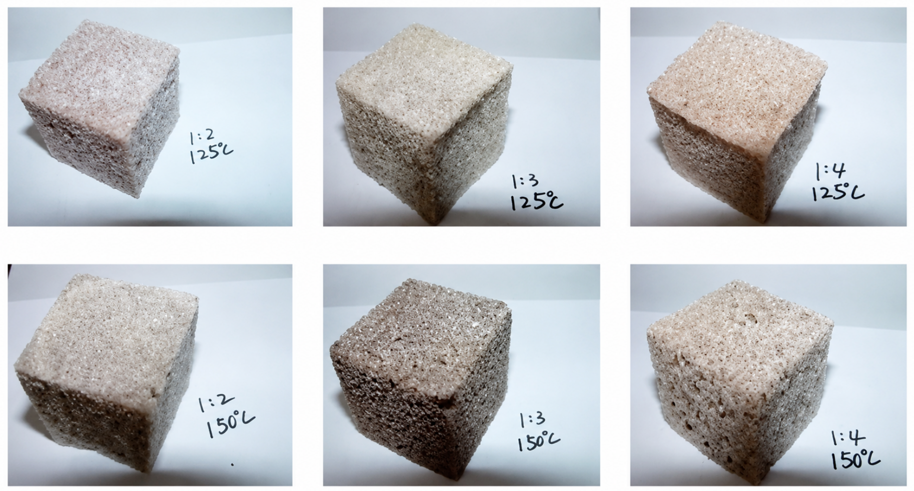

Figure 9. Bio-polyurethane foams from sugarcane bagasse by microwave liquefaction [188]

4.4.3 Tannin-based adhesives

Tannin can be extracted from a variety of sources from botanical plant species, including bark, buds, leaves, roots, seeds, stems, and wood. For the extraction of the component from the plant, ethanol, acetone, as well as deep eutectic organic solvents, supercritical liquids, or extraction using ultrasound/microwaves, which are less effective, can be used. Tannin is considered the most suitable biomass to produce bioglue, due to the indicators of better reactivity and availability [189–191]. To date, two types of tannin-based resins have been studied: cross-linked resins obtained using networking agents such as hexamine, furfural, etc., and hybrid resins obtained with the addition of other bioresources such as starch, lignin, etc. It is known that tannins are divided into two categories, which are used for various purposes: hydrolysable tannins in the leather industry and condensed tannins in the synthesis of adhesives. It is the condensed type that forms the basis for the further creation of bio-adhesives. Due to the presence of resorcinic and phloroglucinic nuclei in their structure, condensed tannins are obtained by polymerization of flavanol monomer units, which contain phenolic hydroxyl groups and have a high reactivity, which facilitates further processing (mimosa bark tannin, quebracho heartwood tannin, and pine bark tannin). It should be noted that, along with the above advantages and environmental friendliness, there is also a disadvantage—limited water resistance [192, 193]. Nevertheless, there are several contemporary methods to enhance the chemical and physical properties for the effective industrial application of tannin adhesives for wood panels. For example, properties such as solubility, viscosity, and water resistance depend on the degree of sulfination; excessive amounts can worsen them, and a moderate amount has a positive effect on the water resistance of the adhesive joint. Methods have also been studied, using various hardeners such as paraformaldehyde and hexamethylenetetramine (hexamine) to improve water resistance or enhance the reactivity of tannins to aldehydes by using zinc salts (zinc acetate or zinc chloride) without affecting the pH [194].

4.4.4 Closing considerations on cellulose-based and hybrid bio-adhesives

Cellulose and hemicellulose derived from forest waste are also important objects of research to produce formaldehyde-free adhesives, as volatile organic compounds (VOCs) do still represent a significant issue in this regard [195, 196]. Cellulose biomaterials generally lack the property of solubility in water and in conventional organic solvents due to the strong hydrogen bonds between the molecules, which has led to an interest in modifying the basic composition by esterification, silanization, and oxidation to increase the number of active groups and generally the chemical activity and solubility of cellulose [197]. Therefore, forest-derived biomass represents a promising resource for the development of sustainable bio-adhesive systems, despite the remaining challenges associated with feedstock variability and material performance.

5 Scalability and Industrial Applications of Forest Residue Products

As in other circular biomass systems, the efficient utilization of forest residues for both bioenergy and wood-based materials is essential for improving the industrial scalability of sustainable lignocellulosic products [198]. Achieving large-scale industrial implementation requires overcoming the challenges associated with the taxonomic diversity and material variability of biomass feedstocks used in wood product manufacturing. On the other hand, focusing on just one or a few species and overly restrictive screening, e.g., discarding wood with too many knots or defects, may result in inefficient resource utilization and reduced economic and environmental sustainability of the manufacturing process [199]. The variety of species and origins, on the other hand, limits the development of closed-loop and fully traceable large-scale production systems, which would be beneficial for improved resource exploitation [200]. In some cases, the availability of a species database, such as in Turkey, includes distribution areas among broad-leaved, coniferous, and mixed forests. A broader approach to traceability and availability of production data can be suitable for blending different products in particleboard manufacturing, including, e.g., almonds/walnuts [201]. It is also noteworthy that wood biomass also offers opportunities for emerging engineered material sectors, such as it is the case for myco-composites, obtained by leaving fungi mycelium developing in suitable conditions of biomass like wood pine flour [202]. However, the selection of biomass for this purpose can be very wide, also depending on the region and the fungi species adopted [203].

Reintroducing sawn wood residues and wood chips from forest management into wood–plastic composite manufacturing systems can significantly reduce production costs and raw material consumption. However, studies addressing industrial-scale implementation remain relatively fragmented, though, since the dependance over the species is still significant in terms of material yield and quality. This would imply identifying the effect of the deviations experimented over the optimal uses of the above resources, important in a context such as wood-plastic composites, where the recycling of worn-out materials is, in some cases, minor or even minimal at all [204]. In general terms, the use of forest residues appears central to circular bioeconomy, especially when economic surveys are available, such as in Central America countries, namely Costarica or Cuba, though competition with energy recovery is still at the forefront [205]. The integration of forest-derived biomass with post-consumer plastics may provide a more effective pathway toward scalable and circular composite manufacturing systems [206].

6 Conclusions

Forest residues generated from logging activities, forest maintenance, and wood-processing operations represent an increasingly important secondary resource for the development of sustainable wood-based materials. Their utilization in wood–plastic composites, fiberboards, veneer-based products, and bio-adhesive systems provides an effective route for reducing dependence on virgin raw materials and petroleum-derived binders while supporting circular bioeconomy strategies. At the same time, the wide variability in species, morphology, moisture content, and chemical composition of forest biomass remains one of the principal challenges affecting the large-scale and standardized production of engineered wood materials.

The studies reviewed in this work showed that forest residues can be successfully incorporated into a broad range of composite systems, where they contribute to stiffness enhancement, material lightweighting, and partial substitution of conventional synthetic constituents. Considerable progress has also been achieved in the development of lignin- and tannin-based adhesives, particularly in efforts aimed at reducing formaldehyde emissions and improving the environmental performance of wood products. In parallel, emerging approaches involving hybrid biomass systems, densified binder-free boards, and bio-refinery-oriented processing routes further demonstrate the versatility of forest-derived lignocellulosic resources.

Despite these advances, several limitations continue to restrict wider industrial implementation. Feedstock heterogeneity, inconsistent material quality, seasonal availability, and the absence of standardized processing routes still affect the reproducibility and long-term performance of many forest-residue-based products. In addition, the balance between material valorization and energy recovery remains a critical issue in regions where biomass is still primarily considered a low-cost fuel resource.

Future developments should therefore focus on improving feedstock traceability, process integration, and scalable manufacturing strategies capable of supporting continuous industrial production. Greater attention should also be directed toward interfacial engineering, lifecycle assessment, and the establishment of standardized evaluation criteria for bio-based wood materials. In this context, the continued advancement of low-emission adhesive technologies and integrated lignocellulosic composite systems is expected to play an important role in the transition toward more sustainable and resource-efficient wood engineering applications.

Author Contributions

Conceptualization, S.G. and C.S.; methodology, S.G., S.C., and C.F.; software, S.G. and A.Y.; validation, S.G., S.C., and C.F.; formal analysis, S.G. and C.F.; investigation, S.G., A.Y., and S.C.; resources, C.S. and C.F.; data curation, S.G. and A.Y.; writing—original draft preparation, S.G.; writing—review and editing, S.C., C.F., and C.S.; visualization, S.G. and A.Y.; supervision, C.S.; project administration, S.G.; funding acquisition, S.G. All authors have read and agreed to the published version of the manuscript.

Data Availability

No new data were created in this work.

Conflicts of Interest

The authors declare no conflicts of interest.

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Nomenclature

The following abbreviations are used in this manuscript:

CNC	Computerized numerical control
CoPA	Co-polyamide
CoPE	Co-polyester
EFB	Empty fruit bunches
FR	Forest residues
HDPE	High density polyethylene
LVL	Laminated veneer lumber
LVP	Laminated veneer product
MAPE	Maleic anhydride grafted polyethylene
MAPP	Maleic anhydride grafted polypropylene
ME	Mill effluents
MF	Mesocarp fibers
NCC	Nanocrystalline cellulose
NIPU	Non-isocyanate polyurethane
OPF	Oil palm frond
OPL	Oil palm leaves
OPT	Oil palm trunk
OSB	Oriented strand board
PHA	Polyhydroxyalkanoates
PKS	Palm kernel shells
pMDI	Polymeric diphenylmethane diisocyanate
PP	Polypropylene
PRF	Phenol resorcinol formaldehyde
PSL	Parallel strand lumber
STS	Self-tapping screw