Transition from Formaldehyde-Based Wood Adhesives to Bio-Based Alternatives

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Bio-based wood adhesives are increasingly receiving greater attention than those of synthetic formaldehyde-based adhesives from petroleum sources in response to climate change. In this respect, this editorial provides an overview on the transition of formaldehyde-based adhesives to bio-based adhesives for the bonding of wood. This transition is underway in academia and industry for practical applications. Bio-based adhesives offer low toxicity, lower greenhouse gas emissions, and increased sustainability with circular economy by promoting renewable and degradable sources, which generates a driving force for the transition.

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Formaldehyde-Based Wood Adhesives

Formaldehyde-based resins, such as phenol-formaldehyde (PF) resins, resorcinol-formaldehyde (RF) resins, phenol-resorcinol-formaldehyde (PRF) resins, urea-formaldehyde (UF) resins, melamine-formaldehyde (MF) resins, and melamine-urea-formaldehyde (MUF) resins, are widely used as adhesives for manufacturing glued laminated wood products, plywood, and wood-based composite panels. These adhesives have been used for almost 100 years, owing to their low cost, good performance, and applicability to wood. However, these adhesives are posing health and environmental risks, contributing to greenhouse gas emissions, and exhibiting slow biodegradation, which adds to pollution and climate change concerns. Consequently, many countries are promoting bio-based adhesives to reduce reliance on petroleum-based chemicals, fossil fuels, and to improve indoor air quality for the alignment with the UN's Sustainable Development Goals (SDGs). Even if bio-based adhesives may currently be insufficient in obtaining the full adhesion performance of formaldehyde-based adhesives, some research on alternative biomaterials such as soy protein, polysaccharides, lignin, and tannin has shown promising results.

Protein-based Adhesives

Protein-based adhesives are bio-based adhesives derived from animal or plant proteins, such as casein, collagen, gelatin, and soy protein. They offer several advantages such as biodegradability, low toxicity, and strong bonding capabilities, particularly for porous materials such as wood and paper. They are commonly used for plywood and particleboard, as well as in textiles and food packaging. In such applications, these adhesives can compete with synthetic options in the performance. However, challenges such as shorter shelf life, performance variability due to different protein sources, and moisture sensitivity need to be addressed (Huang *et al.* 2024). Ongoing research has focused on enhancing their properties through formulation adjustments and cross-linking, positioning protein-based adhesives as a sustainable alternative in various applications and promoting their wider adoption.

Carbohydrate-based Adhesives

Carbohydrate-based adhesives are also bio-based adhesives derived from polysaccharides such as glucose, starch, chitosan, cellulose, and hemicellulose, which are commonly sourced from plants (Liu *et al.* 2024; Ni *et al.* 2024). These adhesives are valued for their biodegradability, low toxicity, and renewable nature, making them environmentally friendly alternatives to synthetic adhesives. Carbohydrate-based adhesives exhibit good bonding strength, particularly with porous materials such as wood, paper, and textiles, and are often used in applications such as packaging and wood industry. However, challenges include susceptibility to moisture and mildew resistance, which can weaken their performance, and variability in adhesive properties based on the source and processing methods (Hou *et al.* 2024). Ongoing research aims to enhance their water resistance and bonding capabilities through chemical modifications.

Lignin-based Adhesives

Owing to its abundance in nature, high industrial production yield, phenolic nature, and low cost, technical lignin, a main by-product of pulp and paper industry, is an excellent candidate to produce bio-based adhesives as well as bio resin to replace conventional formaldehyde-based adhesives (Abu-Omar *et al.* 2021). Nowadays, a huge amount of technical lignin is being wasted or burned for energy consumption, although it has a great potential of building thermosetting bio-based adhesives (Lawoko and Samec 2023; Yang *et al.* 2023; Ghahri *et al.* 2024). In recent years, approximately 100 million tons/year of technical lignin comes from the pulp and paper industry, showing that it is a highly available raw biomaterial for bio-based adhesives (Bajwa *et al.* 2019). However, transition to lignin-based bio-adhesives brings some challenges of finding effective lignin extraction and fractionation methods from biomass, improving poor reactivity for crosslinking, high chemical heterogeneity, as well as unfavorable odor and color. Among them, poor reactivity of lignin has received significant attention from researchers around the world. In recent years, several reaction schemes, including synthetic and natural crosslinkers, have been applied to enhance lignin adhesion capacity, but this challenge is still under investigation. Researchers have made many attempts to enhance lignin crosslinking for bio-based wood adhesives, using various crosslinking agents, such as glyoxal, formaldehyde, phenol, and isocyanates, as well as modifying lignin through various techniques such as hydroxymethylation, glyoxalation, and amination (Wybo *et al.* 2024). However, despite these approaches, health risks and environmental concerns related to green chemistry and sustainability remain. Therefore, the use of fully green bio-crosslinking agents for lignin is crucial in advancing lignin to bio-based adhesives as sustainable alternatives.

Tannins

Tannins are another set of polyphenolic compounds present in various plants, particularly in bark, wood, leaves, and fruits. They are known for their astringent properties and are classified into two main groups: hydrolysable and condensed tannins. Tannins' common sources include oak, chestnut, quebracho, and various tree barks (Pizzi *et al.* 2024). Tannins from renewable resources provide wood adhesives with sustainability, low toxicity, biodegradability, bonding strength, thermal stability and water resistance, which makes them an environmentally friendly alternative to synthetic formaldehyde-based adhesives for wood industry. As non-toxic natural polyphenols, the condensed and hydrolysable tannins are used for tanning hides to obtain leather as a commercial commodity chemical and for a growing number of other industrial applications of mainly substituting petroleum-based products. Some challenges and limitations for tannins as wood adhesives include their variability from sources, standardized formulations, and curing mechanism which is crucial for improving their performance (Pizzi *et al.* 2024).

Final Remarks

Bio-based adhesives are emerging as sustainable alternatives to formaldehyde-based adhesives, particularly for wood-based products, due to growing concerns over health and environmental impacts as well as climate change. While bio-based adhesives show promising performance and environmental benefits, challenges remaining include the cost, consistency, performance, and scale-up. Technical challenges in employing biomaterials for bio-based wood adhesives are their effective formulation and consistent quality. Other technical challenges are their inconsistent viscosity, which should be controlled for industrial requirement, poor chemical reactivity, and low water resistance. Further research is necessary to find effective solutions of utilizing these biomaterials, to enhance their performance, and to reduce their cost for industrial application. Attention in the industry is increasing, but awareness and understanding will be crucial to a wider public acceptance. For this aim, concerted efforts among researchers, industries, and policymakers will facilitate this transition.

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