A review of preparation of binderless fiberboards and its self-bonding mechanism (Postprint)

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Abstract

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Full Text

Preamble

A Review of the Preparation of Binderless Fiberboards and Their Self-Bonding Mechanism

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Abstract
The demand for fiberboards has been growing in recent years. However, the emission of formaldehyde, a primary component of adhesives used in fiberboard production, has raised significant environmental and health concerns. Consequently, industries are actively pursuing green chemistry technologies to eliminate these issues. Binderless fiberboards have emerged as promising candidates since their manufacturing process involves no resin addition. Several potential mechanisms for the formation of binderless fiberboards have been proposed, with chemical changes in lignocellulosic material components expected to occur during hot pressing, where self-bonding provides the primary bonding strength. This review summarizes various aspects of binderless fiberboard production, including the feasibility of different raw materials, chemical and enzymatic pretreatments, manufacturing processes, and the potential mechanisms of self-bonding. Furthermore, the elucidation of the self-bonding mechanism is discussed, along with future work that may benefit the field.

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Introduction

The presence of adhesives has traditionally been essential for fiberboard manufacture to ensure adequate physical and mechanical properties. Formaldehyde, one of the most common adhesive components, has been widely employed in the industry due to its low cost and desirable performance [**?**, **?**, **?**]. However, formaldehyde emissions from fiberboards have raised serious environmental and health concerns [**?**]. Recently, formaldehyde was reclassified as carcinogenic category 1B under the European labeling and packaging of substances and mixtures (CLP) regulation in June 2014 [**?**]. To address these concerns, formaldehyde-free adhesives derived from natural sources—including lignin [**?**, **?**], soy protein [**?**], wheat protein [**?**, **?**, **?**], and starch [**?**]—have been extensively researched. Nevertheless, high costs and relatively poor performance have limited their industrial application [**?**]. Therefore, producing fiberboards without adhesive addition represents a promising strategy from both economic and environmental perspectives.

Early research demonstrated the feasibility of using bark as a raw material for binderless fiberboards [**?**, **?**]. However, the requirement for high pressing temperatures posed a major obstacle, limiting their application and development [**?**, **?**]. More recently, binderless fiberboards have been successfully produced from refined black spruce bark, though fabrication required a sandwich structure combining wood fibers and bark to achieve acceptable results [**?**]. Systematic research on binderless fiberboards can be traced back to the 1980s, when Mobarak et al. [**?**] prepared binderless lignocellulose composites from bagasse and discussed the potential self-bonding mechanism. Subsequently, Shen [**?**] proposed and patented a process for binderless fiberboard production, making industrialization possible.

Various raw materials, including coconuts [**?**], oil palm [**?**], and bamboo [**?**], have been studied for their feasibility in binderless fiberboard production. Chemical and enzymatic pretreatments have provided new avenues for improving binderless fiberboard properties by generating free radicals on fiber surfaces [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]. Additionally, manufacturing processes involving steam explosion prior to hot pressing and steam injection pressing have been developed to generate more reactive sites that contribute to self-bonding, thereby improving binderless fiberboard performance to meet established industrial standards

[?, ?].

However, most discussions and results on binderless fiberboard production remain limited to the laboratory level, primarily because the mechanisms of self-bonding formation during production have remained elusive. Elucidating the self-bonding mechanism is therefore crucial for further improving binderless fiberboard performance and enabling industrialization. Several potential explanations have been proposed: lignin–furfural linkages [?], condensation reactions in lignin [?], and furfural self-polymerization [?]. Additionally, physical phenomena involving thermal softening of lignin have been suggested to partially contribute to fiberboard formation [?]. In reality, the mechanism varies depending on raw materials and manufacturing processes, with multiple reactions and phenomena likely working collaboratively. Numerous studies have attempted to elucidate the self-bonding mechanism using tools such as Fourier transform infrared spectroscopy (FT-IR), nuclear magnetic resonance (NMR), and gas chromatography–mass spectrometry (GC-MS) to determine compositional changes in binderless fiberboards [?, ?]. While these analyses revealed chemical changes before and after pressing, they provided no detailed information on specific functional group changes during the dynamic pressing process. Since pressing variables regarding temperature and pressure fluctuate over time, understanding the correlation between group changes and variable fluctuations is necessary. Such understanding would benefit manufacturing process optimization. X-ray photoelectron spectroscopy (XPS) appears suitable for this purpose, as it has been used to study surface chemical compositions of cellulosic fibers before and after esterification [?]. Detailed information will be discussed later.

In summary, this review examines different raw materials employed in binderless fiberboard production, discusses chemical and enzymatic pretreatments, covers manufacturing processes, addresses the crucial aspect of self-bonding mechanisms, and proposes future work deserving attention.

Raw Material Resources

Not all lignocellulosic materials are suitable for economically attractive commercial binderless fiberboard production. Attention has focused on woody fibers since binderless fiberboards were successfully obtained from two different fiber furnishes [?]. Additionally, other resources such as bagasse, flax, and corn have been patented for resin-free fiberboard production [?]. Therefore, resources are classified into woody and non-woody categories, described in the following sections.

Woody Raw Materials

Woody materials typically contain high amounts of cellulose and lignin but low hemicellulose content. Consequently, wood-based composites exhibit better water resistance than non-woody materials because hemicelluloses are hydrophilic and can adsorb water [?]. However, synthetic resins are usually required for

wood-based fiberboard production due to weak bonding strength that may result from low hemicellulose content. Specifically, spruce and pine residues have been examined for binderless fiberboard production potential [**?**, **?**], with steam explosion pretreatment applied to determine its effects on board properties. Results showed that steam explosion improved fiberboard physical properties. Other woody materials such as *Pinus radiata* [**?**], spruce fibers [**?**], and beech and rubber fibers [**?**, **?**, **?**] have also been evaluated. However, all woody fibers required enzymatic or chemical pretreatment to generate stable radicals capable of initiating self-bonding between fibers. While poplar fibers showed potential, enzymatic hydrolysis lignin was added to improve fiberboard properties [**?**]. Recently, the authors' group patented a method for producing high-density, thick binderless fiberboards and observed that controlling wood fiber cross-section size and length was essential [**?**]. In general, binderless fiberboards from woody raw materials appear to require additional treatments such as steam explosion pretreatment and fiber surface activation. Adding wax or lignin may serve as an alternative to maintain acceptable dimensional stability without compromising bonding strength.

Non-Woody Raw Materials

Due to increasing wood prices and supply shortages, alternative raw material sources are needed. Lignocellulosic wastes including bagasse [**?**, **?**], coconut husk [**?**], and wheat straw [**?**] have been explored due to their low cost and abundance. Velasquez et al. [**?**] produced binderless fiberboard from *Miscanthus sinensis*, which exhibited desirable performance under optimized conditions after steam explosion pretreatment. Banana bunch suitability has also been evaluated, with steam-exploded materials used to make binderless fiberboard [**?**]. However, low internal bond (IB) strength and high thickness swelling (TS) values were observed, likely related to banana bunch lignin structure and high residual xylose content, respectively. Furthermore, grinding before pressing significantly improved IB without compromising other physical-mechanical properties of fiberboards from steam-exploded *Miscanthus sinensis* [**?**]. Recently, seed cake potential as a raw material was investigated, with mechanical properties comparable to commercial fiberboards under optimized conditions [**?**]. Obviously, raw material chemical composition determines suitability for binderless fiberboard production. Various non-woody raw materials used in binderless fiberboard production are summarized in Table 1.

In summary, poor dimensional stability of binderless fiberboards from non-woody materials represents one of the biggest drawbacks, resulting from high hemicellulose content. Extended steam pretreatment appears to be an option to overcome this limitation, though corresponding energy consumption must be considered.

Pretreatment of Raw Materials

It is well known that adhesives enhance fiber interaction, providing desirable mechanical and physical properties. Therefore, fiberboard production without synthetic resin is challenging. Chemical pretreatments such as alkaline, acid, and oxidation agents have been utilized to activate fiber surfaces [**?**, **?**, **?**, **?**]. Binderless fiberboards made from alkaline-treated black spruce bark possessed higher IB, modulus of rupture (MOR), and modulus of elasticity (MOE) than untreated samples [**?**]. Composition analysis revealed de-acetylation of wood fibers and degradation of significant lignin and hemicellulose amounts [**?**], which might explain the positive effect of alkaline treatment on mechanical properties. Acid treatment is typically considered a pre-hydrolysis step before steam explosion due to its significant effects on raw material structure [**?**]. Nitric acid activation of wood surfaces involves oxidation, nitration, and hydrolysis of wood polymers [**?**, **?**, **?**]. Therefore, alkaline and acid concentrations and treatment times must be carefully controlled to avoid excessive degradation of main components.

This section emphasizes Fenton' s reagent and laccase treatments due to their potential for producing satisfactory binderless fiberboards. Addition of other components is also included considering their potential effects on performance.

Chemical Pretreatment: Fenton' s Reagent

Fenton' s reagent, composed of ferrous chloride and hydrogen peroxide, can activate fiber surfaces. This oxidation pretreatment facilitates adhesive bonding between fibers. The main reaction process is shown in the following equation:

$$RH + OH^{\bullet} \rightarrow H_2O + R^{\bullet}$$

where hydroxyl radicals ($OH^{\bullet}$) are continuously generated by hydrogen peroxide decomposition with ferrous ion assistance. These hydroxyl radicals can react with and attack fibers and lignin to form reactive components ($R^{\bullet}$). The activated components can covalently bond with low-molecular-weight degraded components, contributing to self-bonding in binderless fiberboards [**?**]. Additionally, intra-fiber cross-links are created due to diffusion of degraded low-molecular reagents into the lumen within cell walls, which is believed to increase fiberboard dimensional stability [**?**, **?**].

Halvarsson et al. [**?**] investigated physical and mechanical properties of binderless fiberboards made from Fenton' s reagent-treated wheat straw. Fiberboard strength was further enhanced, and TS decreased when hydrogen peroxide percentage increased from 2.5% to 4.0%. Specifically, TS and water adsorption (WA) of the best-performing fiberboards prepared with 4.0% hydrogen peroxide and 2% $CaCl_2$ addition were 75% and 90%, respectively [**?**]. Oil palm treated with Fenton' s reagent oxidation (4% H_2O_2) was used to prepare binderless fiberboards at 190°C pressing temperature, yielding TS and WA values of 35% and 48%, respectively—lower than those of treated wheat straw fiberboards [**?**].

These results indicate that raw material chemical composition is a key factor for suitability in binderless fiberboard production. While this method shows research promise, several weaknesses exist, including long-term harmful effects on fiberboard properties due to high peroxide charges, board quality instability, and insufficient mechanical strength unless high board densities are used [**?**].

Enzymatic Pretreatment of Raw Materials

Interest in enzymatic treatments of cellulosic fibers is growing [**?**, **?**, **?**, **?**, **?**]. Compared with chemical treatments, enzymatic treatment involves milder reaction conditions, produces fewer by-products, and is environmentally friendly [**?**]. Laccase, widely distributed in plants and fungi, has been intensively studied in the pulp and paper industry for its ability to catalyze oxidation of various phenolic substrates [**?**, **?**, **?**]. During fiber treatment, laccase hardly penetrates fibers and mainly oxidizes surface lignin, generating free radicals that act as potential reactive sites for further cross-linking reactions in fiberboard production. Increased lignin molecular weight from laccase-treated fiberboard surfaces strongly indicates lignin polymerization [**?**]. This process is described in the following equation:

$$\text{Laccase} + 4\text{Phe-OH} + \text{O}_2 \rightarrow 4\text{Phe-O}^{\bullet} + 2\text{H}_2\text{O}$$

Laccase pretreatment of beech fibers promoted adhesion, and the resulting fiberboards possessed significantly higher strength than untreated fibers. Lignin deposition and covalent bond formation between fibers were believed to be primarily responsible for improved bonding [**?**]. Scanning electron microscope (SEM) results showed that enzyme-treated rubber fibers appeared smooth due to lignin removal and surface molecule breakdown, compared to the rough surface of untreated fibers (Fig. 1 [Figure 1: see original paper]).

Nasir et al. [**?**] fabricated binderless fiberboards from rubber fibers treated at 9 U/g enzymes for 60 min and pressed at 200°C, showing acceptable MOE, MOR, and IB performance, though not for WA and TS. Enzyme amounts should be controlled to avoid excessive lignin removal, which dramatically decreases IB [**?**]. Recently, manufacturing binderless fiberboards from enzyme-pretreated lignocellulosic fibers has been reviewed, covering effects of preheating temperature and wood type on fiberboard properties, as well as production method evaluations [**?**, **?**]. While enzymatic pretreatment can improve bonding strength, industrial production attempts face technical and economic challenges, including enzyme inactivation under harsh conditions, enzyme costs, and high facility investment.

Addition of Other Components

Lignin naturally provides adhesion in wood structure, and lignin-based wood adhesives have been prepared and applied in the board industry [**?**]. In binderless

fiberboard production, lignin plasticization and cross-linking reactions between lignin and furfural are considered partially responsible for board adhesion [**?**]. Therefore, lignin addition is regarded as an effective method to enhance board properties.

Angles et al. [**?**] investigated effects of various lignin types on board performance, finding that dimensional stability and mechanical characteristics improved significantly, with kraft lignin performing best. Adding kraft lignin (20% dry solid basis) to pretreated materials decreased TS from 12.9 ± 1.2% to 2.0 ± 0.6% and WA from 38 ± 7.0% to 7.0 ± 0.3%. Lignin can act as a plastic and resist water penetration, improving dimensional stability. Mechanical property improvements were attributed to lignin providing more reactive sites as an adhesive, thus increasing links between cellulose fibers [**?**]. Similar conclusions were observed for steam-exploded *Miscanthus sinensis* binderless fiberboards with kraft lignin addition. However, when lignin was added after pretreatment, bubbles formed at high pressing temperatures, negatively affecting properties. No bubbles were observed when adding lignin before pretreatment, likely due to better mixing and removal of low-molecular-weight compounds [**?**].

Recently, binderless fiberboards made from poplar fibers with enzymatic hydrolysis lignin (EHL) addition exhibited significantly improved physical and mechanical properties. These lignins were produced by enzymatic hydrolysis of pretreated substrates to remove carbohydrates, with oxygen-related functional groups and radicals further generated through oxygen plasma treatment [**?**].

In binderless particleboard production, sugars have also proven effective additives. Adding 20% glucose to oil palm biomass improved MOR from approximately 5.0 to 13.5 MPa and IB from 0.6 to 1.7 MPa, while significantly decreasing TS and WA values [**?**]. Thus, adding other components is a promising method for improving board properties in conjunction with other pretreatments.

Manufacturing Process

Two distinct methods are widely used in fiberboard production: "wet-forming" and "dry-forming"processes. Wet-forming involves distributing cellulosic materials in water, with hydrogen bond formation and lignin' s thermosetting adhesive behavior expected during heating and drying, requiring less or no binder. However, low density, limited strength, and wastewater pollution are main disadvantages. Dry-forming reduces cellulosic material moisture content via drying before resin combination. After mat formation, the mixture undergoes prepressing and hot pressing to produce fiberboards. While a wet process for binderless fiberboards from fiber and particle combinations was recently patented [**?**], industrial binderless fiberboard manufacture mainly uses dry-forming without resin addition. Other processes such as steam explosion before hot pressing and steam injection pressing have been developed to enhance binderless fiberboard performance. The main difference between steam explosion before hot pressing and conventional dry-forming is the use of steam explosion to efficiently

expose components for further hot pressing reactions. In the authors' groups, microwave pretreatment has recently been applied to the dry-forming process, rapidly increasing raw material temperature before pressing and yielding high-density, thick binderless fiberboards with acceptable properties [**?**]. Detailed discussions of current manufacturing methods follow.

Steam Explosion Before Hot Pressing

Traditional binderless fiberboard preparation involves hot pressing, but fiberboards produced solely by hot pressing generally show poor water adsorption and thickness swelling performance. While wax addition has been suggested to overcome this drawback [**?**], steam explosion has proven more effective for improving dimensional stability [**?**]. Steam explosion can liberate lignin from inside cell walls to the fiber surface. SEM analysis of broken fiberboards from softwood residue mixtures showed that liberated lignin covered hemicelluloses and cellulose, limiting water adsorption by these hydrophilic polymers and thus improving dimensional stability. Steam pretreatment also causes defibration and generates numerous shrinkage folds on surfaces, facilitating adhesion through increased contact area. Additionally, lignin droplets observed on fiber surfaces have lower softening points than original lignin, easily enabling lignin plastic flow [**?**].

Angles et al. [**?**] related steam pretreatment severity to treatment time and temperature, finding that high severities within a certain range improved physical and mechanical properties of fiberboards from steam-exploded residual softwood. Acid addition during steam pretreatment promoted further hemicellulose and cellulose hydrolysis, decreasing WA and TS. Furthermore, short fibers packed more compactly, preventing water penetration and reducing WA and TS [**?**].

Steam explosion also applies to non-woody materials. *Miscanthus sinensis* was steam-exploded before binderless fiberboard production [**?**], with basic parameters including TS and WA meeting relevant standard specifications. Increased dimensional stability was highly related to decreased hemicellulose content [**?**]. Saari et al. [**?**] investigated steam-exploded binderless particleboards from oil palm trunks, observing that steam pretreatment enhanced overall physical and mechanical characteristics. As steam temperature and time increased, MOR and IB increased while TS and WA decreased. However, increasing steam exposure time to 50 minutes destroyed particle structure, reducing strength properties, so longer steam exposure is not recommended [**?**].

Shao et al. [**?**] systematically characterized lignin from steam-exploded bamboo. Thermogravimetric analysis (TG) and DSC analysis revealed that steam explosion decomposed lignin, lowering its softening temperature compared to original lignin. Ozonation and NMR analysis confirmed cleavage of -O-4 linkages in lignin [**?**]. Since -O-4 linkage generation has been reported during hot pressing [**?**], steam treatment likely exposed more reactive phenolic hydroxyl end sites, with reactions between these sites expected to contribute to self-bonding

in binderless fiberboards. While evidence supports steam pretreatment' s positive effects, drawbacks including high water and energy consumption should not be ignored.

Hot Pressing

Biomass chemical components can achieve self-bonding under hot pressing, so pressing parameters such as temperature, time, and pressure definitely influence fiberboard properties. The effect of pressing temperature on binderless boards from various raw materials—including oil palm trunk and frond [**?**, **?**, **?**], kenaf core [**?**], and *Miscanthus sinensis* [**?**]—has been examined. Pressing temperature is one of the most important manufacturing parameters affecting board properties. As pressing temperature increases, MOR and IB increase while WA and TS decrease. Similarly, Boon et al. [**?**] concluded that increasing temperature, time, and pressure could improve mechanical strength and moisture stability, with temperature being the most significant parameter while pressure and time had less obvious effects. Temperature should be limited below 200°C to avoid severe burning, and high pressing temperatures are not recommended given energy consumption, making further dimensional stability improvement via temperature increase ineffective [**?**]. Additionally, water presence in raw materials is crucial for heat transfer during hot pressing. Studies on feed material water content (5–20 wt%) suggested an optimum of 8 wt% moisture, with higher contents negatively affecting modulus [**?**].

Steam Injection Pressing

Research on steam injection pressing for large panel fabrication with southern hardwoods began about 30 years ago [**?**]. This technology was subsequently employed for binderless fiberboard production from mixed softwood and hardwood, showing poor bonding strength but improved dimensional stability [**?**]. Recently, few studies on steam injection pressing for binderless fiberboards have appeared [**?**, **?**, **?**]. Conversely, successful development of particleboards from kenaf core using steam injection pressing has been reported [**?**]. These particleboards showed higher IB values (0.43 MPa at 0.50 g/cm^3) and lower average TS (11% at 0.50 g/cm^3) than hot-pressed particleboards (IB = 0.09 MPa, average TS = 169%). Mechanical properties increased linearly with board density, and increased steam pressure improved bonding strength. Extending steam treatment time from 7 to 15 minutes at 1.0 MPa pressing pressure decreased TS from 16% to 9.4% but had less effect on MOR.

Widyorini et al. [**?**] compared steam injection and hot pressing effects on kenaf core chemical changes in particleboard production. Mild steam injection (0.6–1.0 MPa, 7–20 min) caused significant lignin, cellulose, and hemicellulose degradation compared to low-degree degradation under hot pressing. At 1.0 MPa steam pressing pressure, mean TS was 7.47% versus 169% under hot pressing at 190°C. Increased steam injection pressure and time further promoted main component degradation. Manufacturing process differences significantly affected

board properties. In steam injection, board temperature increased rapidly via high-pressure steam injection, with components degrading and re-reacting in a short period. Hot pressing worked less efficiently since it took time for steam to generate from particle moisture [**?**]. Similar observations revealed that steam injection pressing of sugarcane bagasse particleboards produced relatively better properties than hot pressing [**?**]. However, excessive steam caused serious component decomposition and poor board properties.

Self-Bonding Mechanism of Binderless Fiberboards

Regardless of woody or non-woody raw materials, pretreatment operations appear necessary for further application. Mechanical, chemical, biological, and thermochemical pretreatments have been employed separately or in combination depending on desired products [**?**, **?**, **?**]. Given differences in raw material chemical and morphological properties, moisture content, and manufacturing processes, several self-bonding mechanisms have been proposed [**?**].

For hot pressing, understanding substrate thermal reaction chemistry may clarify bonding mechanisms. Observed heating reactions include hydrolysis, dehydration, and oxidation. Hemicelluloses are easily removed due to lower thermal stability than cellulose and lignin [**?**, **?**, **?**, **?**]. Organic acids, acetone, and furfural form from hemicellulose thermal decomposition [**?**]. However, Okuda et al. [**?**] compared kenaf core and resulting binderless fiberboard chemical compositions, observing little furfural formation during production. This discrepancy likely results from condition variations, since hemicellulose degradation is highly dependent on moisture content, temperature, treatment time, and raw material composition [**?**]. Furthermore, Okuda et al. [**?**] suggested that lignin components decomposed during hot pressing could be extracted by methanol, indicating little contribution to self-bonding. They believed lignin condensation reactions and chemical reactions from conjugated carbonyl compounds played important roles in self-bonding [**?**].

More recently, Alvarez et al. [**?**] suggested that organic extractives from leaf plantain decreased fiber surface reactivity, and their removal favored fiber contact, increasing binderless board mechanical properties [**?**]. Conversely, water extractive removal showed negative effects, as these low-molecular-weight compounds facilitated stable free radical formation and better bonding. Additionally, Sun et al. [**?**] comparatively characterized lignin from raw materials and hot-pressed binderless fiberboards. Gel permeation chromatography (GPC) revealed that enzymatic/mild acidolysis lignin (EMAL) molecular weight decreased from 2210 to 1630 g/mol, while NMR showed -O-4 linkage formation in EMAL after fiberboard production [**?**].

For steam explosion, the self-bonding mechanism appears more complex due to steam treatment presence (Fig. 2 [Figure 2: see original paper]). Although Quintana et al. [**?**] observed no obvious cellulose degradation, hemicellulose, lignin, and cellulose depolymerization during steam treatments is widely ac-

cepted [?, ?]. After investigating chemical changes from steam injection and hot pressing, Widyorini et al. [?] attributed satisfactory steam injection binderless particleboard performance to significant cellulose, hemicellulose, and lignin degradation. Researchers have noted that free sugar content from hemicelluloses during steam pretreatment increases to a maximum then decreases, indicating potential conversion to other products [?, ?]. Furthermore, furan monomers found during fiberboard production [?, ?, ?] are believed to generate lignin–furfural linkages or undergo self-polymerization during pressing, providing main self-bonding strength [?, ?]. Physically, cellulose hydrolyzed during steam pretreatment forms new crystals that reinforce the lignin/hemicellulose matrix while contributing to shape fixation and water resistance [?, ?]. Thermal lignin softening also plays an important role in fiberboard properties [?, ?], with in situ lignin plasticization believed to increase final mechanical properties [?].

Although several acceptable mechanisms have been suggested, observations are mainly based on chemical changes before and after fiberboard production, with limited information on chemical changes during production. Therefore, optimizing pressing variables such as pressure and temperature as functions of time is difficult. The authors' previous work investigated wood fiber surface composition (*Bixa orellana*) using XPS, subjecting raw materials to hot pressing in a high-pressure reactor to simulate real manufacturing. Figure 3 [Figure 3: see original paper] shows hot pressing effects on carbonyl group concentration. Carbonyl group content increased within 2 minutes, indicating cellulose and hemicellulose degradation to monosaccharides during hot pressing. Furan monomer generation from monosaccharide dehydration also contributed to this increase [?]. Carbonyl group content then gradually decreased until 6 minutes due to potential furan monomer reactions, during which self-bonding was achieved. Finally, carbonyl group concentration slightly increased, probably from resin degradation under continuous high pressure and temperature. These XPS results support observations that furan monomers are main contributors to binderless fiberboard self-bonding. Future work on lignin and its degraded fractions' role in self-bonding is still needed.

Future Research Directions

Although binderless fiberboard production research has continued for many years, scaling up from bench to pilot and industrial levels remains challenging. The primary obstacle limiting commercialization is difficulty in elucidating self-bonding mechanisms, making product costs and performance uncompetitive with commercial resin-based fiberboards. Given that traditional resin-based fiberboards are environmentally unfriendly, efforts to reduce costs and improve binderless fiberboard physical and mechanical properties must continue. This review offers new insights into self-bonding mechanisms, particularly the role of lignin and furan during hot pressing via state-of-the-art technologies including FT-IR, XPS, and solid-state NMR. Additionally, extensive efforts should investigate other efficient binderless fiberboard preparation approaches, such as

laccase-mediator systems, and effective pretreatment methods to utilize natural fiber components.

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Note: Figure translations are in progress. See original paper for figures.