A Review of Natural Fibers and Processing Operations for the Production of Binderless Boards

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Decreasing wood supplies and the need for formaldehyde-free particleboard have become important issues. This has led to studies about the use of raw materials other than wood, along with the manufacture of particleboard without using any synthetic adhesives. This paper presents an overview of the development of binderless boards from natural fibers using a diverse range of manufacturing processes, such as heat and steam treatments. The features of binderless boards produced with various parameters, such as pressing parameters, particle sizes, and additional substances, under various manufacturing processes, are discussed. Based on the availability of natural fibers, binderless boards are typically evaluated for their physical, mechanical, and thermal properties. This review is approached with an understanding of the processes and contributing factors in producing binderless boards, helping to overcome some critical issues that are necessary for the development of future new "green" binderless boards through value-addition to enhance their usage.

Keywords: Natural fibers; Binderless board; Manufacturing process; Optimum; Board properties; Value-added

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INTRODUCTION

Particleboard is a wood-based composite consisting of various shapes and sizes of lignocellulosic particles bonded with an adhesive and consolidated under heat and pressure. Particleboard makes up about 57% of total consumption of wood-based panels consumed, and demand is continuously growing, at 2% to 5% annually. Uses include housing construction, furniture manufacturing, and interior decoration of wall and ceiling paneling (Drake 1997). The main source of fiber material for the particleboard and furniture industries in Malaysia is rubberwood, which is estimated to be 2,000,000 m^3 annually, leading to a shortage of rubberwood (Anonymous 2009). Wood normally takes a long time to grow to useable sizes, and processing wood as a material is difficult. Thus, it is essential to find alternatives for wood, as the raw wood supply has diminished because of deforestation and forest degradation activities, along with high demand for wood-based panels (Ashori and Nourbakhsh 2008). Research has been carried out on a wide variety of non-wood plant fibers and agricultural residues, such as bagasse, coconut husks, bamboo, and a few more cheap raw materials from many different regions of the world, all of which may serve as a replacement for conventional woods (Miki *et al.* 2003).

Currently, most commercial particleboard is bonded using formaldehyde-based adhesives made from non-renewable sources. Urea formaldehyde is the most common resin used because of its fast curing time, clear color, and low cost compared with other synthetic resins (Hashim *et al.* 2012). Nonetheless, formaldehyde emissions from urea formaldehyde-bonded panels have been subjected to strict legislation and gained attention as a public health concern in the last 30 years. The 10% usage of urea formaldehyde resin from the total dry weight of particleboard makes up about 60% of the overall cost of particleboard production. Also, synthetic adhesives may have effects on human health, such as cancer and irritation of the eyes, nose, and throat, and may lead to environmental pollution (Okuda and Sato 2004).

The manufacturing of binderless board by utilizing lignin present in the lignocellulosic fiber raw material is a good substitution solution for expensive synthetic resin used in current particleboards. Because there is no synthetic adhesive used, it is possible that no curing period is needed, and it is economical. Lignin is a complex phenolic amorphous polymer that plays roles in cell wall development and serves to bond individual cells in plants. Lignin has been reported to play an important role in self-bonding boards, acting as a natural binder for fibers (Okuda and Sato 2004). When heat is applied to the fibers, lignin melts to the surface of fibers, and as pressure is applied to the fibers, lignin binds the fibers together. Previous studies have reported that the glass transition values in a dry state for lignin, cellulose, and hemicelluloses were 200, 220, and 170 °C, respectively (Hashim *et al.* 2011).

Research on binderless boards has attracted interest because of its excellent physical and mechanical properties, environmental friendliness, and renewable sources, and because it is both recyclable and economical. It is highly trusted as a competitive wood supplement in the wood-based industry, as the manufacturing processes for binderless boards are simple; it is hoped that it can be easily applied to commercial production (Panyakaew and Fotios 2011). Binderless boards are still in the research stage. This has left room for development since their introduction in the early 1980s (Baskaran *et al.* 2012). There have been various materials used in manufacturing binderless boards, such as kenaf (Okuda and Sato 2004, 2006; Widyorini *et al.* 2005a; Xu *et al.* 2006; Aisyah *et al.* 2013), oil palm (Suzuki *et al.* 1998; Hashim *et al.* 2010, 2011a,b, 2012; Baskaran *et al.* 2012), date palm (Saadaoui *et al.* 2013), bamboo (Bahari *et al.* 2008), coconut husk (van Dam *et al.* 2004a,b; Panyakaew and Fotios 2011), bagasse (Panyakaew and Fotios 2011), banana bunch (Quintana *et al.* 2009), durian peel (Charoenvai 2013), wheat straw (Luo and Yang 2011), rice straw (Luo and Yang 2012), wood (Angles *et al.* 1999, 2001 Miki *et al.* 2003;), waste paper (Li and Liu 2000), and a few other materials (Velasquez *et al.* 2002, 2003a; Hunt and Supan 2006; Zhou *et al.* 2010; Marashdeh *et al.* 2011; Xie *et al.* 2012). These boards were manufactured using processes such as heat treatment, steam treatment, compression, and extrusion. Most of the targeted applications for these boards involve interior furniture and insulation board for building.

This article briefly reviews the development of binderless boards from various natural fibers. It follows by presenting the manufacturing processing of binderless boards and the effects of section-manufacturing processing parameters on the properties of binderless boards. Then, the properties of binderless boards produced are described, and the last section mentions the current uses of binderless boards.

DEVELOPMENT OF BINDERLESS BOARDS FROM VARIOUS NATURAL FIBERS

Fundamental knowledge of natural fibers and binderless board properties will provide a broader view of the development of binderless boards with specific properties for specific applications. Natural fibers are normally lignocellulosic, mostly consisting of cellulose microfibrils in an amorphous matrix of lignin and hemicelluloses, together with other contents such as pectin, waxes, and fats (Joseph *et al.* 1999; Mohanty *et al.* 2000, 2005). Table 1 summarizes the advantages and disadvantages of natural fibers. Table 2 shows the chemical composition of various types of natural fibers, as reported by several researchers.

Table 1. Advantages and Disadvantages of Natural Fibers (Sreekumar 2008)

Advantages	**Disadvantages**
Low specific weight results in higher specific strength and stiffness than glass	Lower strength, especially impact strength
Renewable resources, production requires little energy, low CO_2 emissions	Variable quality, influenced by weather
Friendly processing, no wear of tools, and no skin irritation	Poor moisture resistance, which causes swelling of fibers
Production with low investment at low cost	Restricted maximum processing temperature
Good electrical resistance	Lower durability
Good thermal and acoustic insulating properties	Poor fire resistance
Biodegradable	Hydrophilic – low wetting with hydrophobic polymers

Table 2. Chemical Composition and Moisture Content of Natural Fibers

Fibers	Lignin (%)	Cellulose (%)	Hemicellulose (%)	Ash (%)	Reference
Flax	2.2	71.0	18.6-20.6	1.7	Li *et al.* 2007
Jute	12.0-13.0	61.0-71.5	13.6-20.4	0.8	
Kenaf	15.0-19.0	31.0-57.0	21.5- 23.0	2.0-5.0	
Sisal	7.0-11.0	47.0-78.0	10.0-24.0	0.6-1.0	Bismarck *et al.* 2005
Coir	40.0-45.0	32.0-43.0	25.0-25.0	2.0-10.0	
Coconut Husk	36.7-45.1	51.1-48.2	67.6-58.8		Panyakaew and Fotios 2011
Bagasse	19.2	56.9	76.3		
Date Palm	31.9	50.6	8.1	6.8	Saadaoui *et al.* 2013
Durian Fiber	10.1		48.6	3.9	Charoenvai 2013
Miscanthus sinensis	19.9	42.6	10.1	0.7	van Dam *et al.* 2004
Banana Bunches	5	63	10	0.8	Mohanty *et al.* 2000
Oil Palm	17.2	60.6	32.5	5.4	Hill and Abdul Khalil 2000

Per Table 2, researchers have studied various types of lignocellulosic waste material for fiberboard production. Among the natural fibers used in manufacturing binderless boards are kenaf, oil palm, coconut husk, banana bunches, and bagasse. These materials will be discussed briefly in this review. Waste materials such as durian peel, date palm, bamboo, paper, corrugated board, and agricultural waste also have a strong potential to be used as raw materials; however, further research is needed.

Kenaf

Kenaf (*Hibiscus cannabinus* L.) is a fast-growing annual plant. The kenaf stem comprises two major parts of fiber, with a ratio of 30:70 of the fibrous outerbast and the woody inner core; these differ greatly in fiber morphology and chemical composition (Voulgaridis *et al.* 2000). The kenaf core is lighter and more porous compared to the bast, with a density of 0.10 to 0.20 g/cm^3. It has the potential to become a sustainable lignocellulosic raw material. It is rich in hemicellulose content, although the lignin content of kenaf is low. A few studies (Okuda and Sato 2004, 2009; Widyorini *et al.* 2005; Xu *et al.* 2006) have been performed on kenaf to produce binderless boards using the heat and steam processes.

Okuda and Sato (2004) manufactured binderless boards using kenaf core through a hot-press method to investigate the properties of the boards using various manufacturing conditions. Results showed that the optimum pressing pressure, temperature, and time were 5.3 MPa, 180 °C, and 10 min, respectively, with a board density of 1.0 g/cm^3. The boards' properties exceeded minimum requirements (JIS - A 5908 2003). In another study (Okuda and Sato 2006), the researchers investigated the water resistance properties of binderless boards. They were able to produce binderless boards with higher water resistance compared to boards produced with synthetic resins. Also, Okuda *et al.* (2006a,b) examined the chemical changes in kenaf binderless board using various pressing temperatures and by adding extra materials such as acetic acid during board production. Chemical changes occurred, as some of the lignin and hemicelluloses decomposed during the hot press process. These extra materials, although optional, helped to accelerate chemical changes as well as improve board properties.

Xu *et al.* (2004) produced low-density binderless boards using kenaf core for thermal and sound insulation purposes. The boards produced exhibited good mechanical properties and reached similar values of thermal conductivity as insulation materials. Although the boards showed good internal bond performance, they experienced high water absorption because of their porous characteristics. Xu *et al.* (2006) furthered the investigation by producing boards *via* a refining process, in which it was discovered that high steam pressure and long cooking time would lead to improved internal bond strength and lower thickness swelling of the boards, but resulted in low strength values. Binderless boards with a higher moisture content could have better properties because the process enables a faster heat transfer to the board's core and lowers the melting point of lignin.

Widyorini *et al.* (2005a) carried out a study of the chemical changes to kenaf core binderless boards manufactured *via* steam-injection pressing and hot-press processes. Mild steam injection caused significant degradation of chemical components, resulting in a dark brown board with high dimensional stability values. It is important to obtain the optimum conditions of steam treatment through proper control of steam pressure and pressing time to get the best board properties. Widroyini *et al.* (2005b) also tried to produce binderless particleboards from bagasse using steam-pressing injection to study the effect of raw materials, storage method, and manufacturing process. It was shown that steam-pressed boards were higher in mechanical and internal bond strength than hot-pressed boards.

Oil Palm

Oil palm is a lignocellulosic material (in the bark, leaves, fronds, and trunks) rich in sugar and starch and contains cellulose, hemicelluloses, and lignin. According to Anis *et al.* (2007), Malaysia generates approximately 13.9 million tons (dry weight) of oil palm biomass annually, including the trunk, fronds, and empty fruit bunches. This agricultural biomass is reasonably cheap, abundant, and sustainable, but it is not used effectively and large quantities of these palms are left in the field as underutilized resources. Open burning and landfills are common practices to eliminate oil palm residues, causing environmental problems. Abundance, sustainability, and carbohydrate richness make the oil palm an ideal raw material for the production of value-added, environmentally friendly, binderless composite panels.

Suzuki *et al.* (1998) manufactured binderless boards from steam-exploded pulps of oil palm fronds. The mechanical strengths of the binderless boards produced met the board standard requirements (JIS - A 5908 2003). The binderless boards produced had a dark brown color with smooth surfaces, which resulted from the degradation of chemical components of oil palm fronds. Rigorous conditions of severe explosion caused great damage, which conferred poor quality on the binderless boards. Hashim *et al.* (2011a,b, 2012) utilized oil palm biomass consisting of bark, leaves, fronds, mid parts, and core parts of trunks to make binderless boards. All parts of this oil palm biomass consisted of high holocellulose, lignin, starch, and sugar required for self-bonding adhesion. The boards had acceptable properties based on the standard (JIS - A 5908 2003), but were poor in dimensional stability because no pre-treatment was used. Hashim *et al.* (2010) also mentioned that strands showed better bonding properties characteristics, which enhanced the mechanical properties of panels compared with fine particles.

Coconut Husk and Bagasse

Coconuts are typically grown in coastal areas of tropical countries. Approximately 15 to 20 million tons of husk is generated annually, making it abundant as a cheap residue from coconut production. Coconut husk comprises 30 wt.% coir fibers and 70 wt.% pith, which must be separated through retting or mechanical decortications, for a wide variety of products such as ropes, yarns, brushes, and mattress padding (van Dam 2002). reinforcement

Bagasse is a waste product from sugarcane processing. It is rich in cellulose, which strengthens the fiber shape, thereby increasing water resistance and reinforcing the matrix of hemicellulose-lignin due to the high degree of polymerization of the natural cellulose (Rowell 2012, Pelaez-Samaniego *et al*. 2013). There are large quantities of this waste product that are still left unused or burnt. Bagasse usually contains residual sugars from cane production. These sugars may not be chemically compatible with resin binders and may interfere with bonding. Thus, to produce good quality board, the pith/core and residual sugars must be removed (Mobarak *et al.* 1982; Widyorini *et al.* 2005b).

van Dam *et al.* (2004a,b) conducted an experiment using coconut husk to make high-density binderless boards. The binderless boards produced showed comparable mechanical properties to commercial boards, which opens commercial possibilities for the development of cheap building materials. The composition of husk material was dependent on the maturity of the nuts. Panyakaew and Fotios (2011) used a hot press method to make low-density binderless boards from coconut husks and bagasse. Both binderless boards produced met all standard board requirements (JIS - A 5908 2003), except for thickness swelling, as the bagasse binderless board provided superior properties compared to coconut husks. The boards produced were suitable for use as insulation materials.

Other Materials

Approximately 88.8% of the total biomass from bananas is discarded. This biomass, which comes from various parts of the banana, such as the bunch, pseudo-stem, and leaves, is classified as high content fibrous materials (Zuluaga *et al.* 2007). Quintana *et al.* (2009) produced binderless boards by performing pre-treatment on banana bunches *via* optimum condition values of 3.55 for severity, 200 °C for pressing temperature, and 1.4 MPa for pressing pressure, respectively. Severity values are related to high pressure and longer time practice during pre-treatment process that change nature of fibers used.

Bamboo has high cellulose and lignin contents, as well as a short maturation period. It is easy to grow in forests or plantations. There are many types of bamboo, and it is sufficiently cheap to meet the extensive need for making boards. Bahari *et al.* (2008) managed to produce binderless bamboo fiberboards through the digesting process. The bending strength of binderless board exhibited a positive correlation with density and lignin content. Strength increased with bamboo age because of an increase in lignin.

Charoenvai (2013) produced new insulating binderless particleboards from durian peels as a green alternative material for insulating products. He replaced formaldehyde-based resin as an adhesive in binderless board with durian peel powder. These binderless boards possessed the best physical properties while yielding the lowest thermal conductivity. Meanwhile, Saadaoui *et al.* (2013) developed a binderless board using four diverse date palm lignocellulosic by-products *via* a hot-pressing process. Fibrillum, as one of the oil palm parts, has become a promising fibrous by-product, with high internal bond strength and low water absorption, as fibrillum has a high lignin content and good mechanical resistance. Lu *et al.* (2011; 2012) utilized wheat straw and rice straw with steam-explosion and liquid hot-water pre-treatments, respectively, to evaluate the influence of pre-treatment on the properties of panels. The results showed that pre-treatment using both methods was amongst the best ways to increase the degradation of chemical components, leading to excellent properties. The effects of pre-treatment are discussed in the next section.

Angles *et al.* (1999) stated that pre-treated material leads to better strength and a smooth appearance. They produced binderless composites from pre-treated residual softwood *via* hydrolytic pre-treatment at a density of 1.0 g/cm^3. Angles *et al.* (2001) expanded their study to investigate the effect of pre-treatment severity and lignin addition. They concluded that the addition of 20% lignin caused no significant changes in density and dimensional stability, but improved internal bonds and strength properties of boards. Geng *et al.* (2006) treated black spruce bark with an alkaline treatment to manufacture binderless fiberboard. The treated board produced showed lighter color with higher mechanical properties than the untreated board produced.

Velasquez *et al.* (2002) ground *Miscanthus sinensis* fibers and placed the fibers in a digester for a steam-explosion process. The boards with ground pulp were of better quality than those obtained with non-ground pulp. Velasquez *et al.* (2003a,b) advanced their study by exploring the optimum pre-treatment and pressing conditions as well as the effect of lignin addition. The boards were of high quality and satisfied the requirements of standard board specifications.

Cotton stalks contain high lignin content with very good flexibility and Runkel fiber ratios. Zhou *et al.* (2010) manufactured an environment-friendly thermal insulation material from cotton stalk fibers. They explained that thermal conductivity increased with board density because of a decrease in voids within and between fibers. Thus, this binderless cotton stalk fiberboard was excellent as an insulating component for building applications.

MANUFACTURING PROCESS OF BINDERLESS BOARDS

In this article, treatment term refers to the method applied to the fibers during the manufacturing process. Meanwhile, the pre-treatment term refers to the method applied before fibers were used in the manufacturing process; the pre-treatment method changed some properties of fibers. Heat treatment is a common manufacturing process in binderless board development. There are, however, binderless boards that have been produced through the extrusion and compaction processes. Pre-treatment processes such as steam explosion and a few others are important to produce better quality binderless boards, particularly in terms of dimensional stability. Meanwhile, pre-heating and grinding processes, which are simpler processes than steam treatment, are often used as another alternative for the pre-treatment process.

Heat Treatment Process

It is clear from previous studies of binderless board production that hot-pressing is widely accepted because of its simplicity compared with other methods (Okuda and Sato 2004; Xu *et al.* 2004; Hashim *et al.* 2012). The basic principle of hot-pressing is the application of heat, which activates the chemical components of the raw materials used. The raw material is basically put inside a mold, and the mold is then placed inside a hydraulic hot-pressing machine. After that, the material inside the mold is pressed depending on the parameters set up. It is necessary to apply enough heat and pressure to melt lignin through the entire board, allowing good distribution of lignin between the fibers during the manufacturing process (Mancera *et al.* 2008; Zhou *et al.* 2010). Cellulose and hemicelluloses are partially hydrolyzed to simple soluble sugars that contribute to self-bonding (Shen 1991; Rowell *et al.* 2000; Widyorini *et al.* 2005a; Panyakaew and Fotios 2011). Several factors, such as pressing temperature, implemented during the manufacturing process of binderless board, have a great impact on the mechanical and physical properties of the boards produced. However, degradation of chemical components for the hot-press process has been found to be much less effective than a steam treatment (Laemsak and Okuma 2000; Okamoto *et al.* 1994; Widyorini *et al.* 2005a). The best properties obtained from this process were under a pressing temperature of 180 °C, a pressing pressure of 5.3 MPa, a pressing time of 10 min, 5.0-mm board thickness, and a board density of 1.0 g/cm^3, using kenaf (Okuda and Sato 2004).

Compaction Process

In addition to the heat and steam processes, binderless boards can be produced through extrusion. Extrusion occurs when the material undergoes the compaction process, in which the compaction device is heated while the compaction loads are poured into the device. Then, the loads are extruded through the die under various conditions. Miki *et al.* (2003) evaluated the effects of extrusion temperature, extrusion ratio, and moisture content, as well as particle size of wood. They found that increasing the extrusion temperature and moisture content of powders increased the fluidity of extruded products up to 200 °C. Extrusion needs a specific machine that might not be appropriate for small industries because of the high cost involved and the particular handling knowledge required to operate the machine. Jain and Handa (1982) also produced binderless boards from agricultural wastes of straw and paper liner particles through the extrusion process. These boards can be used for interior partitions of ceiling and lining. Li and Liu (2000) investigated the process for developing high-density binderless logs from waste paper using the compaction process. Moisture content plays an important role in the compaction process. Reasonably high-quality and cost-effective logs were produced with a compaction pressure of 70% and moisture content of 15%. Hunt and Supan (2006) developed binderless boards from recycled corrugated containers and refined small-diameter treetops. Both panels surpassed minimum commercial hardboard standards through this process.

Steam Pre-Treatment Process

Steam pre-treatment has been known to be effective for improving the dimensional stability of wood-based composites, depending on variables such as pressing temperature and chemical composition of lignocellulosics (Mobarak *et al.* 1982; Widyorini *et al.* 2005a). This process works by injecting high-pressure saturated steam into a reactor filled with material used, where the temperature rises up to 200 °C and suddenly the pressure is reduced, resulting in an explosive decompression of the fiber material. The explosion causes an increase in surface area of the fibers, with degradation of hemicelluloses, low crystallinity of cellulose, and disruption of the lignin matrix. Widyorini *et al.* (2005a) managed to manufacture kenaf cores binderless boards *via* steam-injection treatment. The results showed that the bonding properties of these binderless boards were relatively strong, compared with binderless boards produced by hot-press treatments or even other binderless boards from different processes with the same density.

Angles *et al.* (2001) discovered that the hygroscopicity characteristics of hemicelluloses are responsible for moisture absorption. This means that boards with lower hygroscopicity have smaller values of water absorption and thickness swelling. Some authors (Angles *et al.* 2001; Widyorini *et al.* 2005a; Mancera *et al.* 2008) have attained similar results, in which decreasing hemicelluloses content during pre-treatment leads to improved dimensional stability, but does not lead to any increase in mechanical properties. The presence of cellulose in the crystalline structure helps to prevent water from penetrating the boards and leads to an increase in dimensional stability, as it makes the structure of the boards compact without voids. At the same time, cellulose is also degraded through the steam treatment process, which causes a reduction in the quality of boards (Widyorini *et al.* 2005a,b).

Lignin, which provides rigidity and stiffness to plant cell walls, is much more stable and resistant to steam treatment than hemicellulose (Widyorini *et al.* 2005a; Mancera *et al.* 2008). Steam treatment is considered to facilitate lowering the softening point of lignin and exposure of the more accessible lignin on the surface of the fiber, which contributes to self-bonding (Angles *et al.* 2001). Luo and Yang (2012) reported that hemicellulose and cellulose contents decreased with increasing lignin content from liquid hot water pre-treatment. Mancera *et al.* (2008) stated that pre-treatment temperature and time have no effect on lignin contents.

Other factors, such as the severity parameter, are important during the steam treatment process. The severity parameter is the expression based on calculation of steam temperature and residence time of the steam temperature. Previous studies (Suchsland *et al.* 1987; Geng *et al.* 2006) mention that steam treatment severity clearly have a significant influence on internal bond, as high severities produced higher surface area with high lignin contents. A few previous studies (Angles *et al.* 2001; Widyorini *et al.* 2005a; Mancera *et al.* 2008) also reported the same results, in that high severity led to improved internal bond strength and dimensional stability of boards, although it decreased the mechanical strength properties.

The effect of longer steam treatment resulted in excess steam and caused a rigorous degradation of chemical components. Increased severity not only reduces hygroscopicity, but also greatly reduces abrasive materials that are unnecessary for board manufacturing. The removal of wax and pectin from the surfaces contributed to a significant effect on the wettability of fiber surfaces (Suchsland *et al.* 1987). The manufactured boards turned dark brown, indicating a high degree of hydrolysis or modification of chemical components during steam treatment. Previous research (Suchsland *et al.* 1987; Velasquez *et al.* 2003b) has reported that superior mechanical properties of binderless fiberboards can be gained from steam treatment with low severity, compared with binderless fiberboards obtained from steam treatment with high severity. Low temperature, low steam pressure, and long treatment time were used to protect the structure of fibers and carry out lignin modifications to enhance the adhesive behavior.

Pre-heating and Grinding Process

For lab-scale preparation, another process to improve binderless board is pre-treatment using pre-heating and grinding. The simplest pre-treatment is microwave pre-heating of the fibers before hot-pressing. This helps improve the internal bond strength and properties of manufactured boards. Okuda *et al.* (2006a) reported that pre-heating fibers in a microwave for one minute could accelerate thermal softening of lignin, which resulted in better strength properties. When pre-heating time increased to two minutes, there was no obvious change observed because of the influence of excessive drying, and part of raw material was burned black with very low moisture content.

One of the easiest ways of preparing pre-treatments for fibers is milling or grinding. According to previous studies (Velasquez *et al.* 2002, 2003a; Saadaoui *et al.* 2013), grinding the material before the hot-press process considerably improves the internal bond strength without affecting other physico-mechanical properties of binderless boards. This process, however, does affect the density of the boards, as grinding gave lower density than non-grinding materials because of an increase in compression resistance and more air in milled pulp. Grinding did not cut the fibers, but helped separate the bundles of fibers. This segregation leads to more spaces for inter-fiber bonding, leading to an increase in the strength of the bonds (Velasquez *et al.* 2002). The nature of the bonds did not change, thus it did not affect the dimensional stability of the board. Nevertheless, the particle shape and size have an important impact on the properties of binderless boards, so the degree of crushing in grinding becomes a limiting factor, as it affects particle geometry.

EFFECTS OF MANUFACTURING PROCESS PARAMETERS ON PROPERTIES OF BINDERLESS BOARDS

During the manufacturing process of binderless board, there are a few factors that can affect the properties of boards produced. These factors include the pressing parameters in terms of temperature, pressure, and time, as well as particle sizes and the presence of additional substances.

Effects of Pressing Temperature, Pressure, and Time

Pressing temperature is one of the most important parameters influencing board properties. Past studies (Widyorini *et al.* 2005a; Hashim *et al.* 2011a) have indicated that the yield of extractives increased at a higher pressing temperature. It has been shown in Fourier transform infrared (FTIR) spectra that there were slightly smaller chemical changes during the hot-press process, where part of lignin and hemicelluloses experienced decomposition. Quintana *et al.* (2009) revealed that fibers could be fused together by mechanical entanglement of the softened lignin molecules, possibly accompanied by the formation of a covalent bond. Thermogravimetric analysis (TGA) also shows thermal decomposition of hemicelluloses and cellulose at temperatures around 300 °C. These results are supported by Zhou *et al.* (2010), who suggested that the lignin fluidity of fibers increases with higher temperatures, improving lignin distribution in fiberboards and inter-fiber bonds. The chemical changes described above contribute to self-bonding and improved board properties. The reduction of hygroscopicity resulting from the degradation of hemicelluloses was observed in studies by Xu *et al.* (2006) and Xie *et al.* (2012). They emphasized that high pressing temperature was beneficial for fiber plasticizing. Fibers' lignin melts and flows resulted in full fusion among fibers; the fiber contact thus became closer.

A significant increase in board density and pressing pressure resulted in an improved internal bond strength and mechanical properties, along with greater dimensional stability of the boards. Nevertheless, the thickness swelling of the board was only affected by pressing pressure, while water absorption of the board was affected by all pressing variables, such as pressing temperature, pressing time, and pressing pressure; these properties are closely related, however. Mobarak *et al.* (1982) reported that an increase in pressing pressure during manufacturing of bagasse pith boards had an influence on board strength, attributed to the morphological structure of pith, which mostly consists of parenchyma cells. A study by Quintana *et al.* (2009) demonstrated that mechanical entanglement of the softened lignin molecules was accompanied by formation of covalent bonds, as fibers with lignin-rich surfaces fused together under a high pressing pressure. Conversely, fibers are more distant with lower contact points at a low pressing pressure. Despite that, high pressure means a high process cost, although the superior properties produced by such boards are appreciated.

Li and Liu (2000) discovered no noticeable effect of pressing time when a board was pressed under high pressure. Similar trends can be seen where pressing time has less of an effect on log quality when the board is pressed at the closest moisture content to the optimum. Okuda *et al.* (2006; 2006a) claimed that either a one-step or a three-step pressing schedule could be selected without affecting board properties. Zhou *et al.* (2010) stated that prolonging pressing time resulted in an increased strength of the board. The fibers need to be heated for longer times to make sure the heat is transferred to the core of the binderless board; hence, the lignin is plasticized and flows well.

Effects of Particle Sizes

It is well known that particle size and geometry significantly influence the development of binderless board properties in terms of bonding quality among particles, compared to mechanical strength properties of the fibers themselves. Previous studies (Munawar *et al.* 2007; Hashim *et al.* 2010) have shown that smaller particles improved the qualities of the board with a superior internal bond strength. This is because smaller particles were more compressed with fewer overlapping areas, producing uniform homogeneous cells, which had lower voids. Interestingly, this leads to better dimensional stability and gives a smoother surface for binderless boards compared to larger particles (Mobarak *et al.* 1982; Hashim *et al.* 2010). Additionally, smoother surfaces and appearances are energy saving, as no sanding stage is required. The smaller particles, particularly in powder form, need more energy to manufacture and are difficult to handle during the fabrication process (Okuda and Sato 2004).

Studies conducted by Hashim *et al.* (2010) and Juliana *et al.* (2012) reported that strands led to higher internal bond and mechanical strength compared with particles, as shown in Fig. 1. Strands are thinner, longer, and have a larger surface contact area with a better glue line, which leads to better strength characteristics. Longer particles are high in aspect ratio (fiber length over width) or adhesive content per unit particle surface area. The roughness value of strands is higher because strands are coarser and have a rigid structure of vascular bundles. Juliana *et al.* (2012) again stated that more slender (length over thickness) particles usually provide better bonding than bigger particles because of a greater amount of contact surface. Slender particles require more adhesive to sufficiently bond the particles. Admixture boards consisting of kenaf and rubberwood gave better strength than using 100% of the same materials. Particles of rubberwood were stronger and more slender than the kenaf particle. These results were supported by a study by Charoenvai (2013), in which the manufacturing of particleboard using durian-peel-powder-based adhesive gave similar properties when compared with synthetic adhesives.

Effects of Additional Substances

Numerous studies (Velasquez *et al.* 2003a; Okuda *et al.* 2006b; Ashori and Nourbakhsh 2008; Baskaran *et al.* 2012) have been performed by adding extra materials to binderless boards for the purpose of comparison. A study conducted by Ashori and Nourbakhsh (2008) reported that wax addition in binderless board reduced strength properties, but it helped to improve the dimensional stability of the boards. Moreover, further treatments such as coating or laminates are required for binderless boards without using wax or any hydrophobic substance. Therefore, a small amount (approximately 1%) of wax can be used in binderless particleboard manufacturing.

Velasquez *et al.* (2003a) investigated the effects of replacing fiber with different kinds of technical lignin recovered directly from pulping liquor, without further purification or treatment. The lignin was added in two conditions, which were prior to the steam explosion process and just before the hot-press process, after the material had gone through a steam-explosion process. They discovered that substituting 20% of *Miscanthus sinensis* with lignin had superior effects on board properties. Boards with kraft lignin added before the steam explosion process had superior properties, resulting from the elimination and reduction of low-molecular weight substances during the steam explosion, leading to better homogenization and a good mixture between kraft lignin and the chips. This is applicable for low pressing temperatures only.

It is essential to find the optimum parameters and factors of pressing temperature, pressing pressure, pressing time, and particle geometry and size to produce binderless boards that meet all standard requirements, while consecutively contributing to the internal bond and strength properties of boards. Adding particular materials such as 1% wax or technical lignin can help improve the board properties if the optimum amount is used.

PROPERTIES OF BINDERLESS BOARDS

Table 3 shows the density, strength, and dimensional stability of binderless boards made from various natural fibers and manufacturing processes (Velasquez *et al.* 2003b; Okuda and Sato 2004; Van Dam *et al.* 2004a; Quintana *et al.* 2009; Hashim *et al.* 2010; Luo and Yang 2011, 2012; Xie *et al.* 2012; Saadaoui *et al.* 2013). The binderless boards were produced within a density range of 0.8 to 1.3 g/cm^3 using nine types of materials adapted for various processes. The common tests were conducted according to available standards (JIS - A 5908 2003) to see if the boards met the recommended requirements, which are a minimum modulus of rupture (MOR) of 18 MPa, minimum internal bond (IB) strength of 0.3 MPa, and maximum thickness swelling (TS) of 12%. From Table 3, it can be concluded that high-density boards turned out to have the highest strength. Most of the binderless boards met the minimum requirement of MOR and IB, except for date palm (Saadaoui *et al.* 2013), and a few others (Quintana *et al.* 2009; Luo and Yang 2011, 2012), which did not meet the minimum requirement for IB. However, only wood (Xie *et al.* 2012) and coconut husk (Van Dam *et al.* 2004a) met the requirement of maximum TS of 12%.

It can be seen that the modulus of rupture (MOR) value of *Miscanthus sinensis* board is the highest. It is assumed that the *Miscanthus sinensis* board has gone through a steam process that changed the chemical compounds and improved the internal bond, as well as strength of the board. The second highest MOR value is the board made of wood, followed by the board made from coconut husk and kenaf. These three boards - wood, coconut husk, and kenaf - were manufactured *via* a hot-press process. It is clearly shown in the table that these three boards have high values compared with other boards made from the steam process, except for *Miscanthus sinensis* board. The internal bonds (IB) have a great influence on the dimensional stability of boards. From the dimensional stability in the Table 3, boards made of date palm have high values of thickness swelling (TS) and water absorption (WA) because they have the lowest IB value. Conversely, the IB of kenaf is the highest. Also, the dimensional stability of kenaf board is almost 3 to 5 times higher than that of wood board and coconut husk board. The board produced from oil palm has the lowest value in density, which also affects its MOR value. It also has a low dimensional stability compared with other boards. This is in agreement with the theory stating that the hot-press process only causes small chemical changes in boards, which does not help to improve the TS and WA values.

In conclusion, there are a large number of factors that affect board properties, such as material type, manufacturing process, parameters used, and parts and sizes of materials, which must be considered and given particular attention when developing binderless boards.

Table 3. Properties of Binderless Boards Made of Various Natural Fibers

Process	Author(s)	Natural fiber(s)		Density (g/cm^3)	MOR (MPa)	IB (MPa)	TS (%)	WA (%)
Hot-press (HP)	Hashim *et al.* (2010)	Oil Palm	OP	0.8	24.95	0.95	41.6	80.0
Hot-press	Okuda and Sato (2004)	Kenaf	KF	1.0	36.10	5.70	19.6	40.9
Hot-press	Saadaoui *et al.* (2013)	Date Palm	DP	1.0	12.90	0.03	150.0	275.0
Hot-press	Xie *et al.* 2012	Wood	W	1.2	52.80	0.92	7.6	-
Hot-press	Van Dam *et al.* (2004)	Coconut Husk	CH	1.3	50.00	-	8.0	8.0
Steam + HP	Luo *et al.* (2011)	Wheat Straw	WS	1.0	19.80	0.26	-	61.0
Liquid hot-water + HP	Luo *et al.* (2012)	Rice Straw	RS	1.0	18.10	0.24	-	63.7
Steam + HP	Quintana *et al.* (2009)	Banana Bunch	BB	1.2	24.14	0.14	60.0	55.5
Steam + HP	Velasquez *et al.* (2003)	*Miscanthus sinensis*	MS	1.3	61.00	3.76	23.0	8.9

Most of the reported binderless boards produced using different natural fibers were prepared at laboratory scale and these boards' properties have considerable room for improvements, mainly with respect to dimensional stability attributes. These developed binderless boards are suitable to be used for internal furniture, decorative partition walls, and insulation boards either for sound or thermal. For exterior usage, some extended studies might be required to improve dimensional stability performance of binderless boards. The ideas of surface coating or wrap with waterproof materials or to make these boards as the core for sandwich panels can be considered for future research so that these binderless boards can be used as interior and exterior furniture. On the other hand, the evaluation of health-environment impact and insect fungal resistance seem relevant and necessary for future tests on these binderless boards produced.

CONCLUSIONS

1. This review of binderless boards provides a big picture of previous research on the development of binderless boards conducted worldwide, focusing on the manufacturing process and properties of binderless board.
2. The prospect of natural fibers gives ideas for utilization of lignocellulosic waste materials that have been abundantly left around the world into value-added products, although there are some constraints because of the fibers themselves.
3. The various manufacturing processes for binderless boards also have been reviewed, including optimum parameters needed to obtain the best quality boards.
4. Boards made from kenaf and *Miscanthus sinensis* have the best qualities among boards that have been manufactured using the hot-press and steam processes, respectively. These two boards may be used as good references for future studies.

5. The properties of binderless boards are affected by many factors, and the main one is on divergence of different materials, which agrees with the theory studied in previous research.
6. Further research on health-environment impacts, insect fungal resistance, along with coating or wrapping binderless boards produced are important for exterior and interior usage.
7. It is essential to understand the basic structural components of natural fibers and their effects on the physical, mechanical, and thermal properties to manufacture binderless boards. More studies are required on the manufacturing process, especially for large-scale end products, as well as product commercialization, which has not been discussed here.

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