Review article

Crop residues used as lignocellulose materials for particleboards formulation

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ABSTRACT

Efforts to reduce pressure on use of wood in particleboard formulation have included the use of non-wood materials such as crop residues. Physical and mechanical properties are determined by the number of the hydroxyl (-OH) groups. Hydroxyl (-OH) groups attracts water molecules through hydrogen bonding affecting water absorption (WA) and thickness swelling (TS). WA and TS affect curing process of adhesive. Curing process of adhesives affects the mechanical characteristics of formulated particleboards. These challenges have been acted upon continuously through research. This review paper presents crop residues used as alternative lignocellulose material source in particleboard formulation and the various advances that have been made to improve on the properties of the resultant particleboards. Improvement over time of the non-wood material in composite materials focusses on increasing water resistance and compatibility between lignocellulose and binder. Crop residues-based are used in making medium and low density particleboards. These boards have shown good mechanical characteristics which include modulus of rupture (MOR), modulus of elasticity (MOE) and internal bonding (IB). MOR, MOE and IB have over time been improved by enhancing chemical compatibility of lignocellulose material and the binders. Water absorption and thickness swelling remain challenge. This review paper further explored various methods of improving water absorption and thickness swelling of crop-residue based particleboards.

## 1. Introduction

1.1. Wood use in particleboard formulation

Particleboard is a product formulated from wood particles bonded with formaldehyde-based resins at high pressure and temperature to make sheets [1]. Conventional method of particleboard formulation involves encapsulation of lignocellulose material. Encapsulation occur under two steps; one is the reaction between the resin monomers to form a polymer. The monomers include phenol, urea and formaldehyde. Phenol and formaldehyde reacts to form phenol formaldehyde resin [2] as shown in Eq. (1).

$$HOC_6H_5 + HCHOH \rightarrow HOC_6H_4CH_2OH \tag{1}$$

Phenol formaldehyde molecules undergo condensation polymerization to form polyphenol formaldehyde [3] as shown in Eq. (2).

$$2HOC_6H_5 + HCHOH \rightarrow (HOC_6H_4CH_2)_2O + H_2O \tag{2}$$
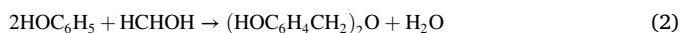
Other side reactions involves hydroxyl groups in phenol formaldehyde and phenols [4] as illustrated in Eq. (3)

$$HOC_6H_4CH_2OH + HOC_6H_5 \rightarrow (HOC_6H_4)_2CH_2 + H_2O \tag{3}$$
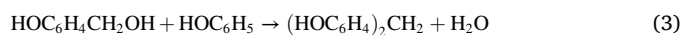
Secondly, the polymer encapsulates lignocellulose materials at high temperature [5] as shown in the Figure 1.

Pressure forces the particles to come together before the resin cures. This may otherwise leave space between resin and lignocellulose material particles that expose the inherent hydroxyl group. Hydroxyl (-OH) groups and water interact via hydrogen bonding which increases WA and TS [6].

Urea formaldehyde is a binder conventionally used with non-wood. Urea formaldehyde is synthesized by the reaction between urea and formaldehyde as shown in Eq. (4)

$$CO(NH_2)_2 + HCHO \xrightarrow{pH=7-8} H_2HCONHCH_2OH \tag{4}$$

Urea formaldehyde undergoes condensation polymerization to form poly (urea formaldehyde) [7] as illustrated in Eq. (5).
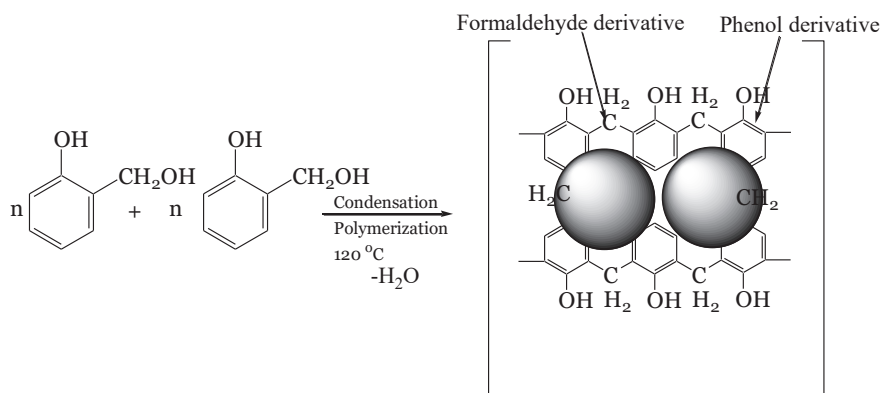
Figure 1. Encapsulation of wood particles using cured phenol formaldehyde resin.

$$2H_2NCONHCH_2OH \rightarrow -[-NHCONHCH_2O-]-N + H_2O \quad (5)$$

Polymers formed encapsulate the lignocellulose material particles [8] as shown in the Figure 2.

Post-industrial waste like sawmill particles, panel edging and post-consumer wood wastes from furniture, window frames, demolition wood and wood-based panels, boxes have become a widely recognized feed stock for making composite materials for particleboards [9, 10]. Saw dust has been used as a lignocellulose material with urea formaldehyde resin as a binder. The particleboard produced was of low density and absorbed water above 50% of recommended rate. Rahman, *et al.*, (2013) used saw dust as a lignocellulose material and polyethylene terephthalate as a binder. Polyethylene terephthalate is a non-biodegradable which may create threat to the environment. Coupling agents are required to be mixed in order to enhance interaction between sawdust and polyethylene terephthalate [11]. Coupling agents such as poly-(methylene (poly-phenol isocyanate) with the longer chains and more functional group are used to enhance interaction between wood fiber-polystyrene composites [12].

1.2. Non-wood use and their limitations

Crop residues widen the scope of raw materials for particleboard formulation [13]. Agriculture residues and other biomass such as corn stem [14], cotton stem [15], walnut shell [16], peanut hull [17], sugarcane bagasse [18, 19, 20], luffa fiber [21], coconut fiber [22], kenaf [23], giant reed [24], grass [25], tomato stalk [26], rice husks [27] and sunflower stalks [28] are alternative raw material in the formulation of particleboard. Particleboards made from these alternative materials low

Figure 2. Encapsulation of lignocellulose particles with Poly (Urea formaldehyde).

mechanical properties such as 0.46 N/mm^2 of internal bonding as shown in Table 1.

Guler, *et al.*, (2006) used sunflower stalks and urea formaldehyde as a binder to formulate particleboard. Ammonium chloride is most commonly applied as a hardener. Ammonium chloride makes urea formaldehyde adhesive layer more fragile [29]. Ammonium chloride (NH$_4$Cl) affects the pH of the reaction of the reaction system in two ways. First NH$_4$Cl reacts with formaldehyde to produce hexamethylenetetramine (CH$_2$)$_6$N$_4$, hydrochloric (HCl) acid and water [30] as presented in Eq. (6).

$$4NH_4Cl + 6HCHO \rightarrow (CH_2)_6N_4 + 4HCl + 6H_2O \quad (6)$$

Secondly the ammonium ions hydrolyze in water [31] as shown in Eq. (7) making the resultant product acidic.

$$4NH_4^+ + H_2O \rightarrow NH_3 + H_3O^+ \quad (7)$$
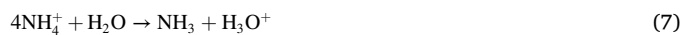
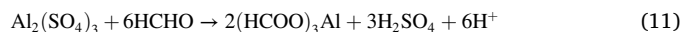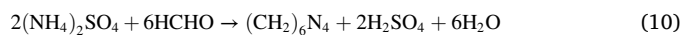NH$_4^+$ react with Hydroxymethylurea to form an acid that lowers pH of the resultant mixture [32]. The reaction between ammine ions and hydromethylurea is shown in the Eq. (8).

$$HOCH_2NHC(NH_2)O + NH_4^+ \rightarrow H_2NCH_2NHC(NH_2)O + H_3O^+ \quad (8)$$
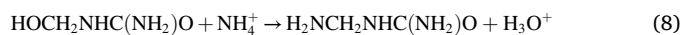
Some authors have used sodium hydroxide (NaOH) to neutralize the resultant acid as shown in Eq. (9).

$$4NH_4Cl + 6HCHO + 4NaOH \rightarrow 4NaCl + (CH_2)_6N_4 + 10H_2O \quad (9)$$

Other authors have used ammonium sulphate and aluminum sulphate [33], which also acts as hardener to neutralize the acid [33] as shown in Eqs. (10) and (11) respectively.

$$2(NH_4)_2SO_4 + 6HCHO \rightarrow (CH_2)_6N_4 + 2H_2SO_4 + 6H_2O \quad (10)$$

$$Al_2(SO_4)_3 + 6HCHO \rightarrow 2(HCOO)_3Al + 3H_2SO_4 + 6H^+ \quad (11)$$

Ammonium sulphate leads to reduction in water absorption, no effect on internal bonding and significant increase in modulus of elasticity [34].

Sugarcane bagasse has been used with methylene diphenyl diisocyanate (MDI) and urea formaldehyde resins in formulation of a medium density boards [37]. Sugarcane bagasse has 42.3 % of cellulose, 3.7 % of acetyl groups, 25.1 % of pentosans, 24.7 % of lignin and 3.5 % of ash [45]. Lignin content is equivalent to the average lignin content in saw dust which is 25.6 % [46]. Glucose in sugarcane bagasse has been modified with citric acid to form bondage in particleboard formulation [47] as shown in Figure 3.

Lignin increases the hydrophobic nature of composite material [48, 49] and improve particle bonding [50]. Acetyl groups naturally present in sugarcane bagasse provides an active point in a molecule that is crucial for chemical properties of that specific molecule. Acetyl groups are easily
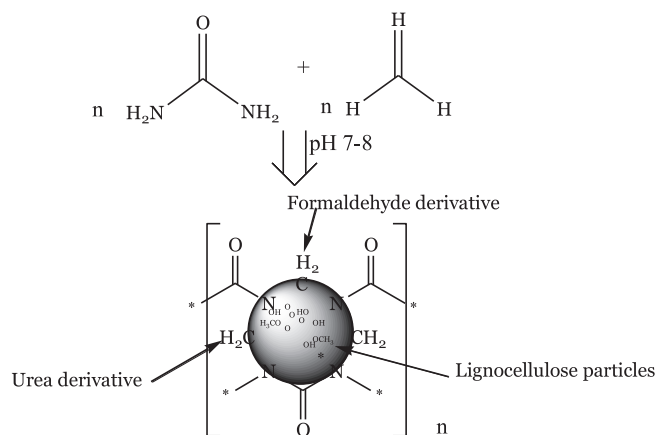
Table 1. Mean Physical and mechanical properties of Particleboard with different Various Lignocellulose materials.

S. No.	Raw Material	Resin Used	Density (gcm^{-3})	Properties						Limitation	Reference
				MC (%)	WA (%)	TS (%)	IB (N/mm^2)	MOE (N/mm^2)	MOR (N/mm^2)		
1.	Saw dust	Urea formaldehyde	436		58.77	-	0.9	55	-	Use of sawdust promote deforestation	[35]
2.	Saw dust	Polypropylene	-	-	9.4	7.8		436	6.358	Use of sawdust promote deforestation	[36]
3.	Saw dust	Polypropylene terephthalate	856.73	2.15	29.5	10	-	1433.93	11.68	Use of sawdust promote deforestation	[11]
4.	Sunflower	Urea formaldehyde	-				0.46	2973	18.7	Sunflower have many alternative uses thus unsustainable	[28]
5.	Sugarcane bagasse	Methylene diphenyl diisocyanate	0.612	11.1	64.2		0.85	2400	16	low MOE, IB and high WA	[37]
6.	Sugarcane bagasse	Castor oil polyurethane	1.0	-	53.2	45	0.35	1879	16.2	Low IB and MOE	[38]
7.	Tomato stalk	Urea formaldehyde	0.95	8.2	-	10.6	0.91	1123.9	20.5	Low MOE	[26]
8.	Tomato stalk	Urea formaldehyde and melamine	0.63	-	-	57.6	0.3–0.73	1328–3041	5.4–12.75	Low MOR and high TS	[39]
9.	Rice husk	Phenol-formaldehyde	0.83	5.6	30	10.5	-	2353	16.3	Low MOE and MOR	[27]
10.	Rice husk	Rice bran adhesives and dephenyl methane diisocyanate	0.7	-	70	17	0.4	2800	17	High WA	[40]
11.	Walnut shell	Urea formaldehyde	-	-	-	-	0.34	2309	5.8	Low IB and MOR	[16]
12.	Cotton stalk	Urea formaldehyde	0.6		66.06	14.74	0.563	-	16.79	High WA and Low MOR	[15]
13.	Corn stalk	Urea formaldehyde	0.75	7	-	17.39	0.523	1950	22.26	Low MOR	[41]
14.	Corn stalk	Diadehyde starch	-	-	-	-	-	2168.5	15.3	Low MOR	[42, 43]
15.	Peanut hull	Urea formaldehyde	0.7	-	57.95	11.46	0.316	1276.76	9.90	Low IB, MOR and MOE	[17]
16.	Luffa fiber	Urea formaldehyde	0.82	11		7.24	0.37	4483.40	44.05	Low IB	[21]
17.	Giant reed	Urea formaldehyde	0.628	7.45	61.23	10.61	0.543	1467.86	9.93	High WA and low MOE	[24]
18.	Waste grass	Urea formaldehyde	-	-	-	33.63	0.08	351.35	4.19	Very low IB and MOR	[25]
19.	Waste and wood chips	Urea formaldehyde	-	-	-	29.82	0.189	838.54	8.39	Low IB, MOE and MOR	[25]
20.	Eucalyptus	Polymeric methane diphenyl diisocyanate and urea formaldehyde	0.75		69.89	31.26	1.31	1564.2	13.6	High WA, low MO and MOR	[44]

Key: WA represents water absorption; TS represent thickness swelling, IB represent internal bonding, and MOE represent modulus of elasticity and MOR represent modulus of rupture.
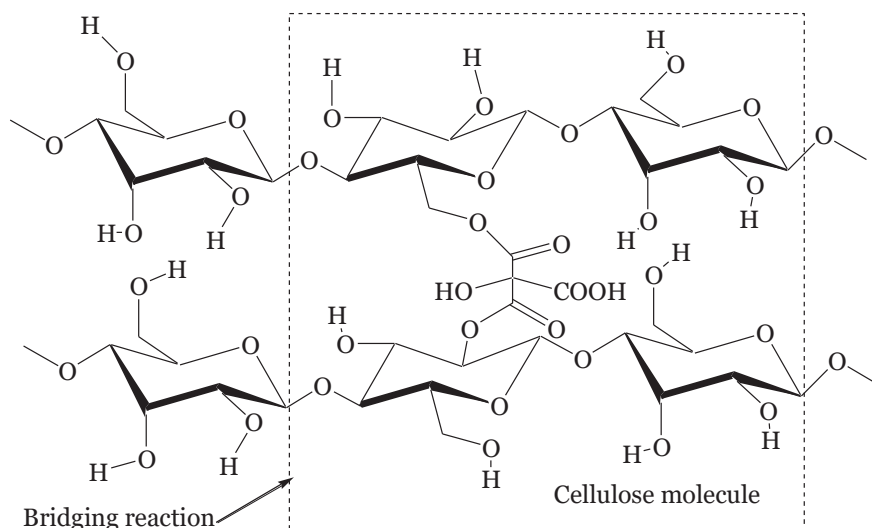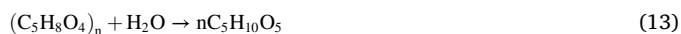
Figure 3. Bondage in particle bond using citric acid and inherent glucose from sugarcane bagasse.

hydrolyzed by hydroxide ions from a strong nucleophile source such as sodium hydroxide [51] as shown in Eq. (12).

$$ROOCH_2CH_3 + OH^- \xrightarrow{H_2O} ROOH + CH_3CH_2OH \tag{12}$$

Pentosans molecules hydrolyze in water to form pentose [52] as shown in the Eq. (13).

$$(C_5H_8O_4)_n + H_2O \rightarrow nC_5H_{10}O_5 \tag{13}$$

Pentose molecules contain inherent hydroxyl functional groups that can be chemically modified to form reactive site for both ether and ester bondage. Pentose undergo dehydration to form furfural [52] as shown in Eq.(14), a chemical with similar characteristic of formaldehyde used in particleboard formulation.

$$C_5H_{10}O_5 \rightarrow C_5H_4O_2 + 3H_2O \tag{14}$$

Research has shown tomato stalk as an alternative lignocellulose material for formulation of particleboard, using urea formaldehyde as a binder [26]. The challenge experienced during hardening process was overcome by use of ammonium chloride. Ammonium chloride undergoes hydrolysis to form hydrochloric acid. Hydrochloric acid causes corrosion [7]. Tomato stalk contains at an average 72 % of holocellulose and 17.05 % of lignin [26]. Holocellulose is a combination of cellulose and hemicellulose whose composition includes simple sugars. Simple sugars include glucose ($C_6H_{12}O_6$), mannose ($C_6H_{12}O_6$), galactose ($C_6H_{12}O_6$), xylose ($C_5H_{10}O_5$), L-arabinose ($C_5H_{10}O_5$), D-glucuronic acid ($C_6H_{10}O_7$), and lesser amounts of other sugars such as L-rhamnose ($C_6H_{12}O_5$) and D-fucose ($C_6H_{12}O_5$). Simple sugars have five hydroxyl groups (-OH) in their cyclic ring and a carbonyl group (C=O) that make them water soluble. Hydroxyl groups in simple sugars are required for ether and ester formation. On the other hand, use of ammonium chloride improved water absorption and thickness swelling [33]. Ammonium chloride reduced the formaldehyde emission thus minimizing indoor pollution of the particleboard formulated [53]. Use of ammonium chloride results to inadequacy of resin content and limits resin distribution in composite material, poor compatibility between substrate and urea formaldehyde adhesive. Porosity of low density particleboard leads to water absorption of more than 73.39 % and thickness swelling of upto 55.97 % [27]. Poor WA and TS limit applications of the particleboards. WA and TS were improved by adding wax as a hydrophobic substance.

Density is increased by improving the interaction between lignocellulose material and adhesive for formulating particleboards. Interactions between the components of the board may be improved by chemical modification of the inherent functional groups in the raw material.

Particleboards formulated from tomato stalk and urea formaldehyde gave very low MOE attributed to low number of hydroxyl groups involved in bond formation. Large number of unreacted hydroxyl groups creates weak adhesion making particleboards not to attain minimum standards especially MOE. Guuntekin, *et al.*, (2009) used tomato stalk and urea formaldehyde as a binder. This resulted to low MOR, MOE and IB [54]. The particleboards had high thickness swelling of 93 %. This implies that strong polar character of tomato stalk resuts to poor incompatibility between tomato stalk particles and adhesives [39]. WA is reduced by addition of paraffin and phenolic resins when making particleboards [39]. The properties of formulated particleboards can be enhanced by increasing the specific weight of source materials.

Research findings has shown tomato stalk bound with urea formaldehyde resin can achieve MOE of 1123.9 N/mm^2 [26]. The European standards EN 312:2010 for low density boards is 1600 N/mm^2 therefore the tomato stalk particleboards can be compressed for makuing boards for furniture manufacturing applications. Powder ammonium chloride was used as a hardener. Use of ammonium chloride hardener in formulation of tomato stalk particleboards increased curing time of urea formaldehyde which affected the mechanical property of the boards [26]. Water absorption in tomato based paricleboards depends on the following; choice of resin, coupling agent and surface treatment for enhanced moisture resistance. EN 312-4: 1996 standards allows maximum TS of 8–15 % for soaking time of 2 h and 24 h respectively. Use of hardeners produced particleboards with moisture content of 18.1 %, thus did not meet this minimum requirements. Moisture resistance may be reduced by additional of wax during the particleboard formulation process [55]. Wax is a hydrophobic material whose procedure has not yet beeen tested.

Ciannamea, *et al.*, (2017) used rice husk as lignocellulose material bound with phenol-formaldehyde resin. Particleboards formulated showed low MOR [27]. Rice husks consist at an average 50 % cellulose, 25–30 % lignin, and 15–20 % silica [56]. Lignin content is higher than lignin content in wood thus better hydrophobic properties than wood-based products. Silica in rice husks reacts with water in alkaline media to form silicic acid an inorganic adhesive [57] as shown in Eq. (15).

$$SiO_{2(s)} + 2H_2O_{(l)} \rightleftharpoons H_4SiO_{4(aq)} \tag{15}$$

Due to low lignin reactivity in rice husks, a longer pressing time was required. Increase in pressing reduce porosity that lead to lower water absorption. Research has shown that press time only reduces the water absorption and thickness swelling by a small margin. Particleboards made with rice husks and formaldehyde showed very high water absorption between 76.31 and 120.45 % [58]. Curing of
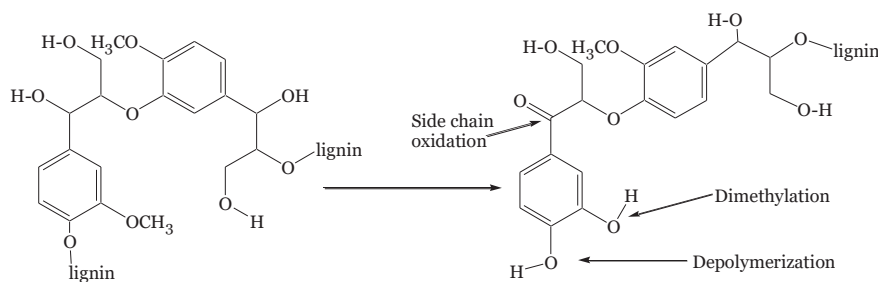
Figure 4. Chemical modifications to a guaiacyl-based lignocellulose complex by brown-rot fungal degradation.

phenol-formaldehyde resin is achieved by addition of catalysts such as hexamethylnetetramine, paraformaldehyde, β-naphthalenesulfonic acid, aqueous solutions of melamine and potassium dichromate, urotropine and hydroxylamine, and sodium bicarbonate and formalin [59]. Lignin chemical modification therefore improved reactivity during formulation of composite material. Chemical modification of the lignin have been developed such as demethylation [60], methylolation [61, 62, 63, 64], phenolation [65, 66, 67, 68], sulphonation [67, 69] and oxidation [70]. Other ways of improving the reactivity of lignin is by use of fungi metabolism [71, 72]. In methylation, methyl group from lignin is replaced with hydroxyl group [73] as shown in the Figure 4.

Phenolation lead to formation of smaller molecules, this exposes the inherent functional groups [74] as shown in Figure 5.

Pirayesh, *et al.,* (2012) observed low MOR of 5.8 N/mm^2 and IB of 0.24 N/mm^2 using walnut shell as alternative of wood in making particleboards bound with urea formaldehyde. Particleboards formulated experienced poor hardening of the binder. This was improved by addition of ammonium chloride which reduces the pH [75]. Results showed high percentages of water absorption and thichness swelling. Thickness swelling showed as high as 18.16 % and water absorption of upto 68.32 %.

Guler and Ozen (2004) utilized cotton stalk as a lignocellulose material and urea formaldehyde as a binder. Results showed low MOR of 16.79 N/mm^2, high WA of 66.06 % and thickness swelling of 14.74 % [15]. MOE and IB were low due to lack of bonding between cotton stalks and the urea formaldehyde (UF). Bondage between lignocellulose material and binders reduces water penetration [76]. MOE is largely influenced by particle shape factor, that is, length to width ratio [76]. MOR is affected by the amount of lignocellulose material due to improved bonding [76]. As a result, the particleboards formulated was of low density of 0.4–0.6 g/cm^3. Low density lead to icrease in water absorption. Permeability is linked to porosity of particleboard components [77, 78, 79]. Due to this spaces, hydroxyl (-OH) groups from lignocellulose material form hydrogen bonding in presence of water. This increases the interaction of the board and water leading to high WA and TS that minimizes the particleboard applications. This limitations can be overcomed by use of a binder that can interact with the inherent functional groups in the lignocellulose material.

Kargarfard and Jahan-Latibari (2011) used corn stalk as a lignoellulose material and UF binders. The composite material is pressed at a

temperature range from 170 °C to 190 °C. The particleboard showed low MOE of 1950 N/mm^2 [41]. The mechanical properties were still very low. These prop erties may be improved by reacting the functional groups in lignocellulose material with those of the binders. Figure 6 shows a proposed bonding mechanism of corn stalk and diadehyde starch [42, 43].

Ye *et al.*, (2018) improved the formulation of the partileboard of corn starch by using modified starch as a binder where MOE improved but MOR decreased. Scanning electron microscopic (SEM) analysis of the cross section of the particleboards showed that the dialdehyde starch had filled the spaces of the corn stalks [80].

Guler, *et al.*, (2007) used peanut hull as a raw material in formulation of particleboard with urea formaldehyde (UF) adhesive. The composite material yielded a medium density particleboard with low MOR is 9.90 Nmm^{-2}, MOE of 1276.76 Nmm^{-2} and IB of 0.316 Nmm^{-2} [17]. These mecanical properties show poor compatibility between peanut hull and UF. Low mechanical properties have been improved by mixing peanut hull and wood chips. Wood chips contain high content of lignin which introduces hydrophobic materials that reduces the water absorption and thickness swelling [17]. Particleboards utilized very high quantities of wood materials for it to meet the the stadards required for MOR and MOE. Use od wood chips encourage cutting down of trees thus reducing tree cover.

Akgul, *et al.,* (2013) conducted a study on the suitability of luffa fiber as lignocellulose material bound with UF resin [21]. Formulated particleboards did not meet the set minimum of IB of 0.55 N/mm^2 according to TS 64-5 EN 622 (1999) since there was no direct interaction between lignocellulose material and the binder. The density can be boosted by reacting the functional groups in the luffa fibers with the functional groups in the binder. Paraffin was used as a temporary measure of reducing water absorption in the particleboard. Alternative use of hydrophillic material is by esterification process which does not limit biodegradability of the composite material. Esterification leads to direct use of inherent characteristic of lignocellulose material functional groups and those of binding resins [81, 82].

Garcia-Ortuno, *et al.,* (2011) utilized giant reed bound with UF as a binder in formulation of the particleboard. The research findings showed a medium density particleboards with high WA of 61.23 % [24]. The low MOE of 1467 Nmm^{-2} and MOR of 9.93 Nmm^{-2} was due to lack of interaction between lignocellulose material and the binder. Giant reed is
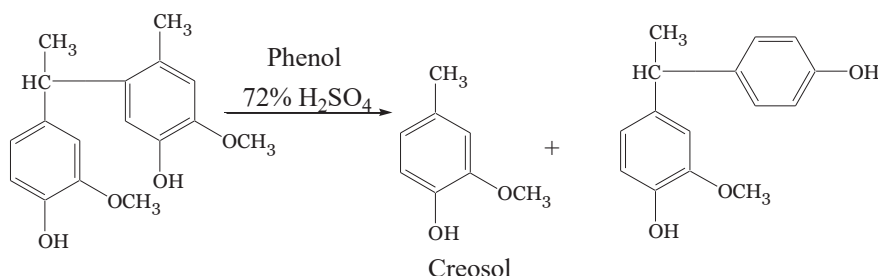

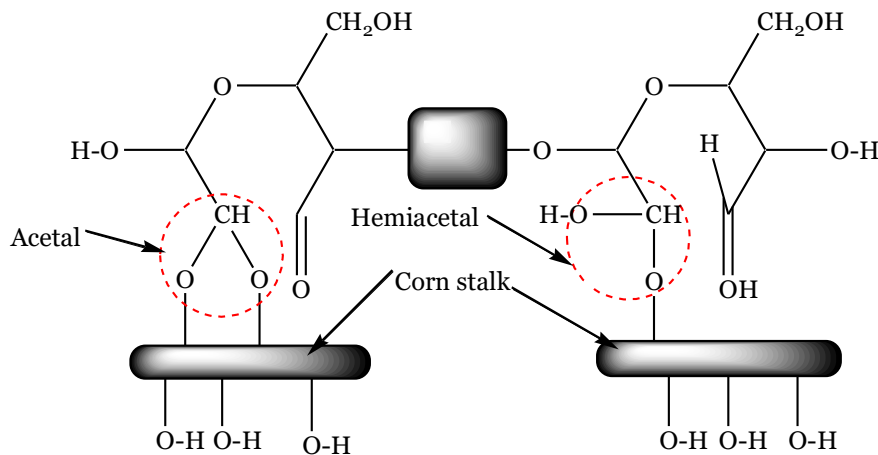**Figure 5.** Phenolization of the model compounds.

Figure 6. Bonding in corn stalk and diadehyde starch.

found in Mediterranian basin thus its avaliability is limited as alternative lignocellulose source.

Nemli, *et al.*, (2009) investigated the feasibility of using waste grass blended with UF as a binder to formulate particleboards. Particleboards formulated had high TS of 33.63 % and low MOR of 4.19 Nmm^{-2}, MOE 351.35 Nmm^{-2} and IB of 0.08 Nmm^{-2} [25]. Water absorption was very high which is attricuted to large number of –OH in cellulose and hemicellulose. Physical and mechanical properties were improved by addition of wood particles. Wood particles provide lignin that is hydrophobic thus reduces water water absorption The reinforcement of upto 75 % by wood chips resulted into a particleboard with improved water absorption.

Pan, *et al.*, (2007) utilized eucalyptus bound with polymeric methane diphenyl diisocyanate (PMDI) in mix with UF as a binder showed TS of 31.26 % and WA of 69.89 % [44]. High WA and TS is attribured to the presesnce of hydroxyl groups in the materials used. Hydroxyl (-OH) groups interact via hydrogen bonding with water molecules. Low MOR of 13.6 N/mm^2 and MOE of 1564.2 N/mm^2 may be improved by bondage in lignocellulose material and isocyanate could be enhanced by first reacting the resin with lignocellulose material [83] as shown in Eq. (16).

$$RNCO + HO - wood \rightarrow RNHCOO - wood \qquad (16)$$
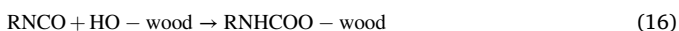
Water melon peels were used to make composite materials using low density polyethylene as a binder [84]. The result showed modulus of elasticity of 1678 N/mm^2, modulus of rupture of 11.45 and internal bonding 0.58 N/mm^2. Water melon particles were embedded with the binder thus no interaction with the binder. This resulted to low MOE. WA was upto 70 % and that of TS was upto 17%. These levels of WA and TS were due to absence of water repellent agents. Water melon peels constitute of high cellulose and hemicellulose contents of 20 and 23 % respectively. Lignin content is 10 % of the total mass. This high cellulose content and hemicellulose content give rise to high hydroxyl groups that influence the interaction of the composite material with water. Chemical modification therefore is necessary to reduce the number of the hydroxyl (-OH) groups. Instead this encountered by use of more binder of upto 60 % recycled low density polyethylene [84].

Durian peels was used to make particleboards using urea formaldehyde, phenol formaldehyde and isocyanate resins as a binders [85]. Durian peels constitute of 60.45 % cellulose and 12.09 % hemicellulose. This means that the number of hydroxyl functional groups was extremely high. Due to this water absorption went upto 189.235 % and thickness swelling upto 104.273 %. The researcher improved the hydrophobic nature of the composite material by addition of coconut coir and paraffin [86]. The high WA and TS made it impossible for the mechanical characteristics of the boards to be characterized. Watanapa and Wiyarath, (2013) used durian peels and polyvinyl alcohol as a binder. The water absorption was at 143.71 % though with a small reduction index [87].

Polyvinyl alcohol contains hydroxyl functional groups that enhance water absorption.

Orange peels bound with a mixture of urea formaldehyde and phenol formaldehyde as a binder was used to formulate particleboard [88]. Cellulose content ranged from 9.19 to 11.93 %, in 84.62 % moisture content. This translated to over 59 % of cellulose in the dry matter content. Cellulose contain high number of hydroxyl groups that determine water absorption The resulting composite material showed water absorption at an average of 0.35 g of water per 1 g of material. This was encountered by use of more binders during formulation of particleboards. Excess use of urea formaldehyde and phenol formaldehyde resins results to emission of more formaldehyde [33, 34, 89].

1.3. Non-wood and formaldehyde free alternatives

Conventional methods of binding lignocellulose materials during formulation of particleboards involves encapsulation. The resin undergoes polymerization to form a network of long chain that encapsulate the lignocellulose materials at high pressure and temperature. Lignocellulose compose of lignin, cellulose and hemicellulose materials. The materials requires chemical modification for the inherent hydroxyl groups to react with other funtional groups other than formaldehyde resins. There are various chemical modification related to lignocellulose materials such as oxidation [90]. In the hydrogen peroxide, lignin under alkaline form peroxide anion as shown in the Eq. (17)

$$H_2O_2 + OH^- \rightarrow HO_2^- + H_2O \qquad (17)$$

Perhydroxyl anion break lignin molecules leading to opening of benzene ring to form ethanedioic acid, methanoic acid and malonic acid as shown in Figure 7 [91].

Molecules produced contains a mixture of functional groups that react to form a covalent bond. A –OH reacts with other hydroxyl groups through condensation reactions to form an ether bond. A –OH reacts with carboxylic (-COOH) group through esterification to form a covalent
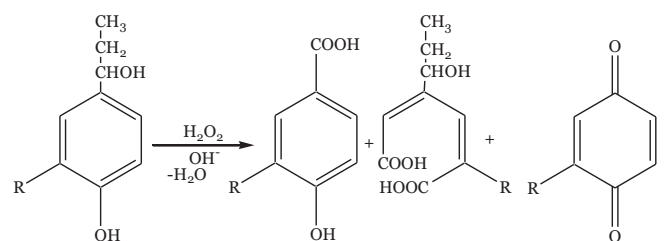

Figure 7. Cleavage and Oxidation of Lignin material in Lignocellulose Material Using Perhydroxyl Anion.

bond. Alternative functional groups may be sourced from biobased materials such as cassava peels starch. To improve the physical and mechanical characteristics of the particleboard, particle surfaces need to be chemically compatible. Chemical compatibility allow formation of strong chemical bond [39].

2. Conclusion

1) Hardening of crop-residue based particleaboards is a challenge. This has been addressed through mixing ammonium chloride with the binder during particleboard formulation. However the resultant particleboards break easily due to reaction between ammonium chloride and the binder.

2) Crop-residue based particleboard generally exhibit poor MOR, IB and MOE due to low density. Increasing compartiblity between the crop residues and binders through surface modification of the materials used that involves chemical modification of hydroxyl groups has helped improve these properties.

3) Crop-residue based particleboards have also shown high WA and TS. This is associated with the increase in porosity of the crop residues particleboards that increases the water absorption and thickness swelling. Additional of hydrophobic materials such as paraffin, lignin, polypropylene and wax reduces the water absoprtion and thickness swelling due to their hydrophobic nature.

4) Crop-residue based particleboards have generally been found to exhibit low densities. Densities can be inceased by increase in specific weightbof the lignocellulose material.

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