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A review on waste wood reinforced polymer composites and their processing for construction materials

Katleho Keneuwe Khoaele[a], Oluwatoyin Joseph Gbadeyan[b], Viren Chunilalla[a,b] and Bruce Sithole[b]

[a]Biorefinery Industry Development Facility, Council for Scientific and Industrial Research, Durban, South Africa; [b]School of Engineering, Discipline of Chemical Engineering, University of Kwazulu-Natal, Durban, South Africa

ABSTRACT
The necessity to utilise environmentally friendly resources has emerged due to environmental management. With the demand for the production of plastics and wood materials, pollution has increased. Consequently, the attraction in natural fibre-reinforced polymer composites (NFPCs) is rapidly emerging in the construction industry, mainly to replace synthetic fibre composites. The intensified interest is associated with manufacturing 'green' and lightweight panels. This review provides insight into the prospects and challenges related to the processing of wood waste-reinforced polymer composites. Using natural fibres, especially waste as raw material, is desirable for developing value-added products to mitigate environmental pollution. The current materials used for the wood-based composites are reviewed as disadvantages associated with wood plastic composites, such as low interfacial bonding. Efforts such as chemical treatment are outlined to wood fibres to manufacture an environmentally friendly, cost-effective, lightweight, and biodegradable composite with enhanced structural properties was provided. Various waste plastics, plant dust, and coupling agents-based composites investigated for applications, and emerging aspects of wood plastic composite for construction materials applications are outlined.

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Waste wood; Thermoplastics; Wood plastic composites; Construction materials

1. Introduction

'It was not raining when Noah built the ark'. Human beings can think, strategize, foresee, and prepare beforehand. The prospect of humanity remains in anticipating and impeding global crises while mitigating our current crises at the local, national, and global levels (Trevors 2010). With the global scarcity of fossil oil resources and forestry, natural fibre-reinforced polymer composites (NFPCs) are anticipated to increase from 12% in 2010 to 18% and 25% by 2020 and 2030, respectively (Gurunathan, Mohanty, and Nayak 2015). Primarily manufactured from biodegradable polymers and biomass fibres from agricultural and forestry wastes (Deka and Maji 2011) NFPCs containing wood as a filler may compete with synthetic/inorganic filler due to their less reliance on fossil sources and 'green chemistry'. Wood fillers are cost-effective, abundant, readily available as waste, and have low density ((Moritzer and Richters 2021).

The demand for plastic materials for various applications has a compounded annual growth of 4.2% between 2021–2028. Consequently, considerable quantities of plastic are used and disposed of (Khoaele et al. 2023). The effect of plastic waste on the environment is alarming to environmental health management, government, and scientific literature due to white pollution (Khoaele et al. 2023; Shen et al. 2020). Overcoming this concern led to different efforts towards plastic waste reduction, in which treatment processes such as reusing, recycling, energy recovery, and landfilling have been employed to reduce environmental pollution. By 2030, the percentage of plastic recycling is expected to reach 55%. The global plastic recycling market was valued at $31.5 billion in 2015 and is predicted to increase at a 6.9% annual pace between 2016 and 2024 (Turku, Karki, and Puurtinen 2018).

Studies are ongoing to work towards the global mandate of recycling waste to produce value-added material, which may be a societal solution. The technology for developing and fabricating high-value NFPCs from wood (i.e. sawdust, wood chips, wood flour, cut-offs, residues from manufacturing, and pulping sludge) can contribute to an improved cascading application in the construction industry with products used in buildings, inner-outer decoration and architecture such as windows, doors, fences, panels, and flooring material (Mwango and Kambole 2019; Teuber et al. 2016; Toghyani, Matthews, and Varis 2020; Xu, Du, and Wang 2021) The main advantages of NFPCs include but are not limited to rapid production rate, durability, cost-attractiveness, and recyclability, which is considered a 'green composite'. An innovative approach for developing the NFPC includes chemical treatment followed by process engineering. Chemical treatment improves the interface bonding, while particle size reduction enhances consistency in the dispersion of wood within the biocomposite, thus improving the mechanical properties (Taheri et al. 2021). Due to superior mechanical properties, NFPCs can

CONTACT Oluwatoyin Joseph Gbadeyan ✉ toyin2good@gmail.com School of Engineering, Discipline of Chemical Engineering, University of Kwazulu-Natal, South Africa

potentially replace wooden laminates used in construction materials (Pickering, Efendy, and Le 2016). The global NFPCs market was evaluated to be U$2.1 BILLION in 2010. It was projected to grow at 10 % annually through 2016, demonstrating growth potential in several industries, including construction, civil, sports, automotive, aircraft, and leisure (Birniwa et al. 2023).

2. Wood waste as natural fibre for composite manufacturing

Natural fibres may be used as reinforcing material for polymer composites and are categorised into two: natural and synthetic or artificial (Amjad et al. 2021). Natural fibres (NFs) are desirable for reinforcement in polymer composites. They are a robust alternative to synthetic carbon-based fibres, glass, and silicates because of their many noteworthy advantages, including low CO_2 emission, low density, low cost, nonabrasive to equipment, no skin irritation, reduced energy consumption, biodegradability, recyclability and lower health risks (Amjad et al. 2021; Ammar et al. 2023; Lotfi et al. 2021). NFs, including fruit, jute, wood, hemp, kenaf, coir sisal, and flax, are illustrated in Figure 1.

The quantity of waste produced during wood-based product manufacturing and utilisation increased with its application (Adhikari and Ozarska 2018). When used properly, these wastes make up a valuable base of raw materials that can help to minimise the need for raw natural wood. Regrettably, most of them wind up in landfills (Akan et al. 2021; Spear, Eder, and Carus 2015). Climate change, such as air pollution, flooding, erosion, and drought, severely affects human and environmental health changes in temperature and CO_2 concentration in the air influence plant growth and pathogens (Anabaraonye 2022). Temperature and moisture are the main factors in pathogen growth in a selective way resulting in the risk of the pandemic of diseases. Increased CO_2 levels can positively or negatively impact disease pandemics initiated by plant-pathogenic bacteria. Because of altered host physiology, improved biomass, and altered microbial environments, elevated CO_2 favour microbial populations (Sreenivas 2022). Considering the escalation of environmental awareness due to the challenges of wood waste disposal by modern-day furniture manufacturing industries, the advancement of wood plastic composites will benefit the long-term viability of forests and increase sustainability (Nyemba et al. 2018; Yue et al. 2022). Wood is categorised into hardwood and softwood. Their chemical and physical characteristics vary considerably. Hardwood has larger pores and uneven surfaces because of vessel elements, shorter ray cells, and parenchyma cells (Effah et al. 2017). Contrarily, softwood has regular, long tracheids and smaller pores, thus frequently used as reinforcements in composite manufacturing. Properties such as fibre length, crystallinity, strength, defects, diameter, and structure require identification before utilising NFs for composites manufacturing and optimisation (Teuber et al. 2016; Väisänen, Das, and Tomppo 2017).

Composites are engineered materials consisting of two or more components, namely reinforcement, and matrix, with distinct qualities, and their blend results in materials with desired properties (Mudavanhu et al. 2017). Reinforcement is the strengthening element of the composite, and the matrix is a polymer that serves as a binder; the purpose of the matrix is to sustain structural integrity. The reinforcement is stiffer and better quality than the matrix, while the matrix retains the reinforcement and offers a homogenous structure (Amjad et al. 2021; Malik 2021). The categorisation of composites according to reinforcement and matrix is illustrated in Figure 2.

Wood plastic composite (WPC) refers to a blend of wood-based materials recovered from the sawmill industry, such as fibres, sawdust, lumber, veneer, or particles which are blended with biodegradable polymers such as thermoplastics or thermosetting from recycling to generate composite material (Friedrich

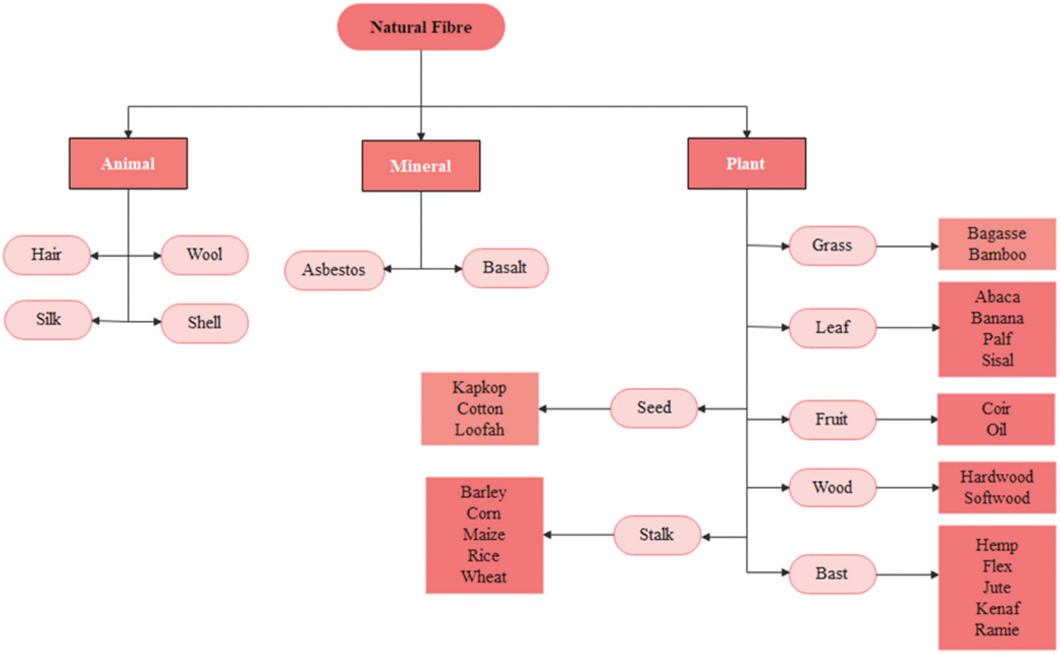

Figure 1. Categorization of natural fibers (Amjad et al. 2021; Chauhan, Kärki, and Varis 2019).

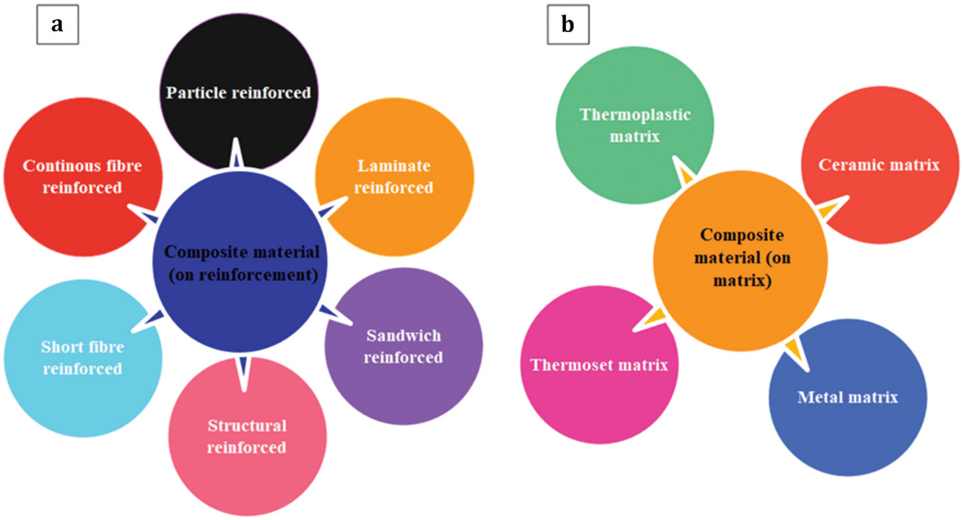

Figure 2. Classification of composites (a) According to reinforcement materials and (b) based on matrix materials (Ibrahim et al. 2015).

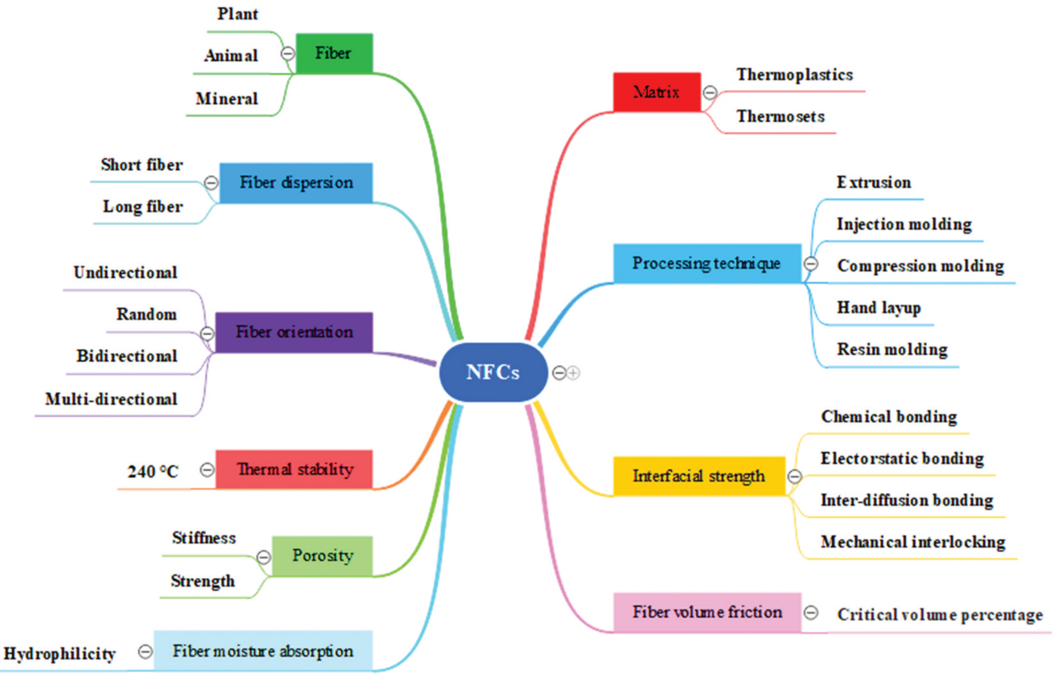

Figure 3. Factors affecting the performance and mechanical properties of natural fiber composites.

2022; Gardner, Han, and Wang 2015; Siddique et al. 2022). Though WPCs are low density, cost-effective, eco-friendly, recyclable, durable, stiff, good in strength, and low maintenance, their significant limit for polymers used requires processing conditions (pressure, melting temperature) that would not thermally decompose the wood filler as the wood decomposes around 220 °C (Srivabut et al. 2022). The properties of the composite comprise excellent stiffness, high strength, low thermal expansion, no catastrophic failure, and resistance to environmental and chemical factors (Amjad et al. 2021).

2.1 Factors affecting natural fibre composites

Compatibility between the fibre filler and polymer matrix is vital in maximising the performance of the NFPCs. It is determined by factors such as fibre type, matrix type, fibre dispersion, fibre orientation, thermal stability, moisture absorption, manufacturing process, interfacial strength, and porosity, as illustrated in Figure 3 (Bootklad, Chantarak, and Kaewtatip 2016; Pickering, Efendy, and Le 2016; Pokhrel, Gardner, and Han 2021).

2.1.1 Factors Affecting NFCs Based on the natural fibre selection

2.1.1.1 Fibre selection. Fibre type is usually classified based on its source: plant, animal, or mineral. All plant fibres are primarily made of cellulose, whereas animal fibres are primarily made of protein (Pickering, Efendy, and Le 2016; Väisänen, Das, and Tomppo 2017).

2.1.1.2 Fibre dispersion. Since NFCs frequently contain hydrophilic fibres and hydrophobic matrices, fibre dispersion is a critical factor influencing the properties of short-fibre composites and a particular challenge for NFCs (Yang et al. 2019). Their propensity to aggregate can be further increased using longer fibres. Good interfacial bonding encourages good fibre dispersion, which lowers voids by guaranteeing that the fibres are entirely encircled by the matrix (Pickering, Efendy, and Le 2016; Väisänen, Das, and Tomppo 2017)

2.1.1.3 Fibre orientation. When the fibre is aligned parallel to the direction of the applied load, composite materials can typically achieve their best mechanical properties. However, aligning natural fibres is more challenging than aligning continuous synthetic fibres. Depending on the matrix viscosity and the design of the mould, some alignment is accomplished during injection moulding (Pickering, Efendy, and Le 2016; Zeyrek et al. 2022).

2.1.1.4 Fiber thermal stability. Natural fibre begins degrading at approximately 240 °C. The behaviour of the fibre's structural constituents, such as lignin, hemicelluloses, and cellulose, is affected by temperature. Though cellulose and hemicelluloses degrade at higher temperatures, lignin begins to degrade at approximately 220 °C. Thermal stability can be increased by chemically eliminating a specific amount of lignin and hemicelluloses from the fibre (Ji et al. 2021).

2.1.1.5 Fiber moisture absorption. When the plant fibre cell wall is dampened, the hydrogen link cracks, and the hydroxyl establishes new hydrogen bonds with the water molecules. When replaced with a hydrophobic resin, this causes the matrix to expand, resulting in poor mechanical properties, poor fibre-to-matrix adhesion, matrix cracking, and dimensional variability. Moisture absorption can be reduced by applying chemical treatments to remove hydrophilic hydroxyl linkages on the fibre's surface before composite manufacturing (Amjad et al. 2021; Nurazzi et al. 2021).

2.1.1.6 Fiber volume fraction (V_f). Volume is the percentage of fibre volume in the total volume of a composite material when reinforced in the matrix. It significantly affects the mechanical and physical properties of composites. According to composites theory, a critical volume percentage exists below where the composite's strength will be less than that of a matrix for NFPCs consisting of stiff reinforcing fibres in a flexible polymer matrix (Pickering, Efendy, and Le 2016). Two potential failure rules are subjective to the fibre volume above or below the minimum value. When a composite with fewer fibres than the minimum volume fraction experiences stress, fibre failure will not culminate in composite failure because the polymer can withstand the applied load. The broken fibres, which now hold no loading, can serve as a series of gaps in the matrix. This signifies that the reinforcement diminished the composite material, and the composite strength has reduced compared to the matrix individually. Contrarily, if the fibre content exceeds the critical volume percentage, fibre failure yields composite failure. The polymer cannot old added loading transferred to the matrix from the reinforcement (Lotfi et al. 2021).

2.1.2 Factors Affecting NFCs Based on the polymer matrix selection

2.1.2.1 Matrix selection. Matrix selection is a significant parameter as it uniformly distributes the loading exerted by the composite to the reinforcing fibres, serves as a barrier against harmful environments and shields the fibres' surfaces from mechanical abrasion and the effects of chemicals. The matrix sustains the reinforcement in a suitable position. The commonly utilised polymer matrix in the fabrication of NFPCs is lightweight and processed at lower temperatures (Raju and Shanmugaraja 2019).

2.1.2.2 Interface strength. In plant-based fibre composites, there is typically little interaction between the hydrophilic fibres and the hydrophobic matrices, which results in poor interfacial adhesion, restricting mechanical performance and impairing long-term properties. Fibre and matrix must come into close contact for bonding; wettability can be seen as a crucial prerequisite for bonding. Interfacial flaws caused by insufficient fibre wetting can act as stress concentrators (Pickering, Efendy, and Le 2016; Zeyrek et al. 2022).

2.1.2.3 Processing technique. The widely used methods for manufacturing NFPCs are hand layup, injection moulding, extrusion, and compression moulding, further discussed in Section 4.

2.1.2.4 Porosity or void. Volatile chemicals or air may become trapped in the material during the introduction of fibre into the matrix. As a result of the fibre gap between the laminate and the resin-rich sections, micro-voids may develop in the composite after curing, decreasing the strength qualities of the composites. The rate of cure and cooling of the resin can also create vacuum formation. Void content greater than 20.1 % by volume results in lower fatigue resistance, a stronger affinity for water diffusion, and more significant variation (scatter) in mechanical properties (Ji et al. 2021; Pickering, Efendy, and Le 2016). Controlling the viscosity of the polymer is crucial for controlling pore development and shape (Ma et al. 2012).

3. Treatment of natural fibres for practical application

The structure of NFs (cellulose, lignin, hemicelluloses, and extractives) interrelates with environmental water due to the hydroxyl ($^{-}$OH) groups resulting in weak bonds with the polymer (Stanaszek-Tomal 2019). Consequently, the properties of composite decline because of the weaker interfacial bond between hydrophilic (water-loving) NFs and a hydrophilic (water-resistant) polymer, which is unfavourable for structural and industrial applications (Amjad et al. 2021; Parikh 2023). Thus, modifying the NFs is essential for enhanced composites (Stanaszek-Tomal 2019). Chemical or physical treatment or a combination of both should be carried out to reduce the polar constituent of the NFs for (i)

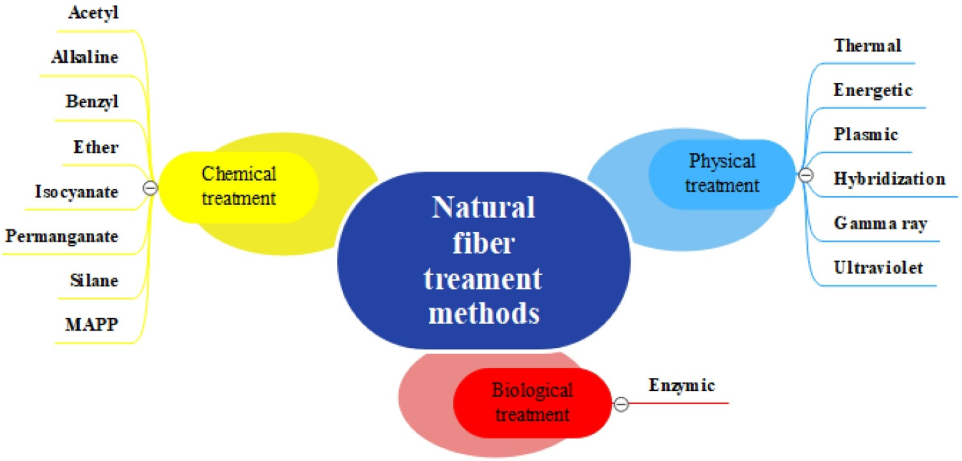

Figure 4. Treatment methods for natural fibers for application.

eliminating impurities, (ii) altering the crystallinity, (iii) improving fibre-matrix interfacial bonding, and (d) good adhesion (Nurazzi et al. 2021). The standard natural fibre surface treatment methods are biological, physical, and chemical treatments illustrated in Figure 4.

3.1 Biological treatment of natural fibres

3.1.1 Enzymic

Enzyme therapy is used more frequently and extensively in processing NFs. Enzymes mainly focus on treating the non-cellulosic constituents of the fibres. They can be regenerated and thus will not be discarded as waste. They are environmentally friendly, which is one of the main arguments in favour of this technology (Birniwa et al. 2023).

3.2 Physical treatment of natural fibres

Physical treatments modify the surface and structural properties and consequently affect the mechanical interface of polymers. Physical treatments include but are not limited to thermal, energetic, plasmic, hybridisation, gamma, ultraviolet treatments, etc. (Nurazzi et al. 2021).

3.2.1 Thermal/Steam explosion

Thermal treatment, also termed steam explosion, involves conditioning wood fibres with heat and moisture at about 230 °C to create an inert surface and eliminate hemicellulose. The thermal treatment heats the fibre from 100 to 200 °C, altering its physical and chemical properties, low-temperature components, water ratio, and crystallinity (Birniwa et al. 2023). Andrusyk et al. (2008) manufactured WPCs using polypropylene and extracted wood flour. The composite's mechanical qualities were significantly improved. Following the treatment, thermal expansion, flame spread, and specific gravity did not change (Andrusyk et al. 2008). Similar findings were discovered in Hosseinaei's study, in which WCPs were manufactured with polypropylene and hot water extracted southern yellow at three different temperatures. The extraction procedure was discovered to increase thermal stability and tensile strength (Hosseinaei et al. 2012).

3.2.2 Energetic

AGD, or atmospheric glow discharge, is a method that combines industrial plasma and high-voltage radio frequency. AGD has the advantage of applying gas treatments to surfaces at atmospheric pressure. AGD was used to treat wood flour in an environment where the surrounding gas was hexamethyl disiloxane. Consequently, the composite's strength and flexural properties significantly improved (D. J. Gardner, Han, and Wang 2015).

3.2.3 Plasmic

Plasma therapy uses ionisation gases to eliminate undesired constituents from the surface of NFs. Various surface modifications can be accomplished depending on the kind and composition of the gases used. It is possible to create and add surface crosslinking, reactive free radicals, and groups and change the surface energy (Faruk et al. 2012). The treatment also reduces surface unevenness by improving the interfacial adhesion of the fibre matrix (Birniwa et al. 2023).

3.2.4 Hybridization

Both natural and synthetic fibres can hybridise. By combining different types of nanomaterials or nanofillers in the same matrix, hybridisation can also be done at the nanoscale to create hybrid nanocomposite materials. Three types of hybrid composites can be categorised: interlaminar, which consists of layers of various fibre types; intralaminar, which consists of layers of various fibre types; and mixed. The choice of material, the production process and preparation, and the interaction of the matrix and reinforcement are the primary factors that significantly affect the properties of hybrid composites (de Araujo et al. 2020).

3.2.5 Gamma ray

Gama radiation with exceptionally high energy can potentially change the properties of polymer surfaces. The appropriate gamma radiation exposure raises the tensile properties of composite materials to a particular degree, allowing them to be used in various practical applications (Birniwa et al. 2023).

3.2.6 Ultraviolet (UV)

UV radiation alters the fibres' polarity, increasing interfacial adhesion between the fibre matrix and wettability.

Additionally, C-C, C-H, C-O, C-F, and C-Si bonds are broken chain clean the fibres (Birniwa et al. 2023).

3.3 Chemical treatment of natural fibres

Chemicals can add functional moieties to NFs by reacting with their surface functional groups. The interfacial bonding between the modified wood surface and polymer matrix will be improved. Chemicals with two distinct functional end groups are coupling agents. The $^{-}$OH of the wood fibre is reacted with by one group, while the polymer matrix is reacted with by the other. Over 40 different coupling agents have been studied to alter wood fibres, with sodium hydroxide, acetic acid, silane, acrylic acid, peroxide, isocyanates, and potassium permanganate being the common ones (Chubuike et al. 2017; Gardner, Han, and Wang 2015). Chemicals can add functional moieties to wood fibres by reacting with their surface functional groups. Chemical reactions between the coupling agent and NFs improve the compatibility and interfacial bonding between WPC materials and reduce the water absorption of fibres (Chubuike et al. 2017; Shen et al. 2021). The coupling types consist of covalent bonds, mechanical inter-blocking, mechanical inter-blocking, secondary bonding (such as van der Waals' forces and hydrogen bonding), and mechanical inter-blocking (Ashori 2008). The mechanism of the coupling agent for composite formation is illustrated in Figure 5.

3.3.1 Acetyl treatment

Acetylation is a treatment that utilises acidic catalysts to improve the interfacial adhesion in NFs. Chemicals consisting of the acetyl (CH_3CO) group, essentially acetic acid, and acetic anhydride, are used for acetylation. The cellulose fibres and the CH_3CO group react to lose $^{-}$OH groups. This reaction results in a reduction of moisture absorption. Acetylation yields a rugged surface topography with less porosity than other chemical processes, improving interlocking characteristics (Birniwa et al. 2023).

3.3.2 Alkaline treatment

Alkalisation or mercerisation treatment improves impurity elimination and decreases hydrophilicity and fibre constituents. The treatment improves NFs' surface roughness, improves the fibre – matrix interfacial adhesion, and reduces the pore diameter (Nurazzi et al. 2021). A measured sodium hydroxide (NaOH) concentration is added to the NFs for alkaline treatment. NaOH reacts with alkali sensitive $^{-}$OH groups on the surface of the NFs, resulting in the discharge of water particles. The moisture absorption susceptibility reduces with the number $^{-}$OH. It further dissolves smaller concentrations of lignin, hemicellulose, pectin, and oil (Birniwa et al. 2023; Nurazzi et al. 2021; Gbadeyan et al. 2021).

3.3.3 Benzyl treatment

Benzoylation reduces the hydrophilicity of NFs. Benzoyl chloride is used to improve the fibre-matrix interfacial adhesion and thermal stability of composites. The $^{-}$OH groups in the NFs are initiated by alkali pre-treatment. The benzoyl ($C_6H_5C_{14}O$) group initiates the treated hydrophilic fibre and reacts favourably with the hydrophobic matrix (Birniwa et al. 2023).

3.3.4 Ether treatment

Etherification is a biochemical process that aids NFs in modifying the matrix's polymeric chain through grafting bifunctional monomers. The thermal stability of the NF polypropylene composites was improved after etherified fibres were added (Birniwa et al. 2023).

3.3.5 Isocyanate treatment

Isocyanate treatment is applied in NFs as a coupling agent. The reaction with the fibre's $^{-}$OH groups improves water resistance and interfacial adhesion. Isocyanates are organic compounds having isocyanate (N-R=O=C) groups. N-R=O=C groups react with $^{-}$OH groups, leading to the production of urethane bonds. These are used to eliminate $^{-}$OH groups via cellulose and lignin (Birniwa et al. 2023).

3.3.6 Permanganate treatment

In treating potassium permanganate (KMnO4), the MnO_4 group reacts with the NF's cellulosic group to produce a complex ion. The reactive Mn ion prompts graft polymerisation. The $KMnO_4$ treatment improves the fibrillation and roughness of NFs. In acetone, $KMnO_4$ releases reactive MnO_4^{-} ions and reacts with cellulose forming cellulose-manganate. This induces graft copolymerisation and leads to fibres with exceptional thermal stability. Usually, fibres undergo alkaline pre-treatment followed by soaking in known concentrations of $KMnO_4$ solution containing acetone for 1 to 3 min (Birniwa et al. 2023). Chubuike et al. (2017) aimed to chemically treat Jute fibres for an improved fibre-matrix adhesion by suspending the fibres in NaOH solution. The alkaline pre-treated fibres were immersed in a 50% permanganate

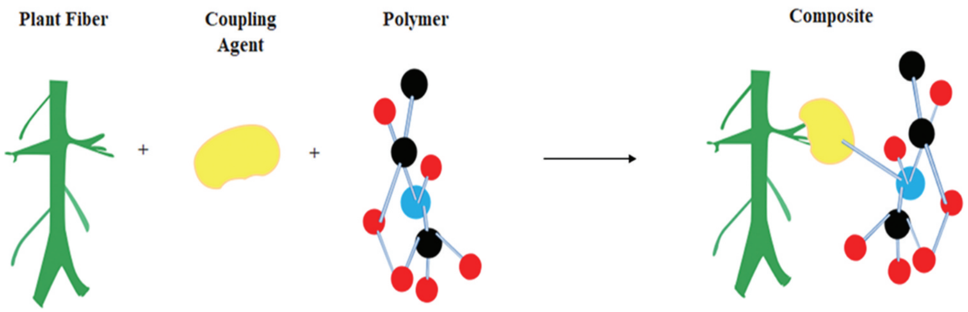

Figure 5. Coupling agent's mechanism linking hydrophilic fiber and hydrophobic polymer for composite fabrication (Ashori 2008).

acetone solution. The study revealed a significant fibre weight reduction. The moisture content eliminated increased fibre strength. Hemicelluloses, lignin, wax, pectin, and oil-covering materials were eliminated during chemical processes. Thus, removing micro-voids causes the fibre surface to become more homogeneous. Improved stress transfer capabilities between alternate cells and increased fibre surface area for solid matrix adhesion were achieved. The impact strength of the treated fibre showed a 20% improvement (Chubuike et al. 2017).

3.3.7 Silane treatment

Silane (SiH_4) treatment yields in the micropore coating of an NF's surface, thus improving interfacial adhesion of fibre-matrix. Pre-treatments, mainly alkalisation, occur to purify existing constituents. Stages of bond formation, condensation, and hydrolysis occur during fibre treatment. Silanol is generated in the presence of moisture and condenses. A side of the silanol reacts with the functional group of the polymer matrix.

Meanwhile, on the side, it modifies the cellulose $^{-}$OH group of the fibre to form a siloxane bond (Nafis et al. 2023). Silane treatment starts with a silane derivative (mostly amine) in alcohol/acetone. The immersion of hydrophilic fibres in silane solution improves bonding with the hydrophobic, resulting in higher thermal stability, tensile strength, flexural stiffness, and tensile modulus (Birniwa et al. 2023). Nafis et al. (2023) revealed that the filament manufactured from polypropylene and wood dust fibre treated NaOH-silane by a twin-screw extruder improved interfacial adhesion. This resulted in a 35.2% improvement in wire pull strength higher than untreated and alkaline-treated wood dust fibre. Porosity and water absorption were reduced.

3.3.8 Maleated coupling agents treatment

Maleated (MA) treatment involves adding a coupling agent to the fibre's surface and matrix. Maleic anhydride is grafted onto polymers to increase the coupling agent and matrix compatibility. MA strengthens the interfacial adhesion between fibre matrix. MA reacts with the hydroxyl groups during grafting and removes them from the fibre surface. This results in a long-chain polymer covalently linked to the fibre's surface. The copolymer is warmed to 170 °C before the treatment, and the esterification is performed. Following this treatment, the surface energy of the cellulose fibre is substantially nearer to one of the matrices (Birniwa et al. 2023).

WPCs were manufactured from wood flour and wood pellets using four different wood species (white cedar, white pine, spruce-fir, and red maple) as fillers, polypropylene (PP) as a matrix with and without maleic anhydride polypropylene (MAPP) as coupling agent. The composite component's weight was wood 20%, PP 78%, and MAPP 2%, while wood was 20% and PP 80% without filler. The circular surface area of the particle sizes increased due to a decrease in the particle size. The observed density for each formulated sample was more significant than the average density of PP (900 kg.m$^{-3)}$. The tensile strength of the wood flour without MAPP was 0.6% greater than the pellets. The tensile strength of the wood flour without MAPP is 1.7% lesser for the softwoods and 7.7% greater for the hardwoods, contrary to the pellets. Likewise, the tensile strength of the wood flour with MAPP was 3.9% greater than pellets. The hardwood and softwoods showed increases of 5.5% and 3.4%, respectively, for the wood flour with MAPP compared to pellets. The average impact strength for the wood flour without MAPP was 8.3% greater than the pellets, while flour without MAPP was 14.3% greater for softwoods and 9.6% less for hardwoods than the pellets.

The impact strength for the wood flour with MAPP was 2.3% more than the value for the pellets. It was more significant for softwoods by 3.7% and lowered for hardwoods by 1.8% when pellets were used compared to flour with MAPP. WPCs manufactured from wood flour and pellets had comparable physical and mechanical qualities. The feedstock distribution was similar for both wood flour and pellet-formed WPCs. However, the dispersion was more significant in WPCs made with pellets than in WPCs made with wood flour. MAPP improved WPCs' physical and mechanical properties for each wood feedstock and species (Pokhrel, Gardner, and Han 2021). Though the authors suggested that softwood offers superior qualities on average, Berger and Stark (1997) contrarily stated that hardwood filler with PP composite performs better than softwood (Berger and Stark 1997).

4. Processing techniques for natural fibre polymer composites

4.1 Polymer as a matrix for composite manufacturing

Thermoplastics or thermosetting polymers are organic compounds with large molecules and can be used as matrix materials in NFPCs (Khoaele et al. 2023; Väisänen, Das, and Tomppo 2017; Raju and Shanmugaraja 2019). Thermosets are non-recyclable polymers owning stiffness and stronger bonds than thermoplastics. They maintain their dimensional stability even at elevated temperatures and cannot be reshaped or remoulded. Contrarily, thermoplastic polymers can melt or soften by heating and toughen when cooling, meaning they can be remoulded. Additionally, they have high impact resistance, are easily recyclable, and are chemically inert. It also takes less time to process thermoplastics (Chauhan, Kärki, and Varis 2019; Yadav, Kamal, and Yusoh 2015). Thermoplastics are often linear or branched polymers, while thermosets are crossed-linked (Ayeleru et al. 2020). Epoxy, polyester, and phenolic are examples of thermosetting polymers. Polypropylene, polylactic acid, polyvinyl chloride, and polystyrene are examples of thermoplastic polymers (Huda and Widiastuti 2021). Due to NFs degrading around 220 °C, thermosetting is restricted for NFPCs manufacturing as they require high temperatures to set (Raju and Shanmugaraja 2019). Due to this limitation, this section will focus on thermoplastic polymers as the reasonable matrix.

Their features typically change when thermoplastics are mixed with wood during composite production. The utilisation of various thermoplastics and quantities is required to assess their impact on the mechanical properties of the panels, which again affects their quality and potential use provided the properties are accomplished (Martinez Lopez et al. 2020). The processing of thermoplastics is illustrated in Table 1 and Figure 6.

A chemical coupling agent is not required for rice husk and offers superior mechanical properties to sawdust (Abdulkareem et al. 2019).

Table 1. Processing of thermoplastics as a matrix for composites fabrication.

Polymer	Filler	Chemical treatment	Processing techniques	Outcomes	Reference
PP	Sisal fiber	No treatment	Extrusion	Adding sisal fibers to the PP matrix enriched the composites' percentage crystallinity and tensile modulus. Recycling did not impact the tensile modulus and strength of the PP/sisal fiber composites.	Ngaowthong et al. (2019)
PLA				The composites' percentage crystallinity and tensile modulus were enriched by adding sisal fibers to the PLA matrix. The tensile modulus and strength reduce significantly following the first recycling because of polymer degradation.	
PET HDPE PP	Cedrela odorata L. sawdust	Calcium carbonate	Extrusion	The thermoplastics content was directly proportional to the density; however, inversely proportional to the physical properties. The 55% and 50% thermoplastic content composites demonstrated improved physical properties.	(Martinez Lopez et al. 2020)
PS	Rice husk	Sodium hydroxide	Hand layup	The high impact strength was achieved at 60 µm rice husk particle size, 15% filler concentration, and 0% NaOH composite at 78.5 $J.m^{-2}$.	(Abdulkareem et al. 2019).
	Sawdust			The high impact strength was achieved at 100 µm sawdust particle size, 15% filler concentration, and 4% NaOH concentration in composite 75.5 $J.m^{-2}$,	

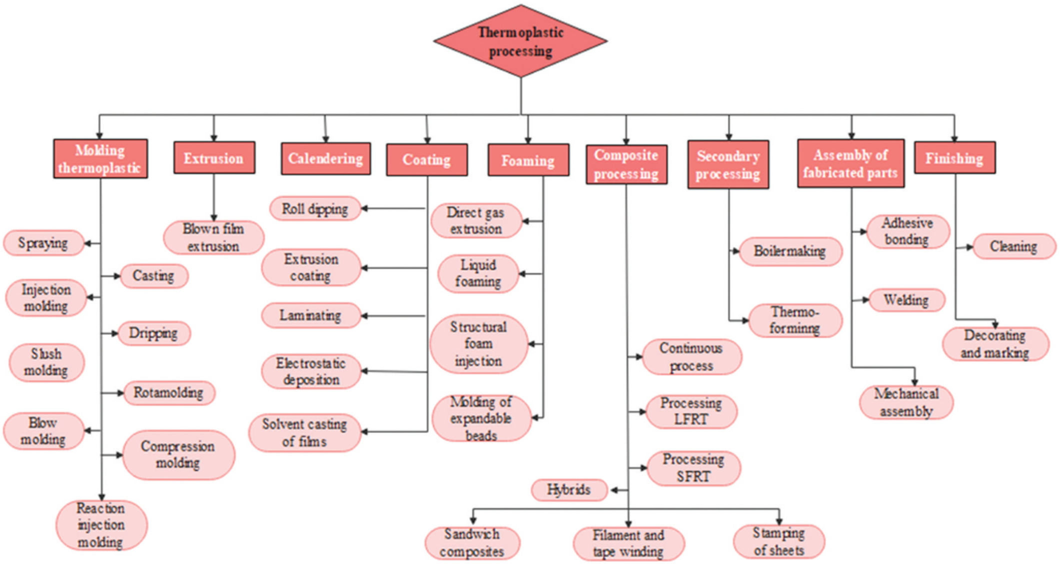

Figure 6. Thermoplastic processing (Biron 2013).

4.2 Methods used for processing thermoplastic polymers for wood composites manufacturing

Manufacturing methods play an essential role in the fabrication of polymeric materials. Processing factors such as the shape of the mould, size, temperature, and pressure affect the performance of the fabricated material. These factors affect friction, strength, density, etc. (Seal, Chaudhary, and Sadhu 2022). Some of the commonly used fabrication methods are discussed in the sub-section below:

4.2.1 Hand layup

Hand layup is an ancient and widely used method for polymer-based material fabrication. In this process, the reinforcement and matrix are placed layer by layer in the mould with a specified size and shape. Following the mould's formulation, the interior surface is lubricated by wax or gel to prevent the sticking manner of resin onto the mould. Dissolved resin is infused into the surface of the reinforcements cut in desired shapes in the mould. (Seal, Chaudhary, and Sadhu 2022). The wet blend is then brushed, rolled, or squeezed to achieve equal distribution of the resin, eliminate trapped air and fuse the composite layers ensuring improved interaction between the matrix and reinforcement and achieving the required thickness. The hand layup method comprises four steps: mould formulation, wax/gel coating, layup, and curing.

Nampoothiri et al. (2022) fabricated three-layered hybrid composites from Indian almond(I) and kenaf fibres(K) and epoxy resin using the hand layup method. The K/I/K composite revealed the maximum average flexural and tensile of 92 MPa and 85 MPa, respectively, owing to the high strength of K fibre as the surface. I/K/I composite revealed the maximum average impact strength of 5 kJ/m^2 owing to the I fibre at the outer surface, which absorbed more impact energy because of the surface cracks. K/I/K composite absorbed (10%) less moisture compared to I/K/I. It can be concluded that the K/I/K composite be used for structural applications due to improved flexural and tensile strength. In contrast, I/K/I composite can be damp due to improved impact strength. (Nampoothiri et al. 2022). In another study by Bhambure, Rao, and Senthilkumar

(2023), three-layered hybrid composites were fabricated from kenaf (KF) and kapok (KP) fibre and polyester using the hand layup method. The KF/KP composite revealed maximum average flexural and tensile of 12.45 ± 0.25 and 25.25 ± 4.29 MPa, respectively. And the maximum average impact strength of 46.65 ± 0.01 kJ/m^2. The results revealed that hybrid composites' impact and tensile strength improved compared to neat composites (Bhambure, Rao, and Senthilkumar 2023).

4.2.2 Extrusion

Extrusion is a commonly used production process and occasionally the preferred practical approach to form complicated thermoplastic profiles. The term extrusion is derived from the Greek roots meaning 'pushing out' or 'squeezing' (Al Sarheed et al. 2022). The main application of the extruder is to soften a polymer matrix and blend the polymer with wood and additives according to the desired process (Gardner, Han, and Wang 2015). The resin blend is dropped from the hopper into the screw container at a pre-set rate. The container is usually heated at a temperature suitable for melting the resin. The screw in the container carries the molten plastic to the heated die, giving it shape. The molten plastic is carried to the water bath to harden the formation of the profile. The yield of the extruder is termed extrudate. After hardening, the extrudate gets aborted and cut to the desired length (Al Sarheed et al. 2022). Four extrusion systems for processing profiles are single screw, co-rotating twin screw, counter-rotating twin screw, and woodturner. A single screw extruder may also be utilised for co-extrusion, which involves two extruders working together to create a multi-layered profile. Co-rotating and counter-rotating double screw extruders can be used to pelletise and mix composite (Al Sarheed et al. 2022; Gardner, Han, and Wang 2015).

4.2.3 Compression Molding (CM)

Compression moulding (CM), also termed thermoforming, is a commonly used method for high-volume composite material consisting of thermoplastics and thermosets with short, long, and unevenly arranged fibres (Lotfi et al. 2021). The application of constant belt presses to produce WPC panels has also been exhibited (Gardner, Han, and Wang 2015). CM is identical to the hand layup method but utilises identical dies, which should be covered before curing by applying pressure. CM methods can occur in two set-ups: cold compression and hot compression. The only pressure is applied in the cold compression method, whereas pressure and temperature are applied to fabricate the composite in the hot compression method. (Seal, Chaudhary, and Sadhu 2022). Essentially, the resin surges to acquire the shape of the mould cavity using either pressure or heat and pressure. The resin begins to harden into the desired part through a chemical reaction called crosslinking of polymeric chains. Once adequately cooled, the part can be taken out of the mould. The reaction remains curing as it cools to room temperature (Mohammed Alharmoodi, Hussain Idrisi, and Hamid Ismail Mourad 2022). Controlling temperature control is critical in fabricating composites as minor temperature instability may cause fibre degradation (Seal, Chaudhary, and Sadhu 2022).

dos Santos, Flores-Sahagun, and Satyanarayana (2015) presented a study on sawdust morphology, density, and chemical composition. WPC was prepared with polypropylene and varied quantities of sawdust with and without a compatibilizer by compression moulding. Regardless of the compatibilizers used to coat the materials, all WPCs' highest tensile strengths were reduced as sawdust content was increased. The WPCs made with uncoated sawdust fibres consumed much more water than those made with compatibilizer-coated fibres, showing that water absorption increased as sawdust content increased (dos Santos, Flores-Sahagun, and Satyanarayana 2015).

Bollakayala et al. (2022) prepared WPC from wood fibre (sawdust) and wasted expanded polystyrene (EPS) by a compression moulding process. The EPS waste (size ≤1400 μ) and sawdust (size ≤500 μ) were blended at different ratios for developing composites. The compression moulding technique was pre-heated at around 160 °C and compressed at specific pressure between 25 to 100 kg.cm^{-2} for five minutes. The area of the composite sheet was 225 cm^2. The prepared composites measured tensile strengths ranging from 4 to 20 MPa, while their estimated flexural strengths were between 16 and 35 MPa. The water absorption values ranged from 7 to 18%. The composites with thermoplastic content of 50% demonstrated improved physical properties (Bollakayala et al. 2022).

4.2.3 Injection Molding (IM)

Injection moulding is used for melting granules or powder of polymeric substances inserted into a container by external heating. The molten polymer of fluidity is pressed into the mould cavity for moulding (Mohammed Alharmoodi, Hussain Idrisi, and Hamid Ismail Mourad 2022). While there is less research explicitly addressing the injection moulding process for WPCs than for extrusion processing, the topics are often related and centre on the composition and characteristics of the materials. Additionally, studies have been published on producing WPC microcellular foams using injection moulding (IM) and WPC made with biopolymers (Gardner, Han, and Wang 2015).

5. Applications of natural fibre polymer composites

Apart from the automobile industry, NFPCs are in construction, building, etc., and are used for ceilings, partition boards, decking, office products, frames, and floor laminates. NFPCs applications focus on non-load property indoor elements in civil engineering due to their susceptibility to environmental outbreaks [72]. (Mohammed et al. 2015). NFPCs require optimised characteristics for efficient applicability illustrated in Figure 7.

NFPCs may replace glass in several applications with critical load-carrying capacity (Karthi et al. 2019). In recent years, wood fibre/PE and fibre/PP have been used in construction industry applications for decking, especially in the United States. NFPCs have gained attention in non-structural construction using window and door frames, floor lamination, and wall insulation (Pickering, Efendy, and Le 2016). NFPCs were revealed to have improved mechanical properties compared to wooden laminates in insulating structural boards. The

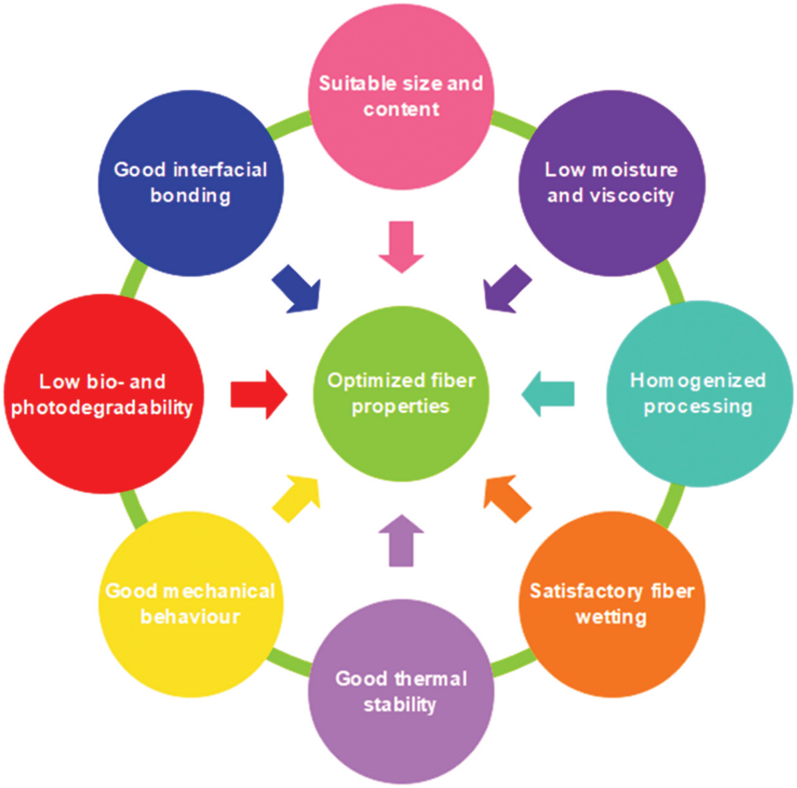

Figure 7. Properties of optimized NFPCs (Faruk et al. 2012; Väisänen, Das, and Tomppo 2017).

flexural strength of the squeezing cavity cross-section of WPCs with 50% wood floor was studied. The study revealed that NF light-duty sheets could substitute steel and concrete sheet piles. NF to reinforce cement for construction materials is also studied (Birniwa et al. 2023). Ramnath et al. (2014) reported abaca and jute fibre-based composites fit for the construction industry. Jute fibres are used in structural applications such as window panels, ceilings, wall partitions and floors, and mobile or prefabricated buildings (Das 2009). The literature revealed that straw bales in polymer composites are suitable for building construction materials Saravana and Mohan (2010). Bamboo fibre has been used to make structural concrete elements Ghavami (2005) (Kumar et al. 2019).

6. Conclusion

The beneficiation of NF compared to synthetic fibres are outstanding in terms of production costs and environmentally friendly. The increasing demand for NFs as a replacement in construction materials could significantly improve the public GDP of agro-based markets as they are easily accessible, cost-effective, and have a high strength-to-weight ratio. Engineered NFPCs have improved thermal stability, stiffness, and strength. NFs can be used as reinforcements following chemical treatment, which allows improved interfacial bonding with the polymer matrix. Three-layered hybrid composites have superior performance compared to NF composites. Thus, hybridisation can permit the application of NFs as reinforcement for composite fabrication.

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Notes on contributors

Katleho Keneuwe Khoaele Just completed her master's degree in Analytical Chemistry and currently works with Council for Scientific and Industrial Research (CSIR) as BDeg Intern·

Dr. Oluwatoyin Joseph Gbadeyan is a researcher at the University of KwaZulu-Natal, and his research interest lies in material development (composite, biocomposite, Nano-composite), Nanotechnology, additive manufacturing, and tribology.

Dr. Viren Chunilall is the research group leader of the Biorefinary Industry Development Facility at the Council for Scientific and Industrial Research (CSIR). His areas of interest lie in chromophore identification and isolation from dissolving pulp, investigating new techniques to improve the reactivity of dissolving pulp for conversion into higher-value products, and extraction of hydrophilic and lipophilic extractives from sawdust waste for conversion into xylitol and pine oil.

Professor Bruce Sithole works as a full professor at the University of KwaZulu-Natal. His research interests lie in pulp and paper-making technologies, integrated forest products, and biorefinery. His work focuses on the revitalization and resilience of the pulp and paper industry by diversifying into biorefinery activities and applications of analytical pyrolysis.

Author contribution

All authors contributed to the review article. Katleho Keneuwe Khoaele wrote the literature study and the article's first draft, and all authors reviewed, revised, and made relevant contributions and suggestions for the submitted manuscript. All authors read and approved the final manuscript.

References

Abdulkareem, S. A., M. K. Amosa, A. G. Adeniyi, S. A. Adeoye, and A. K. Ajayi. 2019. "Development of Natural Fibre Reinforced Polystyrene (NFRP) Composites: Impact Resistance Study." *IOP Conference Series: Materials Science & Engineering* 640 (1): 1–11. doi:10.1088/1757-899X/640/1/012059.

Adhikari, S., and B. Ozarska. 2018. "Minimizing Environmental Impacts of Timber Products Through the Production Process "From Sawmill to Final Products." *Environmental Systems Research* 7 (1). doi:10.1186/s40068-018-0109-x.

Akan, O. D., G. E. Udofia, E. S. Okeke, C. L. Mgbechidinma, C. O. Okoye, Y. A. B. Zoclanclounon, E. O. Atakpa, and O. O. Adebanjo. 2021. "Plastic Waste: Status, Degradation and Microbial Management Options for Africa." *Journal of Environmental Management* 292: 1–12. doi:10.1016/j.jenvman.2021.112758.

Al Sarheed, M., A. Sedaghat, A. Malayer, H. Salem, S. Amir, A. Oloomi, W. K. Hussam, et al. 2022. "Manufacturing Wood-Plastic Composites and Their Thermal Performance in Building Envelope." doi:10.21203/rs.3.rs-1972102/v1.

Amjad, A., M. S. Z. Abidin, H. Alshahrani, and A. A. Ab Rahman. 2021. "Effect of Fibre Surface Treatment and Nanofiller Addition on the Mechanical Properties of Flax/Pla Fibre Reinforced Epoxy Hybrid Nanocomposite." *Polymers* 13 (21): 1–16. doi:10.3390/polym13213842.

Amjad, A., A. A. A. Rahman, H. Awais, M. S. Z. Abidin, and J. Khan. 2021. "A Review Investigating the Influence of Nanofiller Addition on the Mechanical, Thermal and Water Absorption Properties of Cellulosic Fibre Reinforced Polymer Composite." *Journal of Industrial Textiles* 51 (1_suppl): 1–36. SAGE Publications Ltd. doi:10.1177/15280837211057580.

Ammar, Z., H. Ibrahim, M. Adly, I. Sarris, and S. Mehanny. 2023. "Influence of Natural Fiber Content on the Frictional Material of Brake Pads—A Review." *Journal of Composites Science* 7 (2): 1–15. doi:10.3390/jcs7020072.

Anabaraonye, B. 2022. "Impacts of Climate Change on Human and Environmental Health in Nigeria." *~ 17~International Journal of Research in Civil Engineering and Technology* 3 (2): 17–20. doi:10.1007/s41297.

Andrusyk, L., G. S. Oporto, D. J. Gardner, and D. J. Neivandt. 2008. Wood Plastic Composites Manufactured from Hot Water Extracted Wood. Part I: Mechanical Evaluation. *Proceedings of the 51st International Convention of Society of Wood Science and Technology*, Concepción, CHILE, 1–7.

Ashori, A. 2008. "Wood-Plastic Composites as Promising Green-Composites for Automotive Industries!" *Bioresource Technology* 99 (11): 4661–4667. doi:10.1016/j.biortech.2007.09.043.

Ayeleru, O. O., S. Dlova, O. J. Akinribide, F. Ntuli, W. K. Kupolati, P. F. Marina, A. Blencowe, and P. A. Olubambi. 2020. "Challenges of Plastic Waste Generation and Management in Sub-Saharan Africa: A Review." *Waste Management* 110: 24–42. doi:10.1016/j.wasman.2020.04.017.

Berger, M. J., and N. M. Stark. 1997. Investigations of Species Effects in an Injection-Molding-Grade, Wood-Filled Polypropylene. *The Fourth International Conference on Woodfiber-Plastic Composites*, Deer Park, Texas, 19–25.

Bhambure, S. S., A. S. Rao, and T. Senthilkumar. 2023. "Analysis of Mechanical Properties of Kenaf and Kapok Fiber Reinforced Hybrid Polyester Composite." *Journal of Natural Fibers* 20 (1): 1–10. doi:10.1080/15440478.2022.2156964.

Birniwa, A. H., S. S. Abdullahi, M. Ali, R. E. A. Mohammad, A. H. Jagaba, M. Amran, S. Avudaiappan, N. Maureira-Carsalade, and E. I. S. Flores. 2023. "Recent Trends in Treatment and Fabrication of Plant-Based Fiber-Reinforced Epoxy Composite: A Review." *Journal of Composites Science* 7 (3): 120. doi:10.3390/jcs7030120.

Biron, M. 2013. "Thermoplastic Processing." *Thermoplastics and Thermoplastic Composites* Elsevier: 715–768. doi:10.1016/b978-1-4557-7898-0.00005-6.

Bollakayala, V. L., N. Etakula, K. K. Vuba, Y. S. Manne, and A. N. Uttaravalli. 2022. "Preparation and Characterization of Green Composites Based on Expanded Polystyrene Waste and Biomass: Sustainable Management Approach." *Materials Today: Proceedings* 1–7. doi:10.1016/j.matpr.2022.05.275.

Bootklad, M., S. Chantarak, and K. Kaewtatip. 2016. "Novel Biocomposites Based on Wheat Gluten and Rubber Wood Sawdust." *Journal of Applied Polymer Science* 133 (30): 1–6. doi:10.1002/app.43705.

Chauhan, V., T. Kärki, and J. Varis. 2019. "Review of Natural Fiber-Reinforced Engineering Plastic Composites, Their Applications in the Transportation Sector and Processing Techniques." *Journal of Thermoplastic Composite Materials* 35 (8): 1169–1209. doi:10.1177/0892705719889095.

Chubuike, O. M., C. C. Ebele, E. Ifeanyi, I. F, E. S. Okwuchukwu, and O. E. Festus. 2017. "Study on Chemical Treatments of Jute Fiber for Application in Natural Fiber Reinforced Composites (NFRPC)." *International Journal of Advanced Engineering Research and Science* 4 (2): 21–26. doi:10.22161/ijaers.4.2.4.

de Araujo, A. A. R., D. K. Cavalcanti, S. N. J. de Souza, H. M. da Costa, and M. D. Banea. 2020. "Effect of Surface Treatments on Interfacial Properties of Natural Intralaminar Hybrid Composites." *Polymer Composites* 41 (1): 314–325. doi:10.1002/pc.25371.

Deka, B. K., and T. K. Maji. 2011. "Study on the Properties of Nanocomposite Based on High Density Polyethylene, Polypropylene, Polyvinyl Chloride and Wood." *Composites Part A Applied Science and Manufacturing* 42 (6): 686–693. doi:10.1016/j.compositesa.2011.02.009.

dos Santos, L. P., T. S. Flores-Sahagun, and K. G. Satyanarayana. 2015. "Effect of Processing Parameters on the Properties of Polypropylene-Sawdust Composites." *Journal of Composite Materials* 49 (30): 3727–3740. doi:10.1177/0021998314568331.

Effah, B., K. Raatz, A. Van Reenen, and M. Meincken. 2017. "Chemical Force Microscopy Analysis of Wood-Plastic Composites Produced from Different Wood Species and Compatibilizers." *Wood and Fiber Science* 49 (2): 146–157.

Faruk, O., A. K. Bledzki, H. P. Fink, and M. Sain. 2012. "Biocomposites Reinforced with Natural Fibers: 2000-2010." *Progress in Polymer Science* 37 (11): 1552–1596. doi:10.1016/j.progpolymsci.2012.04.003.

Friedrich, D. 2022. "Post-Process Hot-Pressing of Wood-Polymer Composites: Effects on Physical Properties." *Journal of Building Engineering* 46: 1–15. doi:10.1016/j.jobe.2021.103818.

Gardner, D., Y. Han, and L. Wang. 2015. "Wood–Plastic Composite Technology." *Current Forestry Reports* 1 (3): 139–150. doi:10.1007/s40725-015-0016-6.

Gbadeyan, O. J., S. Adali, G. Bright, B. Sithole, and P. Lekha. 2021. "Mechanical, Microstructure, and Dynamic Mechanical Analysis of Nano-Shell and Plant Fiber Hybrid Biocomposite." *Journal of Composite Materials* 55 (24): 3345–3358. doi:10.1177/00219983211013418.

Gurunathan, T., S. Mohanty, and S. K. Nayak. 2015. "A Review of the Recent Developments in Biocomposites Based on Natural Fibres and Their Application Perspectives." *Composites Part A Applied Science and Manufacturing* 77: 1–25. Elsevier Ltd. doi:10.1016/j.compositesa.2015.06.007.

Hosseinaei, O., S. Wang, A. A. Enayati, and T. G. Rials. 2012. "Effects of Hemicellulose Extraction on Properties of Wood Flour and Wood–Plastic Composites." *Composites Part A Applied Science and Manufacturing* 43 (4): 686–694. doi:10.1016/j.compositesa.2012.01.007.

Huda, M. K., and I. Widiastuti. 2021. "Natural Fiber Reinforced Polymer in Automotive Application: A Systematic Literature Review." *IOP Conference Series: Earth & Environmental Science* 1808 (1): 012015. doi:10.1088/1742-6596/1808/1/012015.

Ibrahim, I. D., T. Jamiru, R. E. Sadiku, W. K. Kupolati, S. C. Agwuncha, and G. Ekundayo. 2015. "The Use of Polypropylene in Bamboo Fibre

Composites and Their Mechanical Properties - a Review." *Journal of Reinforced Plastics & Composites* 34 (16): 1347–1356. doi:10.1177/0731684415591302.

Ji, M., F. Li, J. Li, J. Li, C. Zhang, K. Sun, and Z. Guo. 2021. "Enhanced Mechanical Properties, Water Resistance, Thermal Stability, and Biodegradation of the Starch-Sisal Fibre Composites with Various Fillers." *Materials & Design* 198. doi:10.1016/j.matdes.2020.109373.

Karthi, N., K. Kumaresan, S. Sathish, S. Gokulkumar, L. Prabhu, and N. Vigneshkumar. 2019. "An Overview: Natural Fiber Reinforced Hybrid Composites, Chemical Treatments and Application Areas." *Materials Today: Proceedings* 27: 2828–2834. doi:10.1016/j.matpr.2020.01.011.

Khoaele, K. K., O. J. Gbadeyan, V. Chunilall, and B. Sithole. 2023. "The Devastation of Waste Plastic on the Environment and Remediation Processes: A Critical Review." *Sustainability* 15 (6): 5233. doi:10.3390/su15065233.

Kumar, R., M. I. Ul Haq, A. Raina, and A. Anand. 2019. "Industrial Applications of Natural Fibre-Reinforced Polymer Composites– Challenges and Opportunities." *International Journal of Sustainable Engineering* 12 (3): 212–220. doi:10.1080/19397038.2018.1538267.

Lotfi, A., H. Li, D. V. Dao, and G. Prusty. 2021. "Natural Fiber–Reinforced Composites: A Review on Material, Manufacturing, and Machinability." *Journal of Thermoplastic Composite Materials* 34 (2): 1–47. doi:10.1177/0892705719844546.

Malik, A. J. 2021. "The Utilization of Ijuk Fibre and Sawdust for Manufacturing Composite Block with Plastic Waste as the Matrix." *IOP Conference Series: Materials Science & Engineering* 1088 (1): 1–8. doi:10.1088/1757-899x/1088/1/012112.

Martinez Lopez, Y., J. B. Paes, D. Gustave, F. G. Gonçalves, F. C. Méndez, and A. C. Theodoro Nantet. 2020. "Production of Wood-Plastic Composites Using Cedrela Odorata Sawdust Waste and Recycled Thermoplastics Mixture from Post-Consumer Products - a Sustainable Approach for Cleaner Production in Cuba." *Journal of Cleaner Production* 244. doi:10.1016/j.jclepro.2019.118723.

Ma, P., X. Wang, B. Liu, Y. Li, S. Chen, Y. Zhang, and G. Xu. 2012. "Preparation and Foaming Extrusion Behavior of Polylactide Acid/ Polybutylene Succinate/Montmorillonoid Nanocomposite." *Journal of Cellular Plastics* 48 (2): 191–205. doi:10.1177/0021955X11434182.

Mohammed Alharmoodi, K., A. Hussain Idrisi, and A. Hamid Ismail Mourad. 2022. A Recent Trend in the Natural Fiber Polymer Composites: An Overview. *2022 Advances in Science and Engineering Technology International Conferences, ASET 2022*. doi:10.1109/ASET53988.2022.9735113.

Mohammed, L., M. N. M. Ansari, G. Pua, M. Jawaid, and M. S. Islam. 2015. "A Review on Natural Fiber Reinforced Polymer Composite and Its Applications." *International Journal of Polymer Science* 2015: 1–16. doi:10.1155/2015/243947.

Moritzer, E., and M. Richters. 2021. "Injection Molding of Wood-Filled Thermoplastic Polyurethane." *Journal of Composites Science* 5: 1–12. doi:10.3390/jcs5120316.

Mudavanhu, S., J. Blignaut, N. Vink, D. Crookes, M. Meincken, B. Effah, D. Murima, and N. Nkambule. 2017. "An Assessment of the Costs and Benefits of Using Acacia Saligna (Port Jackson) and Recycled Thermoplastics for the Production of Wood Polymer Composites in the Western Cape Province, South Africa." *African Journal of Agricultural and Resource Economics* 12 (4): 322–365.

Mwango, A., and C. Kambole. 2019. "Engineering Characteristics and Potential Increased Utilisation of Sawdust Composites in Construction - a Review." *Journal of Building Construction and Planning Research* 7 (3): 59–88. doi:10.4236/jbcpr.2019.73005.

Nafis, Z. A. S., M. Nuzaimah, S. I. A. Kudus, Y. Yusuf, R. A. Ilyas, V. F. Knight, and M. N. F. Norrrahim. 2023. "Effect of Wood Dust Fibre Treatments Reinforcement on the Properties of Recycled Polypropylene Composite (R-WoPpc) Filament for Fused Deposition Modelling (FDM)." *Materials* 16 (2). doi:10.3390/ma16020479.

Nampoothiri, E. N., J. Bensam Raj, R. Thanigaivelan, and R. Karuppasamy. 2022. "Experimental Investigation on Mechanical and Biodegradation Properties of Indian Almond–Kenaf Fiber-Reinforced Hybrid Composites for Construction Applications." *Journal of Natural Fibers* 19 (1): 292–302. doi:10.1080/15440478.2020.1739592.

Ngaowthong, C., M. Borůvka, L. Běhálek, P. Lenfel, M. Švec, R. Dangtungee, S. Siengchin, S. M. Rangappa, and J. Parameswaranpillai. 2019. "Recycling of Sisal Fiber Reinforced Polypropylene and Polylactic Acid Composites: Thermo-Mechanical Properties, Morphology, and Water Absorption Behavior." *Waste Management* 97: 71–81. doi:10.1016/j.wasman.2019.07.038.

Nurazzi, N. M., M. M. Harussani, H. A. Aisyah, R. A. Ilyas, M. N. F. Norrrahim, A. Khalina, and N. Abdullah. 2021. "Treatments of Natural Fiber as Reinforcement in Polymer Composites—A Short Review." *Functional Composites & Structures* 3 (2): 024002. Web Portal IOP. doi:10.1088/2631-6331/abff36.

Nyemba, W. R., A. Hondo, C. Mbohwa, and L. Madiye. 2018. Unlocking Economic Value and Sustainable Furniture Manufacturing Through Recycling and Reuse of Sawdust. *15th Global Conference on Sustainable Manufacturing*, 21: 510–517. doi:10.1016/j.promfg.2018.02.151.

Parikh, H. H. 2023. "Tribology of Plant-Based Natural Fiber Reinforced Polymer Matrix Composites–A Short Review." *Journal of Natural Fibers* 20 (1): 1–15. doi:10.1080/15440478.2023.2172639.

Pickering, K. L., M. G. Efendy, and T. M. Le. 2016. "A Review of Recent Developments in Natural Fibre Composites and Their Mechanical Performance." *Composites Part A Applied Science and Manufacturing* 83: 98–112. doi:10.1016/j.compositesa.2015.08.038.

Pokhrel, G., D. J. Gardner, and Y. Han. 2021. "Properties of Wood–Plastic Composites Manufactured from Two Different wood Feedstocks: Wood Flour and Wood Pellets." *Polymers* 13 (16). doi:10.3390/polym13162769.

Raju, A., and M. Shanmugaraja. 2019. "Recent Researches in Fiber Reinforced Composite Materials: A Review." *Materials Today: Proceedings* 46: 9291–9296. doi:10.1016/j.matpr.2020.02.141.

Seal, B., V. Chaudhary, and S. D. Sadhu. 2022. "Development of Natural Fiber Reinforced Nanocomposites: Future Scope, Challenges, and Applications." *Materials Today: Proceedings* 78: 614–619. doi:10.1016/j.matpr.2022.11.479.

Shen, M., B. Song, G. Zeng, Y. Zhang, W. Huang, X. Wen, and W. Tang. 2020. "Are Biodegradable Plastics a Promising Solution to Solve the Global Plastic Pollution?" *Environmental Pollution* 263: 1–7. doi:10.1016/j.envpol.2020.114469.

Shen, Z., Z. Ye, K. Li, and C. Qi. 2021. "Effects of Coupling Agent and Thermoplastic on the Interfacial Bond Strength and the Mechanical Properties of Oriented Wood Strand–Thermoplastic Composites." *Polymers* 13: 1–11. doi:10.3390/polym13234260.

Siddique, A., Z. Iqbal, Y. Nawab, and K. Shaker. 2022. "A Review of Joining Techniques for Thermoplastic Composite Materials." *Journal of Thermoplastic Composite Materials* 1–38. doi:10.1177/08927057221096662.

Spear, M. J., A. Eder, and M. Carus. 2015. "Wood Polymer Composites." *Wood Composites* Elsevier Inc: 195–249. doi:10.1016/B978-1-78242-454-3.00010-X.

Sreenivas, S. S. 2022. "Impact of Climate Change on Plant Pathogenic Fungi, Bacteria and Viruses: A Review." *Asian Journal of Research and Review in Agriculture* 4 (3): 35–45.

Srivabut, C., C. Homkhiew, S. Rawangwong, and W. Boonchouytan. 2022. "Possibility of Using Municipal Solid Waste for Manufacturing Wood-Plastic Composites: Effects of Natural Weathering, Wood Waste Types, and Contents." *Journal of Material Cycles & Waste Management* 24: 1407–1422. doi:10.1007/s10163-022-01443-4.

Stanaszek-Tomal, E. 2019. "Wood - Polymer Composites as an Alternative to the Natural Environment." *IOP Conference Series: Materials Science & Engineering* 603 (2): 1–8. doi:10.1088/1757-899X/603/2/022009.

Taheri, H., M. Hietala, T. Suopajärvi, H. Liimatainen, and K. Oksman. 2021. "One-Step Twin-Screw Extrusion Process to Fibrillate Deep Eutectic Solvent-Treated Wood to Be Used in Wood Fiber-Polypropylene Composites." *ACS Sustainable Chemistry & Engineering* 9 (2): 883–893. doi:10.1021/acssuschemeng.0c07750.

Teuber, L., V. S. Osburg, W. Toporowski, H. Militz, and A. Krause. 2016. "Wood Polymer Composites and Their Contribution to Cascading

Utilisation." *Journal of Cleaner Production* 110: 9–15. doi:10.1016/j.jclepro.2015.04.009.

Toghyani, A., S. Matthews, and J. Varis. 2020. "Forming Challenges of Extruded Wood Plastic Composite Products in a Post-Production Process." *Procedia CIRP* 93: 502–507. doi:10.1016/j.procir.2020.04.156.

Trevors, J. T. 2010. "What is a Global Environmental Pollution Problem?" *Water, Air, and Soil Pollution* 210: 1–2. doi:10.1007/s11270-010-0337-9.

Turku, I., T. Karki, and A. Puurtinen. 2018. "Durability of Wood Plastic Composites Manufactured from Recycled Plastic." *Heliyon* 4 (3): 1–20. doi:10.1016/j.heliyon.2018.

Väisänen, T., O. Das, and L. Tomppo. 2017. "A Review on New Bio-Based Constituents for Natural Fiber-Polymer Composites." *Journal of Cleaner Production* 149: 582–596. doi:10.1016/j.jclepro.2017.02.132.

Xu, K., G. Du, and S. Wang. 2021. "Wood Plastic Composites: Their Properties and Applications." *Intech Open*. 1–25. IntechOpen. www.intechopen.com

Yadav, S. M., D. Kamal, and B. Yusoh. 2015. "MECHANICAL and PHYSICAL PROPERTIES of WOOD-PLASTIC COMPOSITES MADE of POLYPROPYLENE, WOOD FLOUR and NANOCLAY." *Kuala Lumpur International Agriculture, Forestry and Plantation* 1: 1–10.

Yang, S. B., Y. J. Kim, I. J. Kwon, S. M. Park, D. J. Kwon, and J. H. Yeum. 2019. "Simple Manufacturing Method for a Thermoplastic Composite Using PP-Straw." *Composites Part B: Engineering* 176: 1–7. doi:10.1016/j.compositesb.2019.107183.

Yue, H., C. Xu, J. Yao, M. He, G. Yin, Y. Cui, C. Yang, and J. Guo. 2022. "Characterization and Properties of Plywood Bioadhesive Derived from Cottonseed Protein and Sawdust Cellulose." *Cellulose* 29 (10): 5869–5881. doi:10.1007/s10570-022-04611-9.

Zeyrek, B. Y., B. Aydogan, E. Dilekcan, and F. Ozturk. 2022. "Author Details Article History Review of Thermoplastic Composites in Aerospace Industry." *International Journal on Engineering Technologies and Informatics* 3 (1). doi:10.51626/ijeti.2022.03.00031.