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Review

Composite Panels from Wood Waste: A Detailed Review of Processes, Standards, and Applications

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Abstract: The global demand for sustainable building materials has fuelled research into composite panels from wood waste. Despite their potential, the widespread adoption of this practice is hindered by the absence of quality standards, inconsistent material properties, and uncertainties about durability and strength. This paper critically reviews existing standards, manufacturing processes, and the suitability of panels from wood waste. A systematic review is conducted to identify the influencing processes and parameters affecting panel performance, from waste collection to the finishing stages. The findings indicate that incorporating 10–30% of wood waste can enhance the mechanical and physical properties, with particularly improved hygroscopic properties and greater dimensional stability. By establishing comprehensive standards and optimizing manufacturing processes, wood waste-based panels can emerge as a viable and eco-friendly alternative. Furthermore, the potential for repeated recycling in a closed-loop process offers promising environmental benefits, though it necessitates balancing resource conservation with product quality. By addressing these challenges, wood waste-based panels can significantly contribute to environmental conservation and resource management.

Keywords: wood waste; recycling; wood panels; cascading wood; timber; engineered wood products

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1. Introduction

With an increase in demand for wood-based products over the past few years, particularly in the construction and furniture industries, wood-based composite panels have risen in popularity due to their cost-effectiveness, consistency, and versatility [1]. The potential of using logs and lumber more efficiently by incorporating lower-grade wood of various sizes has catered to different applications and is considered to be a more sustainable alternative to traditional timber panels. Due to the rising population, urbanization, and increasing disposable income, the global wood-based panel industry is projected to increase in the future, and, by 2030, their consumption is expected to reach over 500 million m^3 [2].

Wood-based panels are defined as sheet-like products made by combining fibres, veneers, and particles, bonded with adhesives and pressed under heat [3]. These can be classified into several diverse types according to parameters such as particle size, density, and manufacturing process type, as shown in Figure 1. Among these panels, plywood, medium-density fibreboard (MDF), particleboard, and oriented strand board (OSB) are most commonly used as building materials, due to their higher density, strength, and durability [4].

In addition to wood particles, these composite panels also incorporate polymer matrix resins, which play a crucial role in binding the wood reinforcements and enhancing the overall mechanical and physical properties. The final panel's characteristics vary significantly depending on the type of wood particles and adhesives used. The polymer matrix ensures the wood particles are bound together effectively, contributing to the panel's overall mechanical and physical properties.

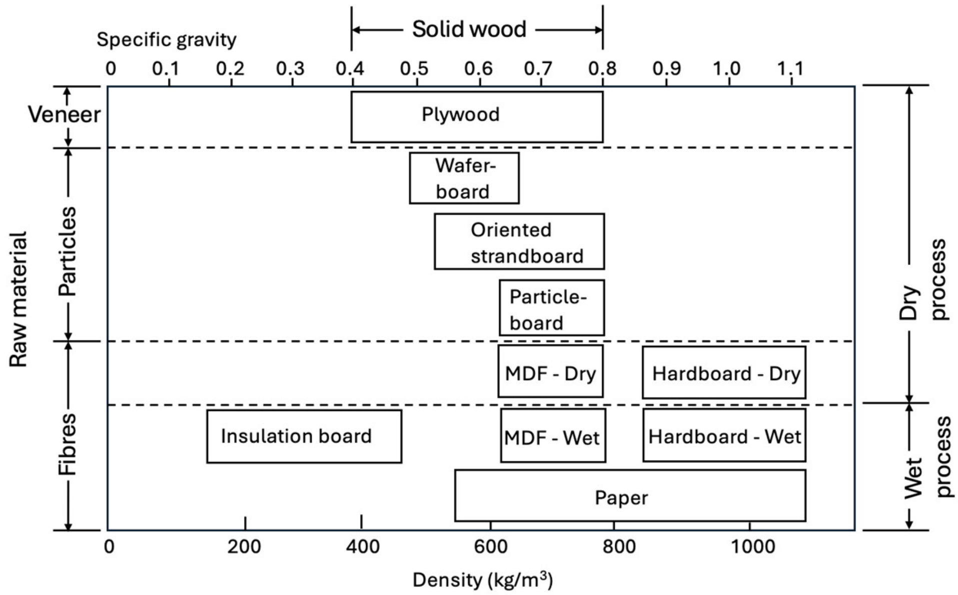


Figure 1. Classification of wood composite boards by particle size, density, and manufacturing process type [5].

The use of alternative biomass with high lignin and cellulose composition in the production of these wood panels has become a popular area of interest due to its wide availability and environmentally friendly nature. Agricultural biomass that can be used as alternatives can be categorized into straw, stalk, bagasse, seed/fruit, leaf, grass, and palm. A thorough review of the different kinds of materials under these categories can be found in the study conducted by Lee et al. [6]. These lignocellulosic materials are found to be a good wood replacement in producing composite wood panels suitable for interior use, but further research is necessary in terms of their dimensional stability and water absorption for more widespread applications [7–9].

Researchers have also explored the integration of various forms of waste materials into the production of wood-based composite panels. Some of the waste incorporated includes rubber chips from waste tyres [10], paper residue [11], recycled plastics [12], and industrial waste such as textiles [13,14]. However, the most popular waste material that has been considered in these studies is the use of "wood waste". "Wood waste" can be in various forms, shapes, and sizes, from large construction timber beams and planks to small fine wood chips and sawdust particles. Some examples of wood waste forms are illustrated in Figure 2. Even though they are termed "wood waste", some of these "wood waste" materials include by-products generated in forms such as sawdust and wood chips, which are often used in the production of panels such as particleboard and fibreboard. For this study, the term "wood waste" will be used hereafter as per the definition of the EU Waste Framework Directive [15], which is "any substance or objective which the holder discards, intends or is required to discard". This can be any form of wood that emerges as a result of in-between production processes or daily activities by individuals or society and is in line with the definition used for similar studies [16–19].

The study by Jahan et al. [20] emphasises the growing seriousness of the wood waste problem, revealing that around 10% of landfill waste comes from construction and demolition wood. Moreover, according to Höglmeier et al. [21], the production of wood in Europe is predicated to be insufficient by 2030, and more clear indicators of the global wood shortage can be seen in countries like Australia where the availability of traditional timber has been severely affected by many recent bushfires and the import restrictions during the

COVID-19 pandemic [22]. The inclusion of wood waste in wood panels promises to be a sustainable solution, with a case study in Germany revealing that up to 45% of recovered wood from building deconstruction is suitable as raw material for wood panel production [23]. By incorporating wood waste in panel production, as the wood is reused multiple times before being disposed of, the resource efficiency is significantly improved [24].

Figure 2. Different forms of wood waste [20].

However, the use of wood waste in panel production has several limitations, due to the heterogeneity of the material. According to the type and origin of the wood waste used, the eventual physical and mechanical properties of the wood panel would differ greatly. Even wood waste from building demolitions will have a different suitability depending on the use, with exterior wall panels tending to have higher wear and the attachment of other materials, while independent parts such as roof trusses and claddings are more suitable for recycling [25]. Treated wood waste introduces additional complications in using it for panel production. The chemical treatments applied for various purposes, including durability enhancement, resistance to decay, and protection against pests, can hinder the panel production process, affect the final panel properties, and pose environmental and health concerns [26–28].

Possibly due to this heterogeneity, there is a lack of adequate standards and guidelines that can be adopted in a global context in terms of the physical and mechanical properties of these wood waste panels. While the existing standards for wood panels can be sufficient in determining the suitability of the final properties of the composite panels made from wood waste, there is a need for proper standards to be established on the suitability of the wood waste as a raw material for the fabrication of composite wood panels. These could include but are not limited to the contaminant limits present in the recycled wood, the dimensional stability, and the compatibility with finishes and coatings.

Therefore, this study presents an overview of the current state of knowledge on the available standards, manufacturing processes, and viability of wood-based panels derived from wood waste for various applications. The manufacturing methods discussed here include the traditional processes of particleboard and fibreboard production from wood waste, as well as emerging innovative technologies. The emphasis is placed on the advancements made in reducing energy consumption, emissions, and enhancing product quality.

Moreover, this study discusses the suitability of these wood waste panels and evaluates their mechanical and physical properties in comparison to the relevant standards available. The environmental impact of the cascading use of wood is also explored, highlighting the immense potential of using wood waste as a sustainable raw material for engineered wood. It sheds light on the current challenges and opportunities faced in the industry, emphasising the need for continued research and industrial technological advancements to ensure the widespread adoption of this eco-friendly solution in the global market.

2. Methodology

2.1. Network Visualisation of Previous Studies

To comprehensively assess the standards of wood waste, manufacturing processes, and the suitability of wood panels made from wood waste, a systematic and rigorous review of the literature was conducted. To initiate the process, a set of keywords and search terms related to wood-based panels, wood waste, particleboards, and fibreboards were identified. These keywords were used to formulate search queries from two major academic databases—Scopus and Web of Science—ensuring the inclusion of studies published until November 2023. Moreover, specific industrial information that is publicly available was also considered, including data sheets and patents relating to wood panel production.

The primary focus was on articles that discussed the standards, manufacturing processes, and suitability aspects of particleboards and fibreboards made from wood waste. The initial search yielded 1498 publications. These were then screened for duplicates and based on their relevance to the topic. For this study, as the focus was the all-wood composite panels produced from wood waste, the research on composite wood panels that included other biomaterials such as cotton, coconut coir, and bamboo, as well as other composite materials such as concrete, polymers, and steel, was not considered. After screening, the remaining 189 publications were subjected to a qualitative content analysis using a VOS viewer to identify the similarities and current trends in the literature [29,30]. A network visualisation of the co-occurrences of the keywords is illustrated in Figure 3, which identifies the clusters of relevant publications in this area.

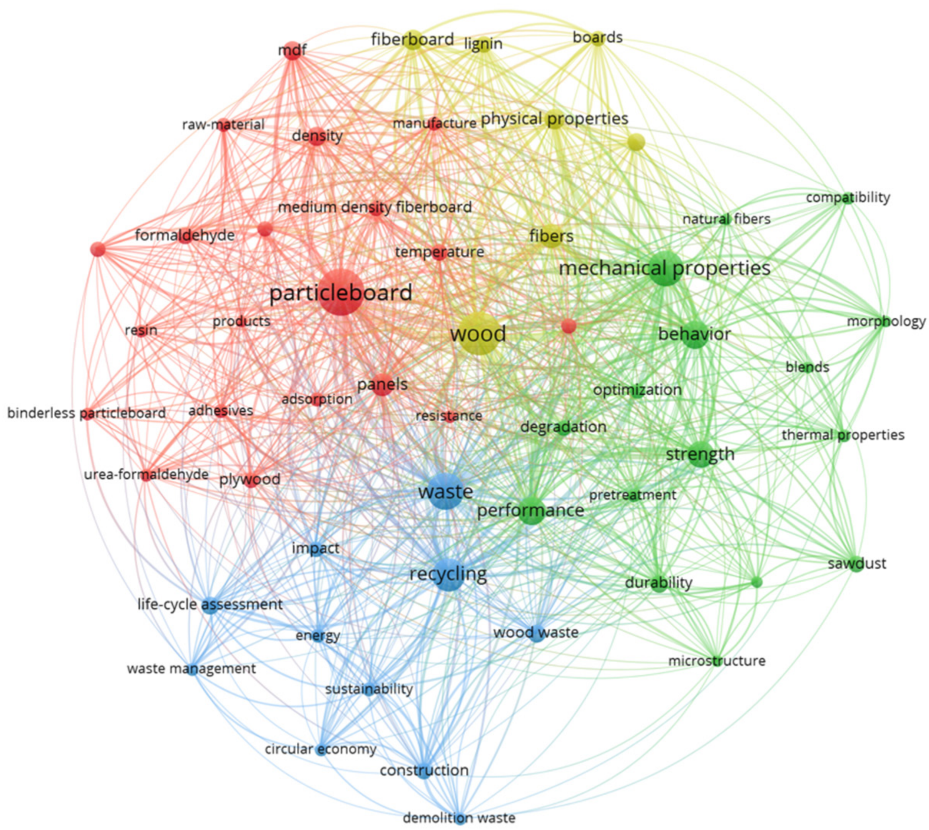


Figure 3. Network visualisation of co-occurrences of keywords.

Four distinct clusters were identified, which are represented using the four different colours: red, green, blue, and yellow. These clusters were determined based on the relationships between the nodes, and the most prominent nodes in these clusters included the keywords particleboard, wood, waste, recycling, and mechanical properties. Moreover, clusters such as durability, microstructure, compatibility, impact, and circular economy were identified as emerging areas.

2.2. Review Studies of Wood Waste Panels

Several review studies have been conducted over the years on the usability of wood waste in wood panel manufacturing. These review studies focus particularly on the characteristics of the wood waste, as well as the characteristics' overall effect on the physical and mechanical properties of the wood panels [6,31,32]. When manufacturing these wood waste panels, the different methods available for each step of the process need to be carefully considered to optimise the productivity and quality of the end products. Some of these steps have been studied and reviewed [33,34]; however, an in-depth review of the production process is lacking, which includes the effect of different wood waste treatment methods, particle size distribution, and manufacturing processes, as well as the thermal, acoustic, and environmental performance of the wood waste panels. A comprehensive overview is needed in the abovementioned areas and on the emerging methods and trends to reduce energy consumption, emissions, and overall carbon footprint.

Other research gaps identified include an overview of the standards of wood waste and recycled wood-based panels and to what extent these manufactured panels are utilized. To address these limitations, this study aims to find answers in the following areas.

- What are the available wood waste quality standards and requirements for these materials to be used in wood waste panels for construction?
- How much of an effect do the parameters within the manufacturing process, including pre-treatment methods, particle size and properties, wood waste percentage, pressing conditions, etc., have on the improvement of the physical and mechanical strength of the manufactured panels?
- How well do such manufactured boards commonly available in the construction industry meet the performance requirements specified by the standards?

This study will be beneficial in planning future in-depth research on incorporating wood waste in wood panel manufacturing, by identifying the best treatment method, wood waste proportion, and manufacturing process. It will assist in identifying the available standards and requirements in terms of structural performance and the suitability of these panels.

One major finding in the study conducted by Nguyen et al. [32] is that there is a lack of research on manufacturing plywood and oriented strand board (OSB) from wood waste. The little research that has considered wood waste inclusion in the manufacturing of OSB has been limited to small inclusions such as substitutes for the core layer [35,36]. The reason for this is the difficulty in processing wood waste material into the veneers needed for plywood manufacturing, which typically involves log peeling or slicing. This demands the log to be straight and cylindrical, a requirement that poses difficulties when working with wood waste and the elevated level of sorting required for OSB. Therefore, this study will mainly focus on manufacturing fibreboards and particleboards using wood waste material. While there are studies available that investigate the production of wood panels directly by treating and laminating larger pieces of recovered wood [37], the focus here will be on the wood panel production from wood waste as a raw material in forms such as chips, strands, fibre, and sawdust. Wood chips are small pieces of wood obtained by chipping or shredding larger pieces of wood, while strands are longer and thicker and created by slicing or peeling. Wood fibres are long thin strands of wood that are much finer than the wood chips generally made by pulping or mechanical refining. The smallest wood residue type is sawdust, which is the fine particles of wood created by sawing, grinding, or sanding wood [38].

3. Manufacturing Process

It is observed that the manufacturing methods of wood panels from wood waste follow a similar process, irrespective of the type of panel being produced [39]. This process is illustrated in Figure 4 and is known as the "dry process", which mixes dried wood particles with small amounts of adhesive before laying out and steam-pressing.

Another manufacturing method available is the "wet process", which is often used for fibreboard production. In the wet process, the wood particles are mixed with water and turned into a pulp before moulding and being steam-pressed. In this process, the sugars in the wood dissolve and the lignin in the wood structure is softened, which acts as a binder to hold the fibres together without the need for an additional binding material to be added [40].

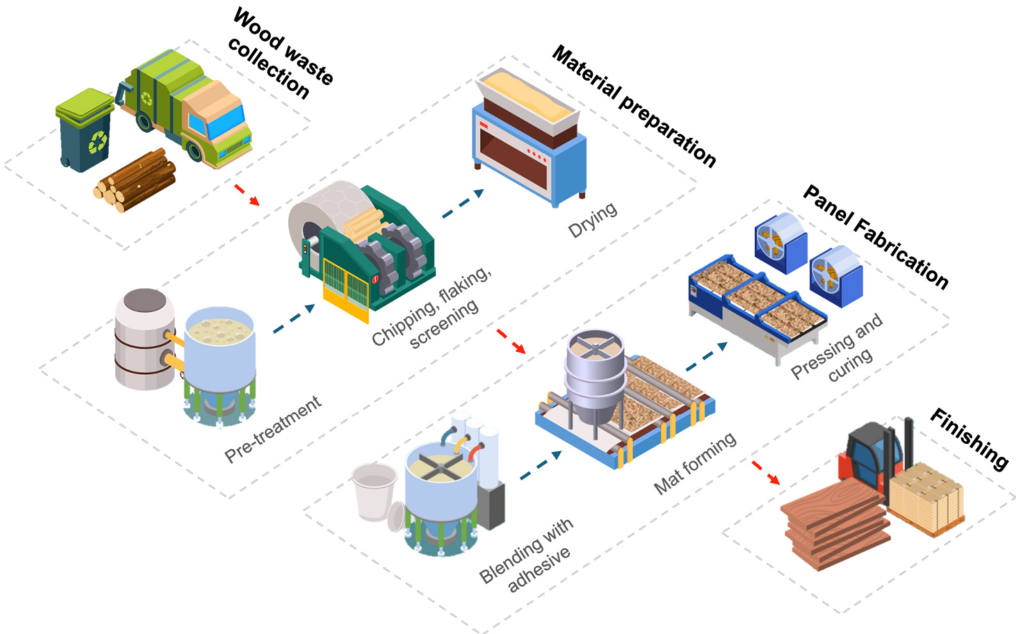


Figure 4. The dry process manufacturing method of wood panels from wood waste, adapted from Forest & Wood Products Australia [41].

However, studies conducted on wood panels from wood waste using the wet process are limited, because most studies have investigated the dry process. This could be due to the main advantage of the dry process being the ability to manufacture boards with higher thicknesses, usually up to 200 mm, while being lighter compared to wet-processed boards, making them ideal for roofing and wall applications [42].

This section will investigate the step-by-step details of the dry process manufacturing of wood panels and how different parameters in each step affect the quality of the wood panels produced from wood waste.

3.1. Wood Waste Classification

The initial step of the process is sourcing the wood waste. The main origins of recovered wood used for wood panel production are offcuts, packaging, construction and demolition waste, renovation, and furniture. For a comprehensive review of the origins and constitution of these wood waste, readers can refer to [32,43,44].

In most European countries, wood waste is classified under either the German or British classification (Table 1). Most other countries do not have separate classifications for wood waste and follow a risk-based classification system for general solid waste [45]. For example, in Australia, both wood waste and any timber from building and demolition waste are categorized as general solid waste, which is non-putrescible, and no further classification is available, which makes it difficult to consider the viability of recovering or understanding the characteristics of the wood waste [46,47].

In contrast, the European classifications give a broader classification of wood waste and denote that untreated and non-hazardous wood waste can be used as the material for wood panel production. However, these classifications are broad and subjective and lack proper guidance or standards on defining the required parameters of wood waste for wood panel production. For particleboards, an alternative classification by the European Panel Federation gives limiting values to certain elements, including metals, halogens, and pentachlorophenol (PCP) in the wood waste [48]. However, other properties such as particle properties and size, density measurements, fibre analysis, chemical and mechanical testing, adhesive compatibility, and formaldehyde emission testing should be carried out to properly identify the suitability of wood waste for wood panel production.

Table 1. European wood waste classifications.

Country	Wood Waste Category	Description	Examples	Applications	Other Adopted Countries
Germany [49]	A I	Untreated/ mechanically treated	Cuttings and shavings from solid wood, pallets, and cable reels made from solid wood	Chips and shavings to produce wood-based materials, synthetic gas, and activated carbon products	Belgium, Denmark, and Poland
	A II	Glued or painted wood (no halogen organic compounds or preservatives)	Pallets made from derived timber products and particleboard		
	A III	Wood containing halogen organic compounds	Particleboards and pallets with halogenated organic compounds	Used as material if varnish and coatings are removed	
	A IV	Contaminated wood	Railway sleepers, telephone masts, and hop poles	Energy use by combustion	
UK [50]	Grade A	Visibly clean and chemically untreated	Solid softwood and hardwood, packaging waste, scrap pallets, and offcuts from sawn timber	Manufacture consumer products such as animal bedding, pellets, and as fuel	Finland, France, and the Netherlands
	Grade B	Chemically treated, non-hazardous business waste	Building demolition materials and domestic furniture made from solid wood	Manufacture of panel board products	
	Grade C	Chemically treated, non-hazardous municipal waste	Municipal wood waste, furniture made from board products	Manufacture for panel board in controlled volumes	
	Grade D	Chemically treated hazardous waste	Agricultural fencing, telegraph poles, and railway sleepers	Licenced disposal	

For wood waste categorisation for particleboard production, the inclusion of any type of fibreboard waste is automatically categorised as "low-quality" wood waste [51]. This is consistent with the study by Daian and Ozarska [18], where MDF offcuts are not an accepted form of wood waste for particleboard manufacturing. One reason for this exclusion is the higher degree of contaminant removal control necessary for the fibreboard waste to be suitable as a raw material. Another is the final boards manufactured using this material have significantly lower mechanical properties compared to other wood waste types. The inclusion of 50% MDF waste shows up to a 55% decrease in the Modulus of Rupture of the manufactured particleboards, which is not desirable [52].

This classification is particularly vital for assessing the appropriateness of utilizing wood waste in the production of wood panels, as the inherent species of the wood significantly influences the mechanical and physical characteristics of the final manufactured panel. Although comprehensive analyses of various wood species and their properties are documented in the existing literature [53,54], there is currently no established method for pinpointing this parameter specifically for wood waste. This absence introduces uncertainty regarding the strength and durability of the end product.

In order to develop and adopt a consistent global standard for wood waste classification, it is necessary to understand the key properties that will affect the particular usage of the waste wood and set limitations to these selected parameters using both chemical and physical testing methods. Harmonizing standards could involve creating a framework that consolidates best practices by conducting a comparative study of the available standards, identifying the key parameters that need to be considered for each end use, and defining the allowable limitations according to the adapting country or region. Developing a unified classification could also include methods for identifying and accounting for the wood species in wood waste streams to enhance quality control.

3.2. Pre-Treatment Methods

The contaminants from recovered wood can include different fastenings such as nails, cement, gypsum, and the organic or inorganic binders that are used in the manufacturing process, as well as the additives used for finishing and protection [55]. Apart from the difficulty in predicting the properties of the manufactured boards due to the heterogeneity of wood waste, the end products created from this waste can have profoundly serious health and environmental impacts. In particular, the most common binders used for wood, formaldehyde-based resins, release toxic emanations during their lifetime [56]. The inclusion of these contaminants can severely affect the recyclability of wood waste, and the proper treatment of the wood waste needs to be carried out before using it in the manufacturing process of new wood panels. There are three main methods available to prepare particles from agglomerated wood waste by way of pre-treatment. These are mechanical, chemical, and hydrothermal treatments.

3.2.1. Mechanical Treatment

As an essential step for wood panel production, mechanical treatment includes grinding, chipping, or hammermilling large wood pieces and breaking them down into chips and fibres. By reducing the size of the wood waste, it is possible to improve the binding properties of the wood particles. Often, wood waste is processed in grinders with an electromagnet to remove any metals present [57]. Several mechanical treatment methods have been developed over the years to treat wood waste and make it suitable for new wood panel production, but most of these methods require large machinery and have been observed as not being very energy efficient [1,58].

The mechanical treatment of wood waste is a dry process and is usually conducted under elevated temperatures to facilitate the separation of wood particles from contaminants. One such treatment includes a twin extruder machine, as used by Roffael et al. [59], where a high shear action was used to defibrate the particleboards and fibreboards from discarded furniture in a temperature range of 90–110 °C to produce fibres. Another study conducted the treatment of wood waste from packaging boxes in a rotating cylindrical stove at a higher temperature, ranging from 180 to 220 °C, for particleboard production [58]. It was observed that the mass loss was significantly small up to a temperature of 220 °C, and the particleboards produced from the heat-treated wood waste particles showed improved dimensional stability and lower hygroscopicity. While the mechanical properties of the panel are lower compared to the panels made from virgin fibre, the internal bond (IB), Modulus of Rupture (MOR), and Modulus of Elasticity (MOE) of the wood waste panels were still able to meet the required standard values.

3.2.2. Chemical Treatment

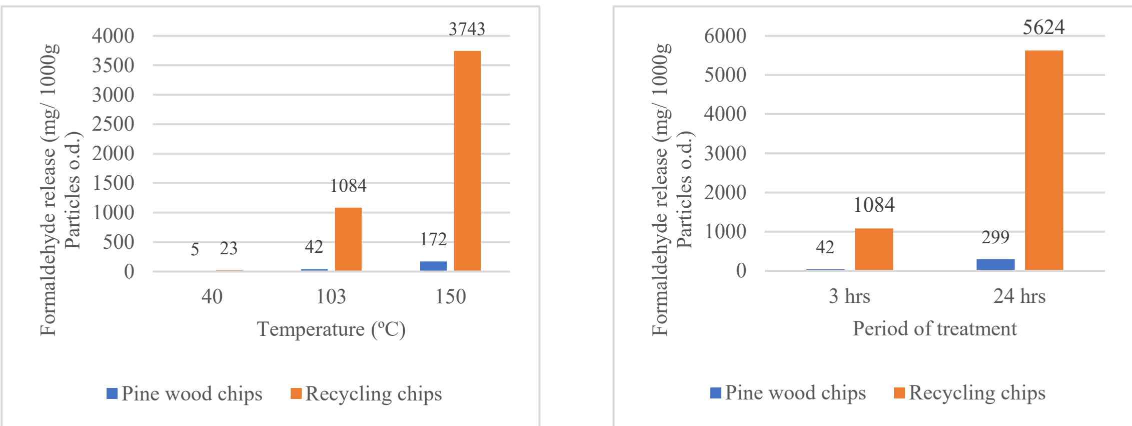
The chemical treatment of wood waste involves the treatment of the wood with chemicals and altering the properties to remove contaminants. A common chemical treatment method is impregnating or submerging the wood with a chemical mixture, often sodium hydroxide or sulfuric acid. By doing this, delignification occurs, where the lignin and hemicellulose components of the wood are broken down and the wood fibres can be extracted. Once extracted, a neutralising agent such as sodium bisulphite is used to balance the pH of the particles [60].

Often, these chemical treatment methods are used to disintegrate non-hydrolysable resins in recovered wood. However, these conditions are often harsh and can lead to the partial or complete disintegration of the wood, which reduces the mechanical properties of the panels drastically, as well as increasing the pH of the manufactured panels [61]. Therefore, while this treatment method can be beneficial for other uses of wood waste, such as for feedstock mixture [62], it is not recommended as a pre-treatment method for wood particles for particleboard and fibreboard production.

3.2.3. Hydrothermal Treatment

The most common method used for wood waste pre-treatment is the hydrothermal treatment, first introduced by Sandberg et al. [63]. Here, the wood waste is exposed to an elevated temperature of steam, water, or buffer solutions, which help separate the resins and other chemical contaminants. As water is used as the main treatment method, this method is preferred, and widely used in the industry, over other treatment methods and performs an 80% or more removal of resins from the fibres [64,65].

The temperature and treatment period play a direct role in determining the effectiveness of the hydrothermal treatment. Traditionally, the temperature used for the hydrothermal treatment is between 180 and 240 °C [66]. However, using higher temperatures to treat wood waste results in reduced water resistance and an undesirable formaldehyde emission of the final panels. By increasing the treatment temperature from 40 °C to 150 °C for the same reaction time, drastic increases in the pH value, formaldehyde release (Figure 5), and formic release can be observed [67]. These results match those from the study by Hüster [68].



(**a**) (**b**)

Figure 5. Formaldehyde release from pine chips and recycling chips under hydrothermal treatment in (**a**) different temperatures for a 3 h treatment period, and (**b**) different treatment periods at 103 °C, adapted from Roffael and Hüster [67].

The type of resin remaining in the wood waste also affects the effectiveness of the hydrothermal treatment. For example, while this method works well with treating wood waste with urea–formaldehyde (UF) resin, which is prone to hydrolysis and offers moderate to low resistance to temperatures above 50 °C, it has less effect in treating wood waste bonded with phenol formaldehyde, which is less subjectable to hydrolysis and more resistant to water, high temperatures, and chemical aging [38,66]. Detailed reviews on the chemical reaction during the hydrolysis of cured UF resin can be found in the literature [69]. Even with the incorporation of acidic solutions of different concentrations into the hydrolysis procedure, while the final panels satisfy the physical properties required by the standards, the mechanical properties are often not reached, and the panels show low bending strength and internal bonding [70].

Therefore, different wood waste has been subjected to different temperatures, treatment types, and solutions to find the most optimum treatment method that is strong enough to extract the resin content from the wood waste but preserves the properties of the wood so as not to degrade the quality of the final panels. As per these studies, mild conditions are recommended to be used for the hydrothermal treatment, as higher temperatures and longer treatment times cause the hydrolysis of wood polymers, which, in turn, reduce the strength properties of the wood waste-treated particles [61,71]. Further, numerical studies found in the literature help identify the optimum hydrothermal treatment conditions more efficiently. A mathematical model developed by Gibier et al. [72] models the behaviour of the formaldehyde and ammonia emissions for varying treatment temperatures, pressures, and time using a pressurised water steam treatment method, and the results show a close match between the experimental and numerical values.

As an alternative to hydrothermal treatment, the use of cold water immersion has also been tested, where the recovered boards are submerged in cold water for disintegration [55,73]. However, the studies could not achieve the complete failure of the bonds between the wood particles, and the samples did not show any signs of breaking down until they were cooked in boiling water. Therefore, the use of cold water in treating wood waste is suggested to be insufficient. Figure 6 shows some examples of wood waste treated by these three main methods.

(**a**) (**b**) (**c**)

Figure 6. Wood waste treated by (**a**) mechanical treatment [74], (**b**) chemical treatment [61], and (**c**) hydrothermal treatment [75].

A study by Wan et al. [61] compares these three treatment methods by means of hammermilling (mechanical), steam explosion (hydrothermal), and chemical impregnation (chemical). The most effective breakdown of the particles was observed from the hydrothermal treatment, and the particles showed high pH values and buffer capacities. While this can be expected from the chemically treated wood waste, the reason for the increased values of the particles from the hydrothermal treatment is due to the balance between the hydrolysis of the wood components releasing acids and the hydrolysis of the UF resin releasing a basic solution. This phenomenon is further proven in the study conducted by Fu et al. [76].

3.2.4. Combined Treatments

In most studies, several of these treatment methods are combined to treat the wood waste particles more effectively. The most common combination uses both hydrothermal and mechanical treatments, where the initial wood waste is broken down by hammering, followed by a hot water or steam treatment [71,75]. A study carried out to treat recycled particleboards, using water impregnation before hydrothermal treatment, reports the optimum recovery parameters to be 45% water retention and a 150 °C temperature for 10 min [77]. Lower temperatures and higher water retention rates show undesirable formaldehyde content values, as well as an adverse effect on the IB values. Similarly, some studies that use combined treatment methods are shown in Table 2.

Table 2. Combined treatment types used for wood waste for wood panel manufacturing.

Treatment Name	Treatment Method			Description of Treatment Method	Temperature	Duration (min)	Manufactured Wood Panel	Reference(s)
	Mechanical	Chemical	Hydrothermal					
Thermohydrolytic disintegration	✓		✓	Steam-treated and broken down using centrifugal device	95 °C	20–30	MDF	[71]
					100–160 °C	20–100	-	[76]
					150–190 °C	10–20	MDF	[75,78]
					105–160 °C	150	MDF	[79]
Hot water treatment and disintegration	✓		✓	Particles cooked in hot water and disintegrated using a drum chipper	100 °C	30–180	Particleboard	[55,80]
						60	MDF	[81]
Chemo-thermo-mechanical method	✓	✓	✓	Crushing and impregnating waste particles with aqueous chemical solution and heating	100–120 °C	-	-	[82]

Apart from the three methods of wood waste treatment, new recycling processes have been introduced in recent years that have focussed on retrieving the wood particles more efficiently while retaining quality. Some of these methods include low-temperature pyrolysis [83–85], an electric method [86], and hot-pressing wood particles as a treatment process [87].

3.3. Chipping and Drying

Once the wood waste is treated, the particles are broken down into smaller sizes if necessary, usually utilizing a defibrator [59,88]. The particles are then sieved, sorted, and dried to reach a moisture content (MC) of 2–4%. A low MC of the particles is necessary to ensure that the panels do not delaminate during the hot-pressing procedure. Considering the effect of the different particle size distributions of the recovered wood particles, as well as conducting microscopic and spectroscopic analyses, helps identify the effect of these particles on the final properties of the particleboards and fibreboards manufactured [89].

3.3.1. Particle Size Distribution of Wood Waste

Particle size distribution is an important consideration in manufacturing wood panels from wood waste. According to Niemz and Sandberg [90], particle geometry has a direct influence on the mat density, where a longer length of particles tends to result in lower density mats, while thicker and wider particles create higher density mats. For particleboards, the particles can be divided into four groups, namely, large wood chips (4–10 mm), medium particles (2–1.25 mm), fine particles (0.63–0.32 mm), and dust (less than 0.32 mm) [88].

Particle geometry is one of the main parameters that affect the properties of the final board [91]. Particles that are thinner and longer, which have a higher aspect ratio (the ratio between the particle length and width), have larger surface areas, giving better bonding but requiring more adhesive per unit of particle surface area [91]. In particleboards made from wood waste chips, the use of finer particles has shown an increase in some of the physical and mechanical properties of the panels compared to the use of coarser particles [92]. It has been observed that the panels with fine particles have lower thickness swelling (TS) and higher Modulus of Rupture (MOR) and internal bond (IB) values, compared to those made from coarse particles. In particular, for layered particleboards, the use of finer wood waste particles, such as sawdust for the core and larger chips for the surface layers, can improve the mechanical properties of the panel [93]. In this study, a higher sawdust percentage in the core layer showed improved thickness swelling (TS) and higher Modulus of Rupture (MOR) and internal bond (IB) values.

For the wood fibre classification by sieve analysis for fibreboard production, the equivalent results are obtained and they confirm that virgin fibres are coarser than recycled fibres [81,94]. The treated particles have shorter average lengths and widths, and the quantity of finer particles will increase (Figure 7). As the particles of wood fibre are comparatively finer than wood chips, a more complex method than sieve analysis is required to precisely measure the lengths and determine the size distribution. Several studies incorporate the use of a fibre classifier machine for this purpose [61].

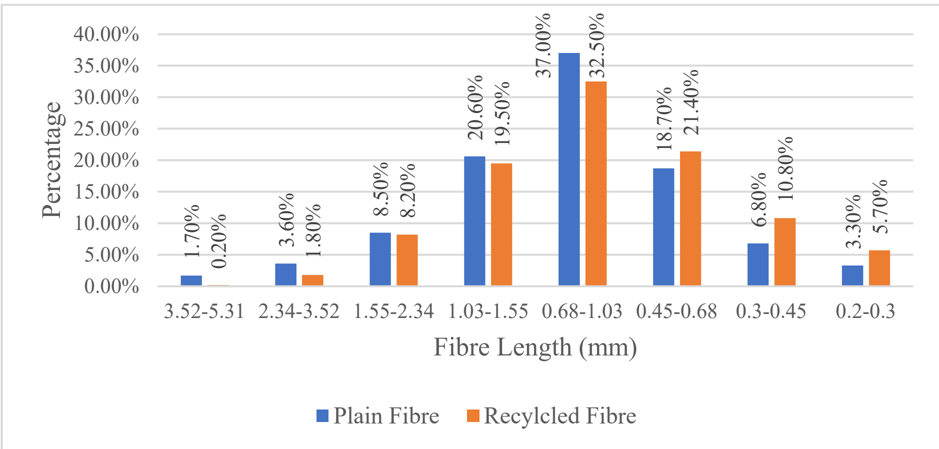


Figure 7. Length distribution of recycled fibre (RF) and plain fibre (PF) [81].

The percentage of this particle size reduction depends on the original condition of the wood waste, as well as the treatment method used. For example, the wood fibres treated by cooking in water and using a pulp beater show an average length reduction of 12% compared to natural fibres, while using more impactful treatment methods, such as steam explosion, can bring this value up to a 30% reduction [61,81]. Thus, due to this reduction in fibre lengths, a decrease in the mechanical properties of the manufactured panels also reflects the same percentage decrease.

3.3.2. Microscopic and Spectroscopic Analyses of Wood Waste Particles

Microscopic and spectroscopic analyses of wood particles are often conducted before the formation of the panels to get a better understanding of their composition and characteristics. While treatment methods can remove contaminants from the wood particles to some extent, the remaining pollutants need to be identified and either removed or mitigated through specialized processes or modifications to ensure the quality and performance of the final wood-based panels [95]. Several methods, including X-ray Fluorescence Spectroscopy (XRF), Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy

(SEM-EDS), and Confocal Laser Scanning Microscopy (CLSM), can be used to identify the remaining contaminates in the wood particles and as tools to sort these particles [44]. The authors show that this can be an especially useful tool to determine the efficiency of the treatment methods. The comparison of the resin (in red) remaining in the wood fibre before and after a decontamination treatment using a CLSM analysis is shown in Figure 8.

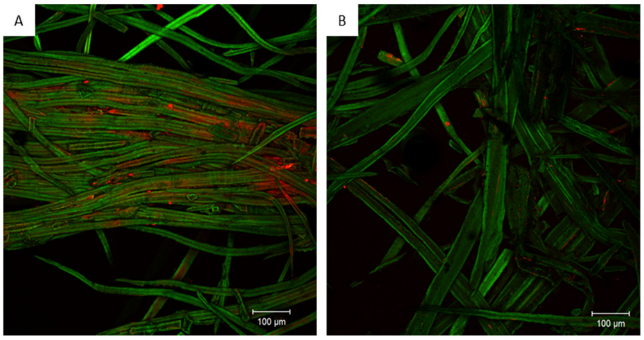


Figure 8. Contaminant identification of wood waste fibres (**A**) before pre-treatment, and (**B**) after pre-treatment using Confocal Laser Scanning Microscopy (CLSM) [44].

Fourier transform infrared spectroscopy (FTIR) is another analysis method that is often used to detect the structural composition of the wood particles and the chemical changes due to varied factors. By plotting the absorption spectrum of the wood particle sample, it is possible to identify the different functional groups and chemical bonds present in the sample. The wavenumber (υ) is expressed in reciprocal centimetres (cm^{-1}) and the range used for the analysis of the wood particles using FTIR is usually in the range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1} [96]. The categorisation of the wavenumbers of the wood to its corresponding compound is available in the literature [97,98] and often the major changes in the wood spectra are observed in the "fingerprint region" (1800–850 cm^{-1}).

When comparing virgin fibres and recycled fibres using the FTIR analysis, a study by Lubis et al. [94] found that the recycled fibres show significant peaks in the range of 1500–1640 cm^{-1}, which is attributed to the primary and secondary amides in the UF resins, even after going through treatment processes. Another observation was that, compared to virgin fibres, recycled fibres show broader peaks for inter-molecular bonds, particularly C-O-C and O-H bonds from cellulose and hemicellulose, indicating that these bonds are altered during the recycling process. Similar results were observed in other studies [79,99] concluding that the changes to these bonds can cause differences in the mechanical and physical properties of the manufactured boards. In particular, the chemical changes in the recycled wood particles lead to reduced mechanical properties but better dimensional stability and lower wettability [79].

3.4. Blending with Resin and Adhesives

In composite wood panel production, various polymer resins are used to achieve the desired structural integrity and moisture resistance. The most common types of resins used to bond these wood particles include urea–formaldehyde (UF), melamine–urea–formaldehyde (MUF), phenol–formaldehyde (PF), and isocyanate. These resins fall under the category of thermosetting resins, which form a rigid, three-dimensional network structure that is irreversible when cured. Thermoplastic adhesives, which, on the other hand, are reversible when cured, are available, but the consumption of these are very limited due to their lower adhesive strength and higher cost [100]. The most-used UF resins are often preferred due to their lower cost, lighter colour, and ability to produce dimensionally uniform and smooth-surfaced panels [3]. MUF, on the other hand, is often used for exterior-grade wood panels and laminates due to its water resistant properties. The chemical structures of these resins are given in Figure 9. The resins consist of methylene bridges (-CH_2-), which create a strong, stable, and cross-linked polymer network, making the resins resistant to environmental factors. For a thorough review of the different types of polymer resins used for wood-based composite panels, readers are recommended to refer to [100,101].

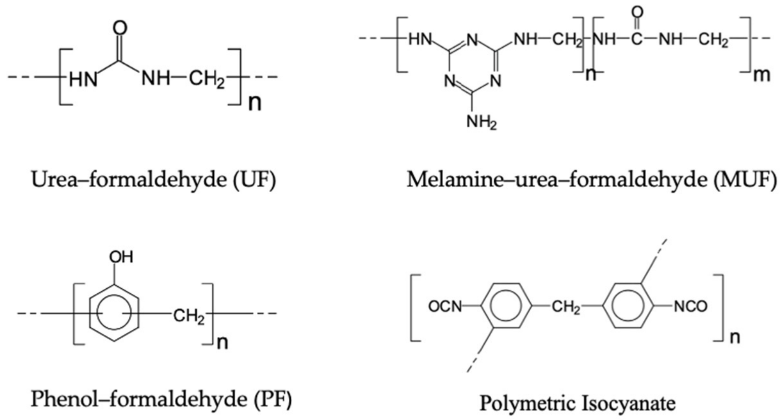


Figure 9. Chemical structures of common types of resins used for composite panels from wood waste [101].

Similar to the conventional manufacturing of composite wood panels, the most commonly used adhesive for waste wood panels is UF, where generally 8–12% of the resin is added based on the dry weight of the wood particles, along with a small percentage of additives, including ammonium sulphate hardener and paraffin emulsion [58,80]. However, there have been several studies conducted that use PF, MUF, and isocyanate to create composite wood panels from wood waste showing favourable outcomes. Notably, the study by Czarnecki et al. [102] used PF resin to produce particleboards from recycled water-resistant boards and concluded that adding recycled particles to the core in amounts as high as 60% gives more favourable outcomes in terms of mechanical and physical properties compared to using UF resin. However, there is a lack of detailed comparative studies in the literature on the effect of different polymer resins on the performance of composite wood panels.

In most instances, the resin is applied to the wood particles using a rotating drum or blender to distribute the resin uniformly. The resin acts as a binding agent, forming a matrix that holds the wood particles together once cured. With the use of wood waste, several other resin application methods have been explored, including spray coating, dipping, and vacuum impregnation, to improve the resin penetration into irregularly shaped wood particles or flakes [103]. One notable study by Yang et al. [104] studies the properties of particleboard made from recycled wood chips immersed in a water-soluble PF resin. It was noted in this study that, with the increase in the concentration of the PF solution, the absorption of the chips increases linearly, and higher concentrations result in better physical and mechanical properties of the boards. These results coincide with several other pieces of research, where higher amounts of adhesives have led to better results in terms of thickness swelling [92,105].

Furthermore, the choice of resin can greatly influence the thermal stability, water resistance, and durability of the final composite, with thermosetting resins like PF and MUF offering superior performance in load-bearing applications, while thermoplastics provide more flexibility and recyclability. Additionally, the curing process—whether through heat, pressure, or catalysis—also plays a critical role in determining the final properties of the composite, ensuring that the resin fully hardens and forms a robust bond between the wood particles.

When creating particleboards and fibreboards from wood waste, one main issue that arises is the lower bonding between the recycled particles and the resin. Due to the changed geometry and larger areas of the wood particles, there is a lower contact area between the particles and the resin [106]. This causes a reduction in the mechanical properties of the final wood panels.

However, the presence of cured resin macromolecules in the wood waste helps prevent moisture absorption by acting as a protective barrier, thus reducing the thickness swelling and water absorption, while increasing the dimensional stability of the panels.

Most studies that tested different percentages of wood waste incorporated into the material mixtures reported better hygroscopic properties of the panels [107]. This improvement can be seen by examining the thickness swelling and water absorption after 2 h and 24 h immersion in water of the manufactured panels. Further, it was observed that by completely replacing natural wood with wood waste particles, it is possible to improve these properties by a significant amount [108]. The literature on the use of several types of resin and adhesives for wood panel production is extensive, and several comprehensive reviews have been conducted [33,109–111].

Isocyanate resins have also become a popular choice of synthetic adhesive for wood-based panel production, generally used in the form of polymetric methylene diphenyl diisocyanate (pMDI). The ability of pMDI to create a moisture-resistant, high-strength, and low-swelling mechanical bond makes it an ideal binder in the wood panel manufacturing industry [112]. A study conducted by Papadopoulos [113] comparing UF and pMDI shows that the MDI resin has better bonding strength and higher dimensional stability when used in particleboard. However, the biggest reason for the preference for isocyanate resins over more traditional formaldehyde resins is the absence of formaldehyde emissions from the manufactured panels, making them an eco-friendlier alternative [114].

As an alternative to synthetic adhesives, environmentally friendly bio-based wood adhesives have also become a field of interest in recent years. These bio-based adhesives are developed using materials from natural, non-mineral sources and include compounds such as tannin, soy, lignin, and starch [115]. Lignin and tannins are both natural compounds found in plant materials, and they can be utilised as natural adhesives in wood panel production. By incorporating these natural components into the adhesive mixture, it is possible to reduce the free formaldehyde present while maintaining a good IB strength in the panels [116]. The general flow of the adhesive production process from lignin and tannin is illustrated in Figure 10.

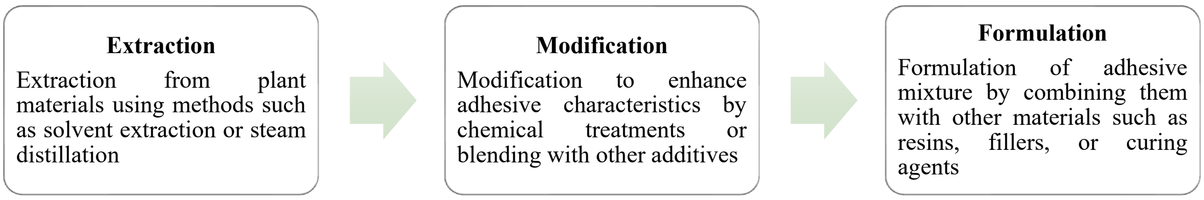


Figure 10. The general flow of the adhesive production process from lignin and tannin.

The utilisation of lignin and tannin as natural adhesives in wood panel production offers several advantages. These include a reduced reliance on the synthetic adhesives derived from fossil fuels, a lower environmental impact, the improved recyclability of the wood products, and potentially lower manufacturing costs [117]. However, while they are available in large quantities for a lower cost, they have shown low reactivity and need to be degraded and polymerized to be used as adhesives, adding an extra cost component to the panel manufacturing process [118].

With the development of the use of wood waste particles for particleboard and fibreboard manufacturing, the use of natural adhesives such as lignin and tannins, which can be extracted from the wood waste itself instead of using synthetic resins, is an area of research that has not been convincingly explored and can be developed into manufacturing more environmentally friendly wood-based panels.

3.5. Mat Forming and Pressing

Once the particles are blended with the resin, they are laid out uniformly across the specified length and width. The forming of these wood panels can be as a single layer or multiple layers. When comparing heterogenous (multi-layer) and homogenous (single-layer) wood panels, heterogenous wood panels show a significant improvement in physical and mechanical properties, compared to the latter [119].

Once the mat is formed, the next step is the pressing. Some studies have opted to pre-press the mat before subjecting it to hot-pressing [99,107,108]. By initially cold-pressing the mat under approximately 1 MPa of pressure, the board can be made more compact and made to release the initial air in the mat, so that, during the hot-pressing stage, there will not be any significant air rush that can damage the panel. Pre-pressing is also useful in the production of batch-formed or continuous-formed mats to reduce the mat height and help consolidate the mat before pressing [1]. Hot-pressing plays a critical part in the wood panel manufacturing process. The heat and pressure during this process cause the adhesive to cure and bond the wood particles together, creating a strong and dense panel. The temperature, pressure, and pressing time for the hot press varies according to the panel type, thickness, and heat transfer efficiency [120].

By using wood waste in the wood panel manufacturing process, the energy used for the hot-pressing is reduced compared to traditional manufacturing processes. This is due to two reasons, with the first being the shorter pressing time required. Due to the higher bulk density of the recovered particles, the mat structure is less compact, and steam can be easily applied to achieve the final mat in a shorter duration [88,121]. The other reason is the use of lower temperatures. It has been observed that by increasing the hot press temperature, there is a considerable decrease in the flexural capacities of the wood panels, due to the breakdown of the crystalline arrangement of the cellulosic chain [122]. One notable study by Iwakiri et al. [123] evaluates the effect of three different pressing temperatures and pressing times to manufacture particleboards and concludes that, while the increase in pressing time did not significantly affect the physical properties of the panels, the mechanical properties were improved. In contrast, a decrease in the properties was observed with the use of higher temperatures. The type of resin used can also affect the pressing temperature.

The use of water-based resins tends to result in a better flow of key lignocellulosic particles at lower temperatures, compared to pressing with waterless binders at higher temperatures [124]. Therefore, this study recommends using a lower temperature closer to 180 °C, and this observation has been extended in recent studies for wood panels made from wood waste, as summarised in Table 3.

Table 3. Hot press parameters adopted for wood panels produced from wood waste.

Pressing Temperature (°C)	Max Pressure (MPa)	Pressing Time (min)	References
Board Type: Particleboard (12–19 mm thickness)			
140–170	4	8–10	[87,125,126]
180	2.5–3	5–8	[58,88,102,104]
190–240	5.75	2.5–4	[108,127]
Board Type: MDF (12–19 mm thickness)			
170–180	2–3	3–5	[80,81,128]
190–200	2.5–5	4–10	[71,129,130]

Once the panels are pressed, they are cured at a temperature of 20 ± 2 °C with a relative humidity of 65 ± 3% for 7 days [71,81].

4. Standards and Suitability Assessment of Manufactured Panels

4.1. Standards and Specifications of Wood-Based Panels from Wood Waste

Currently, there are limited specific standards or guidelines available specifically for wood panels made from wood waste. Most studies adopt conventional wood panel standards as testing methods to determine the required values for physical and mechanical properties. A list of available performance standards for wood panels in the USA is summarised by the U.S. Department of Agriculture [131]. Apart from these standards, the most common standard used for the performance measurement of wood panels is the European Standards. Particleboard specifications are mainly given in EN 312: 2003 [132] and fibreboard specifications in EN 622: 2009 and EN 316: 2009 [133,134]. Most countries have adopted these standards, along with the standards issued by the International Organization for Standardization (ISO), which includes ISO 16895: 2016 for fibreboards and ISO 16893: 2016 for particleboards [135,136], developing country-specific standards to assess the properties of manufactured panels. Some examples of these standards include AS/NZS 1859: 2014 and AS/NZS 4266: 2017 for Australia and New Zealand [137,138] and JIS A 5905: 2014 [139,140] for Japan.

This section will investigate how the properties of wood waste panels from different studies perform in terms of the requirements given by the standards available for conventional wood panels, focusing on particleboards and fibreboards. The testing methods used to determine the physical and mechanical properties of wood-based panels from wood waste are also adopted from those specified for fresh wood panels. According to Niemz et al. [53], the main properties of wood and wood-based materials can be described as biological, chemical, and physical–mechanical. In particular, physical and mechanical properties are used to assess the suitability of the manufactured panels.

4.2. Physical Properties

The main physical properties considered are the density, water absorption, and thickness swelling of the final manufactured boards. The water absorption and thickness swelling are tested after both 2 h and 24 h. According to EN 317: 2002, the thickness swelling of the board can be determined using Equation (1).

$$G_t = \frac{t_2 - t_1}{t_1} \times 100, \tag{1}$$

where t_1 is the thickness of the test piece before immersion (in mm) and t_2 is the thickness of the test piece after immersion (in mm).

Similarly, the density and the water absorption of the panel can be found according to the specification given in EN 323: 1993 and EN322: 1993, respectively [141,142]. Additionally, the formaldehyde content of the produced board can be tested according to the relevant standards, and this can be especially important in the case of wood waste panels, as the formaldehyde emission is usually found to decrease drastically when using recycled wood waste as a key ingredient in the manufacturing process [102,143].

4.3. Mechanical Properties

Concerning the mechanical properties of the manufactured wood panels, the main properties tested are the Modulus of Elasticity (MOE), Modulus of Rupture (MOR) and internal bond (IB). The MOE and MOR are often tested according to the specifications given in EN310: 2002 and the IB as per EN 319: 1993 [144,145], which once again are designed for the testing of general wood panels. In addition to the core mechanical properties, several other factors play a pivotal role in determining the suitability of wood waste panels for specific applications. While there are a few studies that have been conducted to assess wood waste panels on screw withdrawal strength (also known as pullout strength) [94,125], which is the resistance offered to the withdrawal or removal of a screw or fastener, and on thermal and acoustic properties [104], there is very limited research concerning these.

Moreover, it is noted that there is very limited research that has been conducted on the long-term durability of composite wood waste panels. A decay resistance test of 16 weeks was conducted on particleboards fabricated with wood waste particles by Iždinský et al. [108], which showed a slight improvement of decay resistance, which, it was concluded, was due to the presence of some portion of cured UF resin on the surface of the wood waste particles. However, apart from this study, no proper test has been carried out in terms of long-term durability. In order to understand the full potential of these panels, it is necessary to evaluate the physical and mechanical properties under various environmental and mechanical conditions over time. This includes tests such as cycling loading tests and creep tests, as well as long-term thermal and chemical resistance tests, which have been conducted for natural wood panels [146–148].

4.4. Incorporation of Different Percentages of Wood Waste

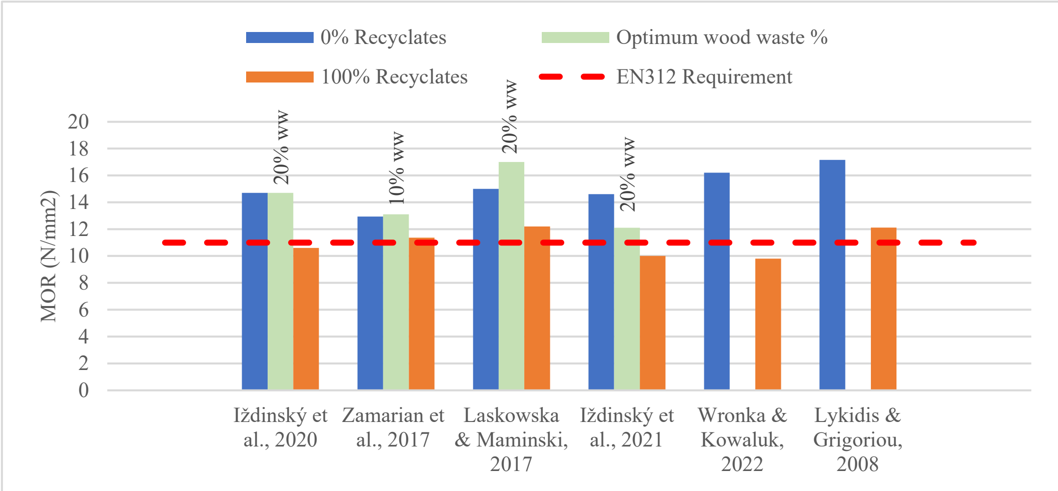
Having different percentages of wood waste in the material mix affects the physical and mechanical properties of the final wood panels, and this has been tested by several researchers over the years. By developing linear correlations between the percentage of wood waste against different properties, Iždinský et al. [108] were able to identify that the inclusion of wood waste improves the dimensional stability of the particleboards, with better thickness swelling (TS) and water absorption (WA) values. The biggest improvement in the physical properties was observed for the particleboards manufactured using a wood waste percentage of 20%. This is consistent with other studies by Zamarian et al. [125], Czarnecki et al. [102], and Laskowska and Mamiński [88], where the biggest improvements in the TS and WA of the boards were seen when the wood waste percentage was in the range of 10–30%. The reason for this improved dimensional stability is said to be due to the presence of cured resin solids in the wood waste. The resin forms a barrier between the wood particles and moisture, which reduces the moisture absorption capacity of the particleboard, as per Roffael et al. [130].

However, while there is an improvement in the physical properties, particleboards made from wood waste often result in weaker final products in terms of mechanical properties. Figure 11 summarises the MOR, MOE, and IB values of particleboard made from wood waste from six different studies and how these values compare against the requirements given by EN 312: 2003 for the P2 type general purpose particleboards in dry conditions [132]. The summary of the recycled wood material used and the production parameters are summarized in Table 4. The first four studies have considered different percentages of wood waste up to 100%, and the last two studies have completely replaced fresh wood particles with recycled ones and compared the mechanical properties of the particleboard with the original board.

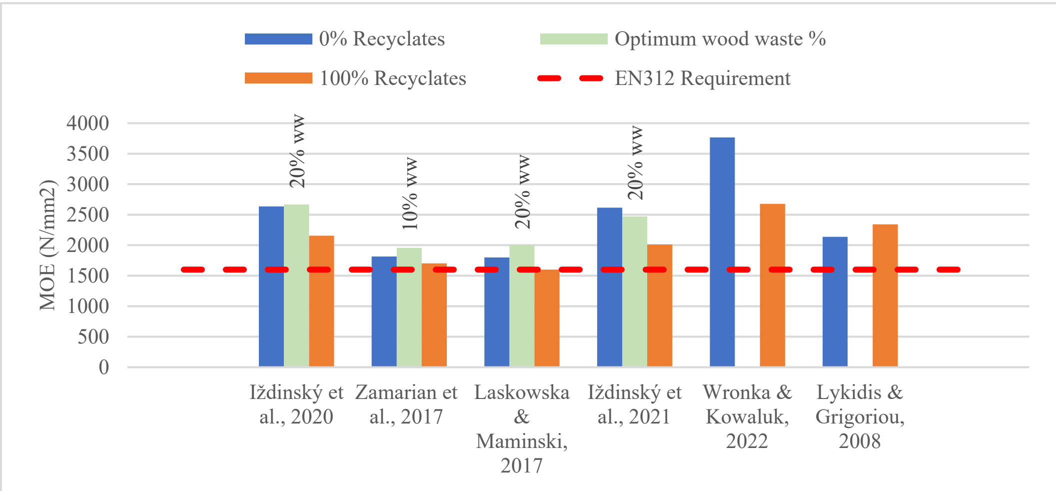
The following have been observed from the abovementioned studies:

- The MOR and MOE of particleboards made using a small percentage of wood waste have a slight improvement compared to the original boards, except for the study by Iždinský et al. [99]. This deviation can be explained by the source of wood waste for this study: recycled wood pallets, which the authors attribute to having a portion of deteriorated and polluted wood.
- The internal bonding (IB) of the particleboards is reduced with the increase in the wood waste % in the material mix, except for the study by Zamarian et al. [125], where the inclusion of wood waste improved the IB.
- All particleboards that completely replaced the natural wood particles with recycled wood have significantly lower mechanical properties than the boards without recycled wood, some having values lower than the requirements set by EN 312.
- For the two studies that had not considered the use of a lower percentage of wood waste in the particleboard mixtures [107,127] a significant jump in the mechanical properties was apparent.

Therefore, based on these studies, completely replacing the fresh wood particles with wood waste has an adverse effect on the mechanical properties of particleboards and cannot be recommended. Using a lower percentage of wood waste (10–30%) is more suitable as it has a lower impact on the performance of the panel and could even improve it. This is consistent with the recommendations given by Nguyen et al. [32] and is also consistent with the results for fibreboard made from wood waste [94,143].



(a)



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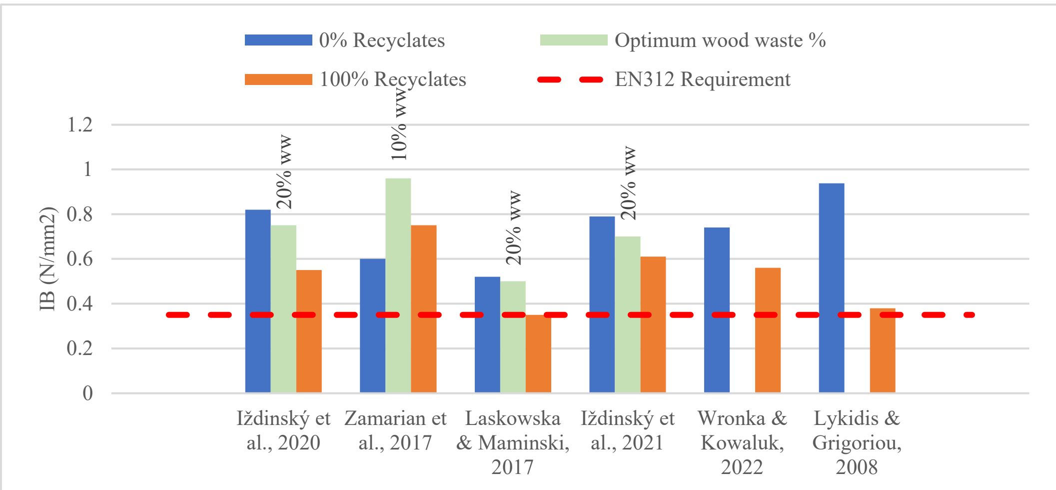

(c)

Figure 11. (a) MOR, (b) MOE, and (c) IB values of particleboard made from wood waste from six different studies and how these values compare to the requirements given by EN 312 [88,99,107,108,125,127].

Table 4. Summary of recycled material and production parameters used for the studies to produce particleboard.

Reference	Recycled Material Used	Pre-Treatment	Particle Size	MC of Particles	Adhesive	Density (kg/m^3)	Thickness of Panel (mm)	Hot-Pressing Parameters	Testing Standards Used
Iždinský et al. [108]	MDF boards, PBs, old furniture, and faulty PBs	Mechanical	Core layer—0.25 to 4.0 mm, surface layers from 0.125 to 1.0 mm	2% for core layer, 4% for surface layers	UF 11% for surface layer and 7% for core layer	650	16	240 °C, 5.75 MPa, 8 s/mm speed	EN 323, EN 322, EN 317, STN 490164
Zamarian et al. [125]	From discarded furniture	Electromagnet for metal removing	-	3%	UF resin 10% +1% paraffin emulsion	700	13	140 °C, 4 MPa, for 10 min	EN 323, EN 317, EN 310, EN 319, NBR 14810-3
Laskowska and Mamiński [88]	Plywood waste	Mechanical	Sieving using 10, 14, 25, and 38 mm screens	-	UF/PF resin—2% face, 10% core, and 1% paraffin emulsion	650	16	180 °C, 3 MPa, for 5 min	EN 323, EN 317, EN 310, EN 319
Iždinský et al. [99]	Recycled spruce pallets	Mechanical	Core layer—0.25 to 4.0 mm, surface layers from 0.125 to 1.0 mm	2% for core layer, 4% for surface layers	UF 11% for surface layer and 7% for core layer	650	16	240 °C, 5.75 MPa, 8 s/mm speed	EN 323, EN 322, EN 317, STN 490164
Wronka and Kowaluk [107]	Recycled particleboard	-	Sieving using 8, 4, 2, 1, 0.5, and 0.25 mm sieves	3%	UF resin +1% paraffin emulsion	680	16	180 °C, 20 s/mm speed, 2.5 MPa	EN 323, EN 317, EN 310, EN 319
Lykidis and Grigoriou [127]	Recovered particleboard	Hydrothermal treatment	Particle fractions <1.5 mm were removed	-	UF 7% +2% ammonium chloride hardener	650	12	85 °C for 240 s	EN 323, EN 317, EN 310, EN 319

It can be concluded that, while the particleboards and fibreboards made from wood waste show improved hygroscopic properties and higher dimensional stability, due to the decrease in the mechanical properties, especially when manufactured using 100% wood waste as raw material, these panels are less suitable for commercial use as structural panels. It is recommended to carry out further studies in improving the mechanical properties and developing proper standards and guidelines for the use of wood waste in manufacturing structural panels. As the study by Mirski et al. [93] recommends, at this stage of study it is recommended to use these wood waste panel boards as non-structural elements in the construction industry and as interior decorations.

However, it is important to note that this percentage of optimum wood waste for wood-based panel production depends on a variety of factors. While the studies mentioned in this section's comparison are particleboard with a 12–20 mm thickness range using UF and/or PF as an adhesive, the optimum percentage of waste wood to be incorporated will vary according to the panel characteristics and the type of resin used. Several other factors including the reliance and availability of wood waste and other environmental, economic, and regulatory compliances affect the optimum wood waste suitability and availability to produce wood-based panels. Even though there is a high consumption of wood in countries in Europe and China [149,150], for the incorporation of wood waste to be maximized in a global context, a comprehensive analysis must be carried out to determine the availability and suitable wood waste percentage for wood-based panel production in different contexts and regions.

5. Repeated Recycling of Wood Waste Panels

Another important consideration when using wood waste in wood panel production is the suitability of repeatedly reusing wood waste for wood panels in a closed-loop circular process. Besserer et al. [44] explain that this "cascading" use of wood waste ultimately makes the carbon storage of the material last longer and is presented as a sustainable solution. Cascading represents a fundamental concept aimed at enhancing the efficiency of wood utilisation. This principle entails the sequential and hierarchical optimisation of bio-resources, prioritising reuse, recycling, and energy recovery before the final disposal [151]. An exemplary cascading use of timber is depicted in Figure 12. The term 'single-stage cascade' refers to the initial product use phase, wherein end-of-life products are directed towards energy generation. On the other hand, 'multi-stage cascade' denotes a process where, after the initial product phase, wood is further processed for additional material utilization or for the creation of other bio-based products. The objective here is to maximize the number of cascade stages.

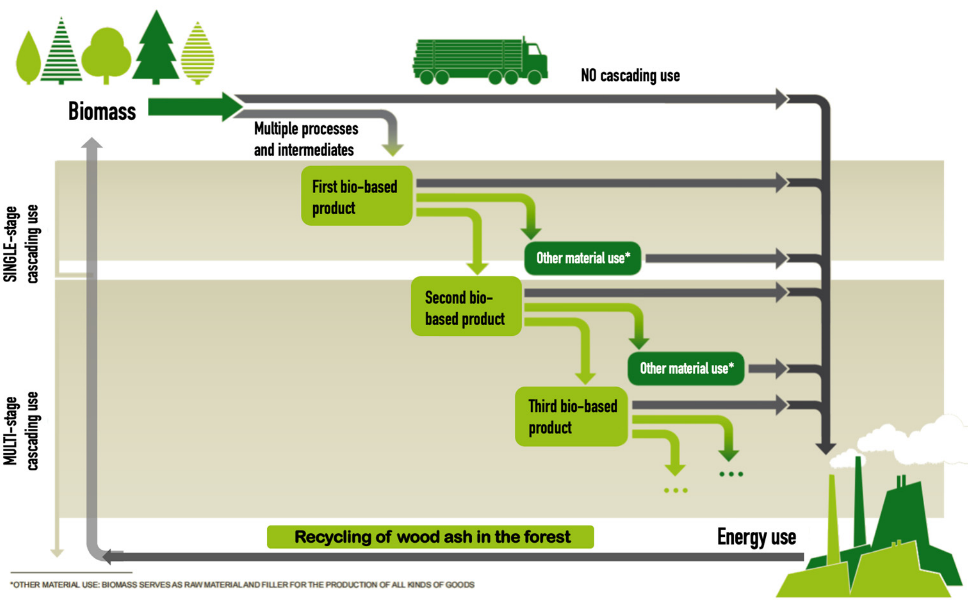

Figure 12. Ideal cascading of wood resources [152].

Across the globe, countries actively promote the cascading use of resources through various policies, initiatives, and incentives. For instance, the European Union (EU) unveiled its Circular Economy Action Plan in 2020, which underscores the significance of sustainable practices in forestry and wood utilisation [153]. Within this framework, Italy has made notable strides in wooden packaging recycling, achieving a recycling rate of 64%, significantly surpassing the EU average target of 30% by 2030 [154]. Remarkably, as of 2020, approximately 95% of wood was recycled to produce wood panels for furniture, facilitating an impressive carbon emission reduction of 2 million tons and creating over 11,000 jobs within the forestry and wood furniture supply chain [155].

5.1. Life Cycle Assessment (LCA) of Repeated Recycling

Life cycle assessment (LCA) stands as the prevailing method used to quantitatively evaluate the environmental ramifications of various processes, providing valuable insights into the potential environmental benefits associated with the cascading wood-based resource utilisation [156]. A summary of several LCA studies investigating the environmental impacts of cascading wood utilisation practices is presented in Table 5. The results of these studies demonstrate that implementing cascading strategies, such as recycling wood into filler or reusing it for particleboard production, can yield considerable reductions in Global Warming Potential (GWP) and carbon emissions [52,157–159]. Furthermore, investigations concerning other environmental impact categories reveal that cascading wood products leads to a substantial decrease in land occupation indicators, primarily due to reduced primary resource extraction [156,160]. Additionally, Taskhiri et al. [161] reveal that the reproduction of wood waste to produce particleboard and OSB can achieve a reduction of up to 24% in life cycle costs.

Notwithstanding the considerable number of studies underscoring the carbon and resource-saving benefits associated with cascading wood utilisation, it is crucial to acknowledge that other environmental impacts have been overlooked [161]. For instance, the recycling processes of wood necessitate the utilisation of chemicals and energy, leading to a potential shift in the environmental burden towards fossil fuel consumption and ozone depletion [162]. Moreover, the widespread promotion of cascading practices encounters significant challenges in the absence of inducements and legislative regulations [163]. Therefore, future research should encompass a broader assessment of other impact categories, along with a comprehensive examination of the economic and social aspects within the life cycle context.

Furthermore, although the concept of repeated recycling is an ideal scenario with no end-of-life disposal, it is important to consider the impact of the end-of-life disposal of these composite wood waste panels when conducting the LCA. Particularly due to the polymer resins used in the production, these panels can pose significant challenges at the end of their life cycle due to their complex composition. Effective disposal strategies must consider recycling, incineration, and landfilling, each with distinct environmental impacts [164].

Table 5. A summary of studies on the environmental impacts of cascading wood utilisation practices.

Authors	Highlights	Environmental Impacts
Kim et al. [157]	Compared the carbon emission of recycling 1 ton of wood pellets with landfill disposal.	• Recycling wood pellets can result in −163 kg CO_2-eq benefits than landfilling. • Compared to production pellets from primary wood, using recycled wood pellets can reduce GWP by 4.8 kg CO_2-eq.
Kim and Song [158]	Compared the carbon emission from 1 ton of particleboard production and energy production between fresh wood and recycled wood.	• Particleboard from recycled wood has 428 kg less CO_2-eq than from fresh wood. • Energy production from wood waste generates 154 kg CO_2-eq less than the combined heat and power process.

Table 5. *Cont.*

Authors	Highlights	Environmental Impacts
Wang et al. [159]	• Compared the environment impacts of recycling timber into filler and incineration for heat production. • Calculated emissions from replacing tubular particleboard and LVL of a 2007 × 850 × 45 mm wood door with recycled residues.	• Processing a recycled wood panel as filler has a higher environmental impact than incineration. • Recycling wood residues can save approximately 7.46 kg CO_2 eq GWP and 143.77 MJ of primary energy deletion for a wooden door life cycle.
Risse et al. [165]	• LCA on recycling 1 ton of solid wood from construction into glued laminated timber. • Compared the environmental and economic performance of reusing recovered solid wood and incineration.	• Recycling reduces 29% of entire environmental impact and 32% of life cycle cost, compared to incineration for energy. • The wood cascading operational process has minor relevance with the environmental and economic performance of the system, while technologies are key drivers.
Niu et al. [166]	Case study of reusing wood from a timber hall in Finland.	• GWP100 reduces about 30% by applying recovered timber. • Reduction in all impact categories, such as marine eutrophication and ozone depletion.
Liang et al. [160]	LCA on a wooden building in the northwestern U.S. and evaluation of the recycling and reuse scenario of mass timber and CLT panels in buildings.	• Recycling mass timber can generate a 364 kg CO_2 eq/m^2 carbon credit. • Reusing 52.5% CLT panels can further reduce GHG emissions by 12% compared to concrete building.
Höglmeier et al. [156]	Estimated the overall environmental impact of wood cascade in Germany by combining the material flow model of current wood application and LCA.	• Cascading contributes a little to the overall system, namely, wood panel production. • Cascading can save up to 14% of annual wood supply in the study area.
Höglmeier et al. [21]	Conducted full LCA of 1 metric ton of cascading wood waste panel and primary wood panel.	• Cascading use of wood waste has a lower environmental burden in all categories than the use of primary wood. • Cascading leads to a 10% lower GWP and near 100% lower land occupation than using primary wood.

5.2. Impact on Physical and Mechanical Properties

It can be reasonably expected that the physical and mechanical properties of the wood panels would reduce with every recycling cycle. However, it was found that, although the repeated recycling process degrades the wood waste particle sizes and results in panels with low flexural capacity, it can increase the internal bond strength of the panel having higher WA and TS values with each cycle [71]. The authors explain that this can be due to the larger surface area helping with greater adhesion, as well as the increasing amount of adhesive remaining after each cycle. It was also observed that, with each recycling cycle, the formaldehyde emission is significantly lower compared to the initial panel. Similar studies show similar results where repeated recycling increases the physical properties of the panel boards [107].

A 20.7% increase was seen in the MOE in the second-generation particleboard, due to the higher elasticity of the chips after the hydrothermal treatment [80]. Further, the fibres from the second-generation particleboards used in this study have been used to produce MDF and have produced satisfactory results but only marginally above the required values for general purpose use. Therefore, it was recommended to use 10–30% of wood waste fibres for the manufacturing process rather than using 100% of recycled wood fibres. This is further supported by the study of Roffael et al. [130], which recommends the use of 30% of wood waste fibres for MDF manufacturing.

6. Conclusions

In conclusion, this paper sheds light on the promising potential of wood-based panels derived from wood waste in contributing to sustainable and eco-friendly building materials. By following established standards for wood waste as a raw material and optimizing the manufacturing processes, these panels can offer a viable alternative to traditional wood panels, thus playing a crucial role in environmental conservation and resource management.

This paper highlights several key findings that underscore the significance of this research:

- **Lack of global standardization for wood waste**: One prominent challenge in this field is the absence of a universally accepted global standard for defining the parameters that determine the suitability of wood waste for panel production. While European countries often refer to German or British guidelines for wood waste classification, there is a clear need for harmonizing global standards to ensure consistency and facilitate international trade and collaboration. In order to do so, it is necessary to consolidate the best practices of existing standards, identify the key parameters to be considered for each wood waste use, and define allowable limitations.
- **Optimal wood waste percentage**: The research suggests that incorporating a small percentage of wood waste in particleboard fabrication with conventional adhesives, typically within the range of 10–30%, can enhance the performance of the panels. This is a crucial finding for manufacturers seeking to balance sustainability with product quality. However, using 100% wood waste as the raw material results in a significant decline in physical and mechanical properties, rendering them unsuitable for structural applications.
- **Hydroscopic and dimensional stability**: Fibreboards and particleboards made from wood waste display improved hydroscopic properties and greater dimensional stability. These characteristics make them attractive for specific applications, especially when combined with controlled proportions of wood waste. Nonetheless, it is essential to acknowledge the trade-off with mechanical properties when considering these panels for commercial use.
- **Repeated recycling potential**: This study also underscores the potential for the repeated recycling of wood panels in a closed-loop process. The "cascading" approach of repeated recycling in wood panel production from wood waste offers promising environmental benefits, as highlighted by various life cycle assessment (LCA) studies, which reveal reductions in carbon emissions and resource use. However, the complex nature of recycling processes also entails challenges, such as increased chemical and energy usage. It is imperative that future research considers a broader range of environmental impacts and integrates economic and social aspects within the life cycle context. While repeated recycling enhances certain panel properties and lowers formaldehyde emissions, the recommendation is to maintain a controlled percentage of wood waste in the manufacturing process rather than relying on 100% recycled content to achieve superior results while adhering to quality standards. Balancing eco-friendliness with material performance remains a key driver for a more sustainable and resource-efficient future in the wood panel industry.

In summary, the research presented in this paper demonstrates the potential possibilities and challenges associated with wood-based composite panels manufactured from wood waste. While the standardization of wood waste as a raw material to produce composite panels remains a crucial area of concern, the benefits of incorporating wood waste in a controlled manner are evident. The lack of established quality standards for wood waste for panel production, as well as the inconsistent material properties and uncertainty about the durability, strength, and other properties of the panels, deter manufacturers from the widespread adoption of this practice.

These panels hold great promise for eco-friendly construction materials and sustainability initiatives. However, manufacturers and researchers must strike a balance between resource conservation and product quality to realize their full potential in the construction industry. This balance, along with continued research and international collaboration, will be instrumental in driving the sustainable evolution of composite panels from wood waste.

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