Challenges and Opportunities in Wood Waste Utilization

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Abstract Wood wastes have the potential to be utilized in the manufacturing of a wide range of products, such as engineered wood products, energy generation, and additive manufacturing. These low-cost biomasses that are only partially exploited have the potential to increase the value that can be added to waste wood products. The objective of this chapter is to address the challenges encountered as well as the opportunities presented by the utilization of wood waste. With the aid of this knowledge, the right approach can be identified for the development of wood waste in the future, which will result in the most long-term benefits for both the environment and the economy. The lack of adaption of more sophisticated technology and the absence of organizations concerned with the potential advantages of making use of such wastes is the source of the problem with wood waste. From this review, it is indicated that wood waste has the potential to be used as a source for the manufacture of a variety of materials; therefore, in order to make the most of the value of wood waste resources, the government should implement efficient guidelines for wood waste management.

1 Overview of the Wood Industry and Its Residue

Back closer to the middle of the 1800s, humans mainly utilized wood for cooking, heating, and lighting. It is a crucial fuel, notably for cooking and heating in several underdeveloped nations, and the main energy source in many nations. The materials that come from logging, the manufacture of wood, and materials that are reused or recycled all fall under the category of wood waste. Wood residues have many advantages, such as fuel in manufacturing facilities where the waste is burnt or used as raw material sources for bioenergy processes. For the pulp and paper industries, wood waste might also be converted into pellets or smaller wooden objects. According to recent studies, wood and wood waste, such as bark, sawdust, wood chips, wood

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scrap, and paper mill byproducts, accounted for around 2.1% of the country's yearly energy consumption [1].

The use of wood, however, can also be a source of some difficulties. For instance, there are several steps in the production of timber goods, from the removal of logs to the creation of the finished goods, all of which have the potential to contaminate the land, the air, and the water. About 50% of wood is transformed into useful items, and the remaining 50% is thrown [2]. Bark, slabs, sawdust, chips, coarse residues, planer shavings, peeler log cores, and end trimmings are a few examples of wood waste produced by significant industrial processes. As a result, efficient use of wood waste significantly reduces environmental repercussions without endangering global forests [2].

Since the evolution of wood technology, it is crucial to understand the properties of wood, its processing method, and the potential utilization of wood waste. One can overcome the wood industry challenges by comprehending the potential applications and finding new opportunities to expand the applications. Therefore, this overview of current challenges and applications of wood residues seems to be one of the most important developments and a novel topic in the vast field of wood technologies. The discussion is also delivered with proper cohesiveness between sub-chapters for better insight.

2 Classification of Wood Waste

Wood waste is a byproduct of wood-related activities, such as from the forest or agriculture sector and mill operations, as well as non-commercial wood resources. Wood waste classification can be clarified as follows [3, 4]:

(1) Material left in the forest in the form of undesired, underutilized species, tops, high stumps, cull logs or bolts, undersized yet damaged trees, shattered material, etc.
(2) The byproducts of mechanically processing wood, including sawdust, shavings, bark, slabs, edgings, trims, faulty pieces, and veneer log cores.
(3) The waste wood products from several industries, including the railroad construction business, individual houses, and the wood packaging, demolition, and building industries.
(4) The extractives, lignin sugars, hemicelluloses, and cellulose that are not recovered in pulp production; the chemicals and gases that are not recovered in the production of charcoal; and the bark that is taken from wood prior to pulping.
(5) The enormous waste is caused by the destruction of wood by fire, insects, and decay in the forest, during storage and use, and by mechanical wear and breakage during service or storage.

Applications for both energy- and non-energy-related uses can be made from this waste wood. The creation of composite boards, surface products, composting, and cement boards are examples of non-energy uses for wood waste, as are the combustion, cogeneration, pellet, and briquette processes.

3 Opportunities for Utilization of Wood Waste

3.1 Biomass for Energy

It is common to practice using logging-related wood debris as a source of biomass for the creation of energy [5]. The stems, branches, and other leftover parts of trees and other plants were utilized to create the woody biomass. Typically, these remnants of forestry operations are burned or left on the ground, which pollutes the environment. The above-ground dry weight of wood in the stem and limbs of live trees with a minimum diameter of 2.5 cm (1 in) was therefore suggested as a method for obtaining woody biomass [6]. Dead plants, foliage, seedlings, and other forest-growing vegetation are removed before harvesting the woody biomass. For instance, most developing countries, such as Nigeria and Indonesia, are actively developing their forest and collecting wood waste to be used as an affordable fuel supply to prevent the higher cost of fossil fuels [7]. Aside from collecting the wood waste from the forest, they also utilize sawdust from sawmills as an investment asset to generate energy. In this context, sawdust has been fabricated into the form of compacted briquettes or pellets by the densifying process [8]. Niño et al. demonstrated that the mechanical properties of the briquettes are highly dependent on the type of wood waste used in the processes, thereby affecting the quality of the energy produced [9]. In addition, the timber industry is also reported to produce sawdust briquettes to generate energy such as heat and electricity. The sawdust briquette from the timber industry successfully supplied large mass quantities, thereby minimizing waste disposal problems.

Other commercial producers of wood products and paper in the United States used the waste from lumber mills and paper mills to generate steam and energy. It is observed that using wood waste has lowered the manufacturing cost instead of purchasing electricity to operate the facilities. In 2020, it was reported that about 2.2 million households in the U.S. utilized wood waste as the primary energy source for space heating fuel [10]. Recent studies demonstrate that wood waste from the bark can also be used as an effective energy generation by gasification. When the synthetic gas from the gasification of wood waste is injected into an internal combustion engine, heat and electricity are produced. In comparison to raw sawdust and wood pellets, it was claimed that bark waste might improve the calorific value in the form of briquettes [11].

Crushed wood waste can be burned in boilers to provide thermal energy in the form of steam or hot water at the interval. In this regard, a device transports the crushed wood waste into a combustion chamber and burns it in a fuel bunker, supplying fuel continuously and regularly [12]. The boilers are typically finished with a solid fuel boiler, ash removal equipment, and chimneys fitted with safety systems and combustion gas purification systems. Another study reported that wood waste in pellet form is much more suitable for combustion using boilers compared to gasification and is increasingly used in many countries [13]. The generated heat energy is sufficient for maintaining industrial enterprises, social objects, and household consumers.

In accordance with the European Commission's waste management guidelines policy, one example of energy recovery is the combustion of wood waste. Since most wood products use resins or adhesives, the wood waste may occasionally contain glues [14]. The combustion emissions will contain one of the following compounds: CO_2, H_2O, SO_2, N_2/NO_2, and O_2 after the full oxidation of all fuel components made up of carbon, hydrogen, sulfur, nitrogen, and oxygen. Contrarily, insufficient air-fuel mixing in the combustion chamber will result in incomplete combustion, which will result in the production of carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDD/F), and polychlorinated biphenyls (PCB) [15]. According to a review by Cesprini et al., several adhesive resins with high nitrogen content may have a negative impact on NO_x production during combustion [16]. The production of NO_x has been significantly impacted by the use of timber biomass and adhesives as solid biofuels. Particularly, the quantities of oxides in the exhaust emissions are increased by the nitrogen-based resins. Since it is a challenge to reduce greenhouse gases emission during waste combustion of wood waste high in carbon, oxygen, and hydrogen, other alternatives to replace traditional adhesives have been developed. In this regard, wood glues were derived from bio-based molecules such as proteins, polysaccharides, lignin, and tannin to ensure reusable wood waste energy. The bio-based adhesives were also reported could overcome the emission of pollutants during combustion.

On the other hand, pollutants mean that certain wood waste has limited potential as reusable biomass. Waste wood burning in combined heat and power (CHP) facilities is becoming a routine practice in many European nations due to the low pre-treatment costs [17]. For instance, the European Union (EU28) produced about 48.46 Mt of wood wastes (including lumber residues), of which 48% were burned with energy recovery, 49% were recycled, 2% were burned, and 1% were dumped [18]. However, it was found that contaminants in the form of deposits and alkali chlorides occurred during the combustion of waste wood. These contaminants raise the possibility of boiler corrosion, slagging, and fouling in biomass CHP plants [19]. Consequently, a small number of studies discovered that using additions such as coal fly ash and halloysite lessens the environmental effects of creating heat and electricity from wood wastes. The additives replace other environmentally damaging energy-producing methods [20]. According to estimates, the use of additives in the combustion of scrap wood might bring potential greenhouse gas emissions down to 2.03 Gt CO_2 eq/yr.

In addition to using wood waste to generate energy, the pyrolysis process may also turn lignocellulosic materials derived from wood into biofuel [21]. Harvested crops and forest trash are gathered, and energy is recovered through thermal breakdown, which results in the breakdown of polymeric chain components without oxygen and the production of char, gaseous chemicals, and oil [22]. A recent study showed that pyrolysis has become a successful method for converting biomass materials derived from wood into liquid fuels. Compared to normal diesel oil, pyrolysis oil often has a higher energy density and is easier to transport.

As was mentioned, it appears that the non-fossil energy market for wood waste is beginning to take off. In conclusion, there are two ways that wood waste can be transformed into biomass: directly through combustion and indirectly through gasification and pyrolysis. These procedures for recovering the materials demonstrated that they may be used as fuels or to provide electrical and thermal energy. Additionally, it is discovered that recycling the urban wood waste produced by trimming bushes and trees in park areas and city streets offers significant potential for energy production [11]. Other waste materials selection and preparation factors, such as particle size and moisture content, would also determine whether the pellets and briquettes produced will provide adequate fuel. Overall, proper wood waste recovery management is critical in raising sustainability requirements.

3.2 Secondary Products for the Construction Industry

Woody biomass from construction and demolition (C&D) is the second-largest component that produces wood waste. In 2018, it was estimated that the C&D component contributes 20–30% of waste; from that, approximately 10 percent of the amount was deposited into landfills. The Construction Materials Recycling Association (CMRA) also reported that 29 million tons of waste were produced and available for recycling after recovery or combustion. It shows that the wood waste from C&D experiences rapid expansion of recycling activities. However, recycling alone might not be enough to maximize wood waste utilization from C&D activities as it might produce a lesser quality product. Therefore, recovery by upcycling into secondary products seems more trustworthy. It allows the substitution of virgin resources as well as minimizes the environmental burdens in the scope of industrial ecology.

The 2030 Agenda for Sustainable Development Goals, which has 169 linked targets, was introduced by the United Nations in 2015. This agenda's primary goal is to offer a solution to the global CO_2 emissions produced by the construction industry as well as other detrimental environmental effects. The need for a better solution that involves building construction using wood waste is essential because construction activities are unavoidable due to the growing human population.

In this context, many researchers have dedicated the use of wood waste to the construction industry by producing particleboard [23, 24]. The high-quality particleboard was obtained from the wood waste formwork and further transformed into cement-bonded particleboard using magnesium oxide cement (MOC). The product was also reported to use a green cementitious binder which exhibits practical and eco-friendly management options for the construction industry [25]. The use of green cement and recycled wood waste has been proven to be superior to that of their conventional and/or virgin counterparts in terms of the life cycle environmental benefits as tested by Life cycle assessment (LCA; ISO 14040-14,044) [26, 27]. The cement-bonded particleboard is well known for its lightweight interior panels, noise barriers, partition walls, and ceilings [28]. It is worth mentioning that the addition of the MOC and wood waste successfully transformed the conventional ordinary Portland cement (OPC) and virgin wood into the production of novel cement-bonded particleboard. On the other hand, rapid-shaping cement-bonded particleboards can be obtained by adding magnesia-phosphate cement (MPC) with timber formwork made from Masson pine [29]. The work presented that MPC particleboards are more advantageous than OPC-based particleboards due to the fast-setting property and short compression time (5 min) [25].

Meanwhile, various types of post-industrial wood waste, including mixed hardwood/softwood powder and bark, can be liquefied and applied as bio-adhesives for particleboards [30]. It was reported that the particleboards produced from recycled wood bonded with urea-formaldehyde resin-modified liquefied wood (LW) approximately 20% qualified the requirements of European standards concerning particleboards. The application of LW in particleboard production significantly increases the use of recycled wood as raw material and expands the exploitation of lignocellulosic biomass [31] reported that a similar liquefied process was utilized on waste pine wood to produce polyurethane foam. The liquefied pine-based polyol was applied to synthesize melamine phosphate modified wood type polyurethane for flame retardant properties. The properties are essential to decreasing fire-related casualties and property loss in construction industries.

Previous studies found that most particleboards were produced by binding the waste wood particles with a thermosetting binder such as formaldehyde, phenol formaldehyde, phenol-resorcinol formaldehyde, and melamine–formaldehyde [31–33]. However, formaldehyde has adverse effects on human health, thereby different solutions to replace it are widely researched, such as employing expanded polystyrene (EPS) waste as a binder [34]. Masri et al. [35] reported that particleboards from date palm and EPS wastes exhibit reliable fiber-matrix interface adhesion with excellent bending strength and stress values of 0.78 GPa and 2.84 MPa [35]. It was also found that particleboards from sawdust and low-density EPS foam waste could form water-resistant particleboards [36]. It is due to the high mobility of EPS resin on the wood surface that forms hydrophobic films within the cells. In addition, formaldehyde-free particleboards were investigated using high-density wood–polyethylene composites from rubberwood flour and sludge [37]. Song et al. [38] also synthesized formaldehyde-free and water-resistant boards with high physicomechanical plywood using polypropylene film as a binder [38]. The results showed that the polypropylene film bonded plywood more than the urea formaldehyde bonded plywood.

Aside from particleboard, wood waste can be mixed into concrete or mortar for building materials. For instance, wood waste aggregation in gypsum or ash wood waste is introduced in mortars or concrete mixture [39–41]. Ramos et al. [42] first reported that wood waste ash was successfully utilized as a pozzolanic partial substitution material for cement, with minimal strength loss. The durability of the product is significant and thus contributes to sustainable construction. It is also found that using the optimal percentage of biochar in the concrete mixture would positively affect the concrete and subsequently aid in the development of building materials for a sustainable economy [43]. Wood waste powders and fibers are also recommended as raw materials for manufacturing cement mortars [44]. They support delivering a more environmentally friendly alternative to the current waste management choices for recycling industrial trash and conserving natural resources.

It's interesting to note that wood waste is also discussed in the formulation of low-strength concrete materials [45]. Research has already been done to create a novel material called "Wood-crete," which uses concrete products and wood waste as fillers for wall panels and hollow blocks as a thermal insulators [46]. With a density of 473 kg/m^3, the "Wood-crate" forms thin blocks that act as insulating materials. Its thermal conductivity ranges from 0.046 to 0.069 W/m K, and its tolerable compressive strength is 0.08. Overall, using various wood wastes in cementitious composite successfully improves the thermal insulation properties of the building construction element.

3.3 Additive Manufacturing (AM)

The possibility of using wood waste from primary and secondary wood processing in additive manufacturing technology is higher. Using additive manufacturing (AM), which has cheap manufacturing costs and little waste, it is possible to create objects with complicated shapes more automatically [47]. Wood waste is thought to be one of the most effective natural resources for lowering the use of petroleum resources [48]. Wood waste is included in AM because it has better characteristics and a smaller environmental impact. The capacity to be upcycled or downcycled at their end of life is improved when using wood waste with biodegradable or recycled polymers.

The potential of wood waste as additive material in various 3D-printing technologies is reviewed by Krapež et al. [47]. It has been found that a variety of performance levels in the compounds can be achieved by combining wood waste particles with polymers in the proper proportions in terms of size, distribution, and content. In this sense, wood fibers have a low aspect ratio (length/width), whereas wood flour contains random shapes and dimensions that are roughly the same. Therefore, when the polymer matrix is reinforced with distinct wood types, different mechanical strengths would be attained. It is anticipated that the total strength of wood-plastic composites made from wood fiber will be higher than that of wood flour. Wood fiber is preferable because 3D printing comprises methods for binding the material and deposition of the material [49]. Sawdust was mentioned as another inexpensive filler and reinforcement for bending and tensile strength for AM use in addition to wood fiber [50].

Fused Deposition Modelling (FDM), which has been extensively studied in relation to 3D printing, is now the production process utilized for desktop 3D printers. To create wood-polymer filaments, the wood particles are frequently included with FDM materials. The foundation of long-used wood-plastic composites (WPC) serves as the basis for the technology of wood-plastic filaments. WPC is well known for being used as an alternative to real wood for door and window profiles, packaging, automotive dashboard components, and other applications. As its creation is based on melting thermoplastics mixed with wood particles and extruding via a matrix or in molds, WPC exhibits favorable hybrid qualities between wood and plastic. Given that the pre-preparation of WPC entails grinding the wood particles to a specified size before mixing them with polymers and additives, it is important to note that a variety of wood waste is viable for this use.

Therefore, wood industry sawdust appears to be a valuable waste source for producing high-quality 3D polymer materials, as Narlıoğlu et al. [51] reported. Waste pine sawdust was employed in the study as reinforcement and was extruded with polylactic acid (PLA) polymer. Other than that [52], reported on the use of wood flour, lignin, and cellulose nanofibers as functional additives and reinforcements in thermoplastic and thermoset matrices used in 3D printing. Waste pine sawdust was employed in the study as reinforcement and was extruded with polylactic acid (PLA) polymer [52].

Furniture trash may be recycled and used as a feedstock for wood-plastic filaments, according to a study by Pringle et al. [53]. In order to make wood mixable with PLA, it has been found that solid slabs and sawdust from medium-density fiberboard (MDF), low-density fiberboard (LDF), and melamine wood waste can be milled and ground into powder. The author claim that the mixture with 30% wood waste is the most usable but did not take environmental implications into account.

Wood waste could also be used as panel plywood or veneers by laminating object manufacturing (LOM) technology [54]. LOM is considered an AM technology where complex geometries and higher strength of wood are achieved by cutting and laminating veneers. The process is more advantageous if compared with subtractive manufacturing techniques. Furthermore, lesser wood defects can be achieved by manipulating the orientation of the layers, thereby producing higher-strength products.

Overall, employing wood waste in AM technology, particularly 3D printing, has a wide range of applications and motivations. Products manufactured from renewable, biodegradable, and non-petroleum-based materials, such as wood waste, are becoming more and more in demand from both consumers and businesses.

4 Challenges in Wood Waste Utilization

There are still some challenges to overcome despite the opportunities presented by wood waste. It frequently has to do with wood waste that has been chemically preserved, such as waste wood that has been preserved with older preservatives or formaldehyde adhesives. Because recycling this wood debris has a negative impact on the environment, it could have major health consequences. In addition, when nonbiodegradable binders are applied, the secondary product of wood waste with binder could not be completely biodegradable [55].

A variety of environmental effects could be led by wood products at different stages of the production process, from harvesting to disposal. Environmental effects are mostly caused by the energy required to make wood products and the greenhouse gas emissions (GHG) that occur throughout the manufacturing process from raw materials to finished goods. Despite the fact that forests and wood function as carbon sinks by absorbing carbon dioxide from the atmosphere through carbon sequestration, the production of wood products emits carbon [56]. However, up to 17% of GHG emissions into the atmosphere are attributed to the forestry sector as a whole and tree removal due to deforestation [57]. Other types of environmental effects associated with wood products include the transportation of timber commodities, the use of chemicals, and wood waste [58].

In the process of making wood, a variety of chemicals are used, mainly for coating the finished product, applying adhesive, and preservation treatment. Although these substances have increased the longevity of wood products, they can also have a negative influence on the environment because of the components they contain. Another significant environmental concern, for instance, is the disposal of wood from demolished construction sites that still employ high quantities of preservatives. There are laws against the use of dangerous chemicals in several countries.

Although adhesives, which are materials made of both natural and manmade substances, are necessary for gluing wood components into wood products, they may have negative environmental impacts [59]. Phenol-formaldehyde (PF) and urea-formaldehyde (UF) are the two adhesives most frequently employed in outdoor settings because of their excellent weather- and water-resistance properties [60]. Even cured adhesives that are thought to be safe and innocuous might release chemicals that are bad for the environment and people [59].

Wood coatings shield the wood from harmful environmental elements such as moisture radiation, mechanical, chemical, and biological deterioration. However, they have the ability to produce volatile organic compounds and contain organic solvents or liquid (VOC). From the viewpoint of air pollution, human health, and safety, VOCs, such as those containing chlorofluorocarbon, are seen as a major environmental issue [61].

The disposal of wood products has several negative environmental repercussions, particularly in urban settings. Commercial and industrial garbage, construction and demolition work, pallets and packaging, and utilities are the main sources of urban wood waste [62]. When products are thrown away rather than reused, recycled, or repaired, they contribute to toxic waste that can leach from landfills, they take up a lot of space in landfill sites, and they necessitate the construction of new waste disposal facilities. This results in outside pollution and GHG emissions from transport from the source to the landfill site.

Similar to this, burning used materials results in the release of gases, pollution, and smoke into the environment. For example, solid contamination causes disposal issues by decreasing burning efficiency and producing waste, whereas too much chlorine during burning also reduces burning efficiency and can lead to the production of dioxins [63]. It appears that additional research is required to study the engineered wood products made by using various types and sizes of wood waste in order to gain a better understanding of the performance, given the identification of potential sources of environmental impact and the difficulties in utilizing wood waste. The utilization of thermal energy produced by sawmill byproducts, ecologically friendly chemical preservatives, adhesives, coatings, and integrated industrial sites are just a few strategies that can be used to address the related problems.

5 Future Outlook

According to a prediction made in 2010, Malaysia's forest area will produce less wood as a result of the shrinking size of forested regions and the designation of the majority of the land for development. Based on these assumptions, the Ministry of Plantation Industries and Commodities constructed a number of forest plantations to address deforestation issues. Several other governments forbid the export of lumber in order to protect their remaining forests. Additionally, the availability of raw materials in the wood sector may be negatively impacted by rising costs for raw materials as a result of greater competition for them on the global market. The local industry should adjust its practices in this regard to boost domestic wood production and decrease imports [64].

The sustainability of raw materials has become a concern in the wood industry. Numerous agricultural wastes, such as oil palm trunk (OPT), an oil palm frond (OPF), empty fruit bunch (EFB), palm fruit bunch (PPF), pineapple leaves (PALF), kenaf, bamboo, and jute, remain limited unutilized. Some of these products, such as OPT, have shown potential as alternative materials for the wood sector despite being considered raw material wastes. Due to the lengthy maturation period of forest trees, forest plantations produce few resources slowly. Alternative sources for the wood-based industry may include waste from plantations and other commodities. As a result, the government is launching a variety of initiatives to find alternate resources for the wood processing industry [64, 65].

The Malaysian government has launched many programs to look for alternate materials derived from other sources because it is aware of the limitations of the timber industry. One example of a substitute raw material that the wood processing sector might use is the employment of various chemicals that can produce agricultural waste. Southeast Asia's biocomposite market is still growing, and the shift to this substitute material is expected to limit the availability of skilled workers and the local labor force. The government developed numerous wood training institutions in Malaysia and abroad to support the biocomposite sector. Resource conservation and environmental protection have been hotly contested issues among the global community for more than a decade. Global demand for "green" or environmentally friendly items has increased, particularly in poorer nations. These changes put pressure on Asian wood producers and their goods [64, 66].

The issue with the wood market is that it could limit the availability of natural resources while also increasing the cost of those resources. To maintain ongoing growth, stability, and competitiveness, the government should promote the use of substitute wood products. Therefore, scientists are researching biocomposite materials that could replace the wood products now on the market. Biocomposite materials, which provide wood product manufacturers an alternative by combining biomaterials or natural fibers, have been well embraced on the international market. Additionally, biocomposite materials need to be readily available globally and able to meet market demand. Manufacturers are becoming more confident in biocomposite-based materials, which are innovative and could be useful for furniture and other uses. In addition, the most crucial considerations for manufacturers when looking at biocomposite as an alternative material for the manufacturing industry are the availability of natural fiber-like resources from forests and the use of agricultural wastes in biocomposite materials [34, 64].

On the market for agro-based biocomposites, one might anticipate fierce competition from overseas companies [64]. Future challenges could affect the market for composite-based goods, including strict requirements, purchasing rules and policies, environmental issues, and law enforcement. Southeast Asia has a solid history in the global wood market, but its market has grown competitive. Each country must provide a range of creative answers to these problems in order to stay competitive in the business.

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