**Wood Waste Utilization in the Forest Industry: Innovations for Sustainable Management**

**ABSTRACT**

The forestry sector produces considerable quantities of wood waste throughout the processes of harvesting, processing, and manufacturing. This waste poses a significant environmental challenge, leading to greenhouse gas emissions, the accumulation of waste in landfills, and the depletion of resources. Nevertheless, wood waste is also a precious resource that has the potential to support a circular economy and improve the sustainability of the forestry sector. This paper investigates the challenges and opportunities related to the utilization of wood waste, emphasizing innovative technologies and strategies for sustainable management. We analyze both current and emerging uses of wood waste, such as bioenergy generation, composite materials, wood-derived chemicals, and soil enhancements.

**Keywords:** Wood waste, sustainable forestry, bioenergy, composite materials, forest industry, resource management.

1. **INTRODUCTION**

Worldwide, the forestry sector is crucial in supplying timber, paper, and various other important wood products. Nevertheless, this sector also produces considerable quantities of wood waste, which is generally characterized as the residues and byproducts generated during forestry operations, timber processing, and manufacturing activities (such as logging slash, sawdust, bark, and discarded timber (Chandra et al., 2021). Historically, a large portion of this wood waste has been incinerated, disposed of in landfills, or merely allowed to decompose, leading to a loss of economic value and considerable environmental consequences.

Wood waste is a category of waste that encompasses discarded wood products from various sources, including wood packaging, demolition and construction activities, the wood processing industry, as well as private households and railway construction (Van Benthem et al., 2007; Bhardwaj et al., 2023). This type of waste can serve as a secondary source of raw materials for energy production and the creation of a variety of new potential products, such as chemicals, biofuels, and other lignocellulosic materials (Packalen et al., 2017). For instance, wood bark contains both lipophilic and hydrophilic extractives that can be transformed into high-value products, including cosmetic chemicals and pharmaceutical products (Routa et al., 2017; Tiwari et al., 2024). Similarly, Yang et al., (2014) discovered that bio-oil derived from waste wood resources serves as an effective extender and modifier for petroleum asphalt binders in asphalt pavement. The generation of biofuels and wood-based composites represents additional high-value applications for wood waste. Furthermore, minimizing wood waste can help the timber industry reduce its environmental impact while simultaneously addressing the increasing demand for wood without further endangering the world’s forests (Eshun et al., 2012; Chandra et al., 2024). Consequently, the strategy for forest-based industries should focus on reducing, recovering, and enhancing the utilization of wood waste generated from the harvesting and processing of wood.

Wood waste and byproducts generated from wood-based industrial activities can be utilized to produce a diverse array of valuable industrial products (Lykidis and Grigoriou, 2008; Darro et al., 2022; Bhardwaj et al., 2024). For every 1000 board feet of lumber manufactured, sawmills collect 1 ton of sawdust, shavings, slabs, and edgings; roughly 75% of this seemingly useless material consists of wood, while 25% is bark (Saal et al., 2019). This material can be transformed into both energy and non-energy applications. Energy generation from wood waste encompasses methods such as combustion, cogeneration, and the production of pellets and briquettes, whereas non-energy applications include the creation of composite boards, surfacing products, composting, and cement boards (Murphy et al., 2007; Kumar et al., 2024; Limanpure and Kumar, 2018). Numerous research studies have uncovered various value-added opportunities for converting wood waste into other beneficial products. For instance, a study conducted in Finland identified several emerging markets for wood-based products, including textiles, chemicals, biofuels, and plastic alternatives (Cai et al., 2013). Research in Zimbabwe revealed that most offcuts and chips from wood-based enterprises are utilized as firewood by local communities and are also employed at commercial sawmills to produce steam for kiln dryers (Charis et al., 2019; Kumar et al., 2022 Aashutosh et al., 2024). Additionally, a study in Japan discovered that furniture manufacturers generated 15 million cubic meters of wood waste, with over 90% being recycled into wood-based panels and fuel (Hiramatsu et al., 2002). Furthermore, under-utilized wood from the fast-growing species paulownia (*Paulownia fortuniei*) was found to meet the minimum value requirements for general-purpose oriented strand board (OSB) as specified in EN 300 Type 1 (1997) for use in dry conditions (Salari et al., 2013).

## Wood is utilized in the construction of both large and small structures globally (Ramage et al., 2017). A significant portion of land in Nepal is designated for forests and shrublands (DFRS, 2015). The use of timber in the nation plays a crucial role in the building of residential homes, commercial and industrial facilities, livestock shelters, and furniture (Kanel et al., 2012). The timber demand was recorded at 3.37 million m3 in 2011, increased to 3.75 million m3 in 2020, and is projected to reach 4.80 million m3 by 2030 (Kanel et al., 2012). Despite the growing demand due to population growth, wood remains underutilized or mismanaged in developing nations like Nepal, primarily due to outdated sawmill technology and untrained personnel. Industries based on forest resources have the potential to enhance the management of natural resources while providing income and job opportunities (Acharya and Acharya, 2007; Pandit et al., 2009; Kumar et al., 2023). The various sectors that utilize wood produce substantial amounts of wood waste, which requires effective management, repurposing, marketing, or disposal (Owoyemi et al., 2016). However, the main challenges stem from a lack of incentives for utilizing wood waste, inadequate information regarding the economic advantages of wood waste utilization, poor enforcement of environmental regulations, and the absence of policies for managing wood waste.

## 2. WOOD WASTE FROM FOREST INDUSTRIES

The production of timber products involves several processes, ranging from log extraction to the creation of finished goods, all of which can lead to environmental pollution in the forms of land, air, and water contamination. Approximately 50% of wood is converted into valuable products, while the remainder is classified as waste (Zeng et al., 2013; Vaishnav et al., 2021). Examples of wood waste produced during primary industrial processes include bark, slabs, sawdust, chips, coarse residues, planer shavings, peeler log cores, and end trimmings (refer to Table 1). Consequently, the effective utilization of wood waste plays a crucial role in mitigating environmental impacts without harming the global forest. As noted by Dionco-Adetayo (2001), nearly half of every cubic meter of tree harvested from the forest results in waste due to damaged residuals, with additional losses from abandoned logs (3.75%), stumps (10%), tops and branches (33.75%), and butt trimmings (2.5%). In 2015, Germany generated 11.9 million tonnes of wood waste, primarily from wood packaging, demolition, construction, and the wood processing industry (Garcia and Hora, 2017). In Finland, around 207,000 tons of waste wood is produced annually from packaging, with a recovery rate of approximately 31,000 tons per year, while the remaining portion is utilized for energy purposes, totaling 176,000 tons per year (Manninen et al., 2015). According to the Wood Recyclers Association 2021 (https://woodrecyclers.org/), the UK generates about 4.5 million tonnes of wood waste, of which 1.3 million tonnes are recycled. Sweden, which comprises 1% of the total global forest cover, contributes to over 10% of the global forest industry, including swan timber and pulp and paper products (Kumar et al., 2021).

**Table 1: Wood sources and their various residues.**

| **Source** | **Types of residues** |
| --- | --- |
|  |  |
| Forest operation | Branches, stumps, low graded and decayed wood, needles, leaves, roots, slashings and sawdust |
| Sawmilling | Bark, split wood, sawdust, planer shavings, trimmings, sander dust |
| Plywood production | Bark, core, veneer clippings, sawdust and waste, panel trim, sander dust |
| Particleboard production | Bark, panel trim, screening fines, sawdust, sander dust |

### 3.  WOOD WASTE UTILIZATION

Wood waste can be reduced by enhancing the efficiency of primary wood usage and by utilizing raw wood materials sourced from sustainably managed forests, thereby avoiding further harm to the world’s forests (Magi, 2001; Kumar et al., 2022). There are numerous potential applications that provide opportunities for the effective use of a significant amount of wood waste generated from harvesting to processing. Eshun et al., (2011)] propose five distinct strategies for wood waste utilization, namely technological innovation, sound operational practices, recycling, reuse, and recovery, as well as a combination of technological innovation, sound operating practices, and recycling (fig. 1). Although technological innovations are costly, they can decrease wood waste production from plywood manufacturing by 6%, from veneer production by 9%, and from furniture component production by 19% (Shin et al., 2008). Loehnetz et al., (1994) discovered that certain sawmills in tropical regions, such as Venezuela (60–70%) and Malaysia (54.5%), successfully recovered sawn wood of commercial dimensions. According to Lykidis and Grigoriou (2008), wood waste has the potential to serve as a resource for producing various materials through reformation or the creation of new products. In Zimbabwe, the majority of offcuts and chips from wood-based industries are utilized at commercial sawmills to generate steam for kiln dryers and are also used as firewood by local communities. Similarly, Japanese furniture manufacturers produced 15 million cubic meters of wood waste, of which 90% is recycled for the production of wood-based panels and fuel. As noted by Bruns,(2017), Australia has effectively utilized wood waste on a large scale, generating annual revenue of approximately 7.3 million Euros. Various building materials and engineered wood products, such as plywood, laminated veneer lumber, and glued-laminated lumber particleboard, are produced from wood waste. This indicates that the utilization of wood waste for the creation of new products is a financially viable strategy. Several techniques are employed for the utilization of wood waste.

**3.1 Wood waste as a source of energy**

Wood waste generated by furniture manufacturing facilities is repurposed for energy conversion. The research indicated that the lumber, plywood, pulp, and paper sectors incinerate their wood by-products in substantial furnaces and boilers, providing 60% of the energy required to operate factories (Bruns, 2017). In the United Kingdom, approximately 10 million tons of waste wood are repurposed annually for energy production (Steierer, 2007). Canada exports 1 million tons of wood pellets derived from waste to Europe, serving as a raw material for power plants as alternatives to fossil fuels (Edo et al., 2017). Wood pellets, which are essentially compacted sawdust, can be utilized as fuel, thereby alleviating the strain on forest resources. According to Goetzl (2015), there is a growing trend of using wood pellets on an industrial scale for electricity generation and in industrial and commercial applications in developed nations. Presently, numerous developing countries are also manufacturing wood briquettes, which are considered a more efficient energy source compared to traditional firewood (Asresu, 2017). Charis et al., (2019) noted that from 2013 to 2017, modified 'smokeless' briquettes were produced in Zimbabwe through innovative densification methods. In Peru, wood waste from the timber industry has proven to be an excellent fuel substitute for 55.81% of families in the area (Sánchez et al., 2014).

**3.2 Using wood waste to create engineered wood products**

Engineered wood products are items made from small pieces of wood that are bonded together using various adhesives. Utilizing wood waste in the production of engineered wood products contributes to the reduction of climate change by preventing further tree harvesting and promoting ongoing carbon storage (Hill et al., 2015). Examples of engineered wood include oriented strand board, particleboard, Medium Density Fiberboard (MDF), glue-laminated timber, laminated lumber, and others (Williamson, 2002). Structural wood panels, such as plywood and oriented strand board, are produced by laminating different wood-based materials to enhance the strength, stiffness, and stability of the panels (Stark et al., 2010). Typically, these panels are not intended to support loads; rather, they are commonly used in interior applications as alternatives to solid wood. According to Braghiroli et al., (2020), planer shavings constitute over half of the wood components in particleboard produced in the United States, followed by other mill byproducts like sawdust and wood chips. Various types of resins, including Amino-formaldehyde and Melamine, are employed for their cost-effectiveness and water-resistant properties. Medium-density boards (MDF) are utilized for high-quality products such as stereo cabinets, moldings, and table and furniture tops with profiled edges. Due to its smooth surface and edge finishing characteristics, MDF serves as an excellent substrate for wood veneer, vinyl films, and heat transfer foils (Stark et al., 2010). In 2013 and 2014, Italy recycled 95% of waste wood to manufacture particleboard, while Germany and the United Kingdom accounted for 34% and 53%, respectively (Garcia and Hora, 2017). Despite these advantages, the production of engineered wood products is costly in terms of time, money, and energy.

#### 2.3 Wood chips for mulch

#### Mulches consist of layers applied atop the soil to assist in weed control, safeguard roots from temperature variations, minimize water evaporation from the soil, and enhance visual appeal. Wood chips, which are abundant in lignin, tannins, and various complex compounds, provide nutrients and gradually absorb substantial quantities of water (Chalker-Scott, 2007). Consequently, developed nations acknowledge wood chip mulches as an environmentally sustainable option for gardens and green areas.

#### 2.4 Wood chips for animal bedding

#### Bedding materials refer to any substance that offers comfort to animals within their enclosures. They can mitigate adverse environmental effects in livestock facilities and enhance animal comfort by absorbing excess moisture and lowering ammonia (NH3) emissions (Ahn et al., 2020). Additionally, wood chips used for animal bedding are manageable, economical, and absorbent, creating a clean, warm, and dust-free environment (Panivivat et al., 2004). The bedding can be mixed with cattle dung and used as compost manure.

#### 2.5 Chemical utilization of wood waste

Wood waste and byproducts represent a promising source of a diverse range of green chemicals. A typical softwood, such as spruce or fir, contains approximately 67% carbohydrates, 27% lignin, and 6% extractives. Similarly, hardwoods like maple consist of about 73% carbohydrates, 22% lignin, and 5% extractives (Pavlovich and Paylovna, 2020). Research indicates that the sulfite pulping process can only utilize half of the wood for pulp, while the remaining unusable half is composed of roughly equal amounts of carbohydrates and lignin (Li et al., 2015). The carbohydrate component of wood includes two types of materials, namely alpha-cellulose and hemicellulose. Alpha-cellulose, which constitutes 50% of wood, is resistant to mild chemical treatments and is composed of glucose polymers. Hemicellulose consists of simple sugars such as pentoses and hexoses, uranic acids, and acetylated compounds. The most effective use of wood residues is achieved by converting them into fiber for paper and paperboard production. The chemical utilization of wood residues may involve several stages, with economic considerations posing significant challenges. Typically, wood residues are hydrolyzed using acid to produce simple sugars and lignin. Research has shown that lignin can be employed for various commercial applications, including battery storage, tanning agents, adhesives, road construction, and dispersing agents in cement.

**Fig. 1: Minimization of wood waste.**

**4. CHALLENGES TO WOOD WASTE UTILIZATION**

Despite the many advantages, various obstacles impede the broad adoption of wood waste utilization:

**4.1 Collection and Transportation Costs**

The scattered nature of forest residues, along with the relatively low economic value of wood waste, can render collection and transportation financially challenging (Soni et al., 2025).

**4.2 Variability in Feedstock Quality**

The diversity of wood waste, which includes differences in species, moisture levels, contaminants, and particle sizes, can influence the efficiency and effectiveness of specific processing technologies (Soni et al., 2025).

**4.3 Technological Barriers**

Certain advanced technologies for converting wood waste, such as gasification and pyrolysis, remain in development and necessitate further optimization (Soni et al., 2025).

**4.4 Lack of Awareness and Information**

A limited understanding among stakeholders regarding the potential uses of wood waste and the technologies available can obstruct its adoption (Soni et al., 2025).

**4.5 Policy and Regulatory Barriers**

Insufficient policy frameworks, absence of financial incentives, and complicated regulatory requirements can deter investment in wood waste utilization initiatives (Soni et al., 2025).

**4.6 Market Competition**

Products derived from wood waste frequently encounter competition from less expensive alternatives that are based on fossil fuels or virgin materials.

**5. INNOVATIONS AND STRATEGIES FOR SUSTAINABLE MANAGEMENT**

Addressing these challenges necessitates a comprehensive strategy that emphasizes technological innovation, supportive policies, and collaborative partnerships (Bargah et al., 2024). Below are several essential strategies:

**5.1 Enhanced Harvesting Techniques**

Adopting more effective harvesting practices that reduce waste generation and aid in the collection of residues.

**5.2 Pre-Processing and Standardization**

Creating economical pre-processing methods to enhance the consistency and quality of wood waste feedstock. This may involve chipping, grinding, drying, and screening procedures.

**5.3 Technological Advancements**

Allocating resources to research and development aimed at increasing the efficiency and cost-effectiveness of wood waste conversion technologies, including gasification, pyrolysis, and enzymatic hydrolysis.

**5.4 Integrated Biorefineries**

Establishing integrated biorefineries capable of transforming wood waste into various high-value products, such as bioenergy, chemicals, and materials.

**5.5 Life Cycle Assessment (LCA)**

Performing LCAs to assess the environmental impacts of wood waste utilization technologies and confirm that they provide real sustainability advantages.

**5.6 Policy and Regulatory Support**

Enacting policies that encourage wood waste utilization, such as feed-in tariffs for bioenergy, tax incentives for incorporating wood waste in manufacturing, and regulations that limit the landfilling of wood waste.

**5.7 Public Awareness and Education**

Raising public awareness regarding the advantages of wood waste utilization and the availability of products derived from wood waste.

**5.8 Collaborative Partnerships**

Encouraging cooperation among forest owners, processors, researchers, policymakers, and consumers to create and execute sustainable wood waste management strategies.

**5.8 Development of Robust Supply Chains**

Creating dependable and efficient supply chains for the collection, processing, and distribution of wood waste.

**5.9 Digitalization and Data Analytics**

Utilizing digital technologies, such as sensors and data analytics, to enhance the efficiency of wood waste collection, processing, and utilization.

**6. CONCLUSION**

Wood waste represents a significant underutilized resource with the potential to contribute to a more sustainable and resilient forest industry. By adopting innovative technologies and strategies, we can transform wood waste from a disposal problem into a valuable resource that contributes to renewable energy production, bio-based materials, and a circular economy. Overcoming the challenges associated with wood waste utilization will require a collaborative effort from forest owners, processors, researchers, and consumers. By investing in research and development, implementing supportive policies, and fostering public awareness, we can unlock the full potential of wood waste and create a more sustainable future for the forest industry and the environment. The transition towards a more circular and bio-based economy necessitates a paradigm shift in how we view and manage wood waste, recognizing its inherent value and promoting its responsible utilization.

**DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during writing or editing of manuscripts.

**COMPETING INTERESTS**

Authors have declared that no competing interests exist.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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