West Science Interdisciplinary Studies
Vol. 03, No. 12, December and 2025: pp. 2257-2264

The Potential of Forestry Sector Waste for Biochar Production: Characteristics and Production Challenges

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ABSTRACT

Timber harvesting has long been the primary focus of forest utilization as a major economic resource, yet more efficient strategies are needed to reduce excessive logging by implementing measured harvesting and maximizing the use of all wood components. Branches, logging residues, sawmill by-products, and discarded wooden furniture remain underutilized and are often treated as waste. These materials have high potential to be converted into value-added products such as biochar. Forestry waste is particularly suitable as a feedstock for biochar due to its lignocellulosic richness. Biochar is a carbon-rich material produced through pyrolysis. Biochar derived from forestry waste has significant potential to improve soil structure and water-holding capacity, while also contributing to long-term carbon storage and climate change mitigation. However, challenges remain, including variability in biochar quality, absence of global standards, high production costs, contaminant risks, and limited formal guidelines.

Keywords: *Biochar, Challenges, Forestry, Pyrolysis, Waste.*

1. INTRODUCTION

Indonesia's forests are among the richest tropical ecosystems globally, both in biodiversity and natural resource potential. However, forest utilization has traditionally focused on timber extraction as the primary economic output. Indonesia's roundwood production has reached 64.84 million m^3 [1]. Rather than relying solely on continuous logging, a more efficient strategy involves controlled harvesting combined with maximizing the use of all tree components, including materials commonly regarded as waste. Forestry waste includes all unused parts of the tree generated before or after processing. It can be classified into primary wood waste and post-consumer wood waste [2]. Primary waste includes branches, logging residues, sawdust, offcuts, and bark, as well as defects found in harvested trees [3], [4]. Post-consumer wastes consist of discarded furniture, wood-based panels, and interior components such as MDF [2]. These materials can be converted into bioenergy, composite materials, adsorbents, and compost [5]. One rapidly developing biomass conversion method is biochar production, a carbon-rich product generated by heating biomass in low-oxygen or oxygen-free conditions through pyrolysis [6]. Forestry residues are particularly suitable feedstock due to their lignocellulosic content. The lignin, cellulose, and hemicellulose components influence the stability and carbon content of the resulting biochar [7], [8], [9]. Biochar from forestry waste can improve soil structure, enhance water retention, and reduce nitrogen losses, thereby supporting increased crop productivity [10], [11]. Additionally, biochar provides long-term carbon sequestration benefits and contributes to climate change mitigation [12].

From an economic and technological perspective, utilizing forestry waste for biochar production can be financially viable particularly when applied at appropriate rates and supported by incentives such as carbon credit markets [13], [14]. Technological advancements, including microwave-assisted pyrolysis and flash pyrolysis, increase production efficiency and biochar quality, while chemical modification improves sorption capacity [7], [15]. Nevertheless, significant challenges persist, including raw material variability, non-optimized pyrolysis efficiency, the need for quality standards, logistical constraints, high production costs, and environmental risks related to pollutant release [16], [17]. These challenges highlight the need for comprehensive studies on the characteristics and potential of forestry waste based biochar, as well as the technical and nontechnical barriers in its production, to support sustainable and industrial-scale development [18]. This review provides an integrated overview of forestry waste characteristics and the major challenges associated with biochar production.

2. METHODS

The research adopted a qualitative methodology, utilizing a systematic literature review (SLR) to identify, classify, and interpret the results of previous studies. The study utilized multiple academic databases and search platforms, such as ScienceDirect, Google Scholar, Scopus, ResearchGate, and Taylor & Francis. Relevant literature was retrieved from the selected databases by applying keywords including "biochar," "sources of forestry waste," "challenges in biochar production, " "standardization challenges," "economic challenges," "environmental challenges," and "regulatory challenges." The scientific articles used were written in English or Indonesian. These studies examined various aspects of forestry waste, including physicochemical characteristics, pretreatment requirements, biochar yield and quality, and technical, economic, and environmental production challenges.

3. RESULTS AND DISCUSSION

3.1 Sources of Forestry Waste

Waste from the forestry sector arises from a range of activities within the industry and can be classified into different types according to their types and *Characteristics*.

1. Types of Waste

Forestry waste suitable for biochar production includes primary wood waste and post-consumer wood waste. Primary waste includes sawdust, wood chips, and other sawmilling residues that typically exhibit high carbon content and low contamination levels [19], [20]. Bark and branches can also be used as feedstock, producing highly porous biochar suitable for pollutant adsorption [21]. Industrial wood defects may also serve as potential feedstock, although contamination risks must be evaluated beforehand [20]. Primary waste originates from forest management and wood processing activities, including logging residues, processing waste, and urban forestry residues.

Table 1. Classification of Forestry Waste

Waste Type	Example Materials	References
Logging Residues	Stumps, branches, twigs, broken wood	[22], [23]
Processing Waste	Sawdust, chips, bark, defective wood	[24], [25]
Urban Forestry Waste	Leaves, pruned twigs	[26], [27]

Post-consumer wood waste such as discarded furniture or wood panels remains carbon-rich and can be converted into biochar. This pathway contributes to long-term carbon storage, with each kilogram of biochar able to store nearly two kilograms of CO_2 that would otherwise be released through decomposition or open burning [28]. However, post-consumer waste may contain added chemicals from manufacturing processes, raising concerns about potential contaminants such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) in the resulting biochar [29]. Additional treatment or monitoring is therefore required to ensure environmental safety.

2. Basic Characteristics of Wood Waste

The composition and characteristics of forestry waste vary depending on species and origin. These variations include lignin content, holocellulose levels, moisture content, density, and particle size all of which influence energy potential and biodegradability [23], [24], [30]. The chemical structure of lignin, cellulose, and hemicellulose in softwood and hardwood plays a crucial role in defining biochar properties. Softwood generally contains higher lignin levels than hardwood, producing more aromatic, stable, and carbon-rich biochar due to lignin's broad decomposition temperature range and its formation of degradation-resistant aromatic residues [31]. Hardwood, in contrast, contains higher cellulose and hemicellulose, which decompose at lower temperatures, producing biochar with distinct porosity and surface area while still enabling high carbon sequestration potential [32], [33].

The greater fraction of cellulose and hemicellulose often results in hardwood-derived biochar exhibiting higher alkalinity and cation exchange capacity, supporting soil amendment applications [34]. Differences in lignocellulosic composition also influence responses to pyrolysis temperature: lignin-rich softwoods yield more stable and aromatic biochar at moderate to high temperatures (500–700°C), while the rapid decomposition of cellulose and hemicellulose in hardwood contributes to pore development and biochar yield [35], [36]. Additionally, bark-derived biochar typically offers larger surface areas and enhanced microstructure development, making it effective for water and soil remediation applications [37], [38].

3.2 Challenges in Biochar Production

Biochar production holds considerable potential for promoting environmental sustainability and improving waste management, yet it is confronted with numerous challenges that span technical, standardization, economic, environmental and regulatory.

1. Technical Challenges

Technical challenges stem primarily from the heterogeneity of feedstock, which leads to variability in biochar's physical and chemical properties such as surface area, adsorption capacity, and volatile matter content. These variations arise from differences in biomass type, moisture content, particle size, and lignocellulosic composition, complicating efforts to produce consistent-quality biochar [39], [40].

Optimizing pyrolysis conditions including temperature, heating rate, and residence time remains a key challenge, as even minor adjustments can significantly affect pore structure, surface area, and adsorption capacity [41], [42]. Although high temperatures generally enhance biochar quality, they also reduce char yield and increase energy consumption. These complexities intensify at larger production scales, which require stable equipment and the ability to handle diverse feedstock characteristics [43].

2. Standardization Challenges

The absence of globally unified standards for biochar quality, characteristics, and performance presents a significant challenge. Feedstock and pyrolysis condition variability complicate the establishment of universal parameters [40] . Laboratory inconsistencies across regions further hinder standardization efforts. Current standards remain largely regional, and universal adoption is limited. Different applications agriculture, remediation, energy, or construction require distinct quality criteria, yet comprehensive guidelines remain unavailable [44]. These issues highlight the need to integrate standardization with life cycle assessment and application-specific categorization [45].

3. Economic Challenges

Biochar production from forestry waste faces several economic challenges, particularly related to biomass collection and handling costs. Transporting and storing forest residues from remote locations to processing facilities can be expensive, affecting the overall economic feasibility [46], [47]. Minimum selling prices (MSP) vary widely based on technology and efficiency. Portable systems can generate MSPs between USD 580 and USD 5,000 per ton, though government subsidies may reduce costs by 30–387% [47].

Market demand for biochar remains emerging and highly dependent on its value in agricultural and environmental applications. Despite its soil-enhancing and carbon-sequestering benefits, market adoption remains limited, resulting in fluctuating profit margins [48], [49]. However, compared to conventional waste management methods such as open burning, biochar offers environmental benefits and creates new market opportunities for underutilized forest biomass

Production scale and policy support strongly influence economic viability. Large-scale production reduces unit costs through economies of scale, while small-scale operations often face higher costs [47], [50]. Government incentives, subsidies, and carbon market support can reduce production costs and stabilize biochar markets, though the effectiveness of such policies relies on consistency and long-term financial support [13], [51].

4. Environmental Challenges

Although forestry-waste biochar supports soil improvement and biodiversity, it can also cause environmental issues. Biochar enhances nutrient retention and reduces greenhouse gas emissions, but in certain conditions it may alter soil pH, disrupt nutrient balance, or affect soil biota communities [52], [53]. These uncertainties pose barriers to widespread adoption.

Contaminant risks represent another major environmental concern. Feedstock containing heavy metals or PAHs can transfer these contaminants to the biochar. Inadequate temperature control during pyrolysis increases the likelihood of contaminant leaching into soil and water [54], [55]. Thus, strict quality control protocols are necessary.Furthermore, life cycle assessment (LCA) is essential to ensure that biochar's environmental benefits outweigh the impacts associated with pyrolysis energy use, transportation, and distribution. Without proper management, biochar's carbon footprint may increase significantly [45].

5. Regulatory Challenges

Regulatory challenges persist due to limited policies governing biochar production, distribution, and application. In Indonesia, specific regulations related to biochar remain underdeveloped, necessitating government support to establish processing facilities and create production standards [56]. Farmer awareness, education, and financial incentives are crucial for local-level adoption [21], [57]. Collaborative platforms, such as the Indonesian International Biochar Association (ABII), have been established to advance technology and utilization.

Globally, regulations remain inconsistent. The European Union and the United States rely on voluntary standards such as the European Biochar Certificate (EBC) and the International Biochar Initiative (IBI) Standard, which emphasize feedstock quality, heavy metal limits, and environmental safety [58], [59]. As biochar is increasingly recognized as a carbon removal tool, several countries are integrating it into sustainable energy and carbon management strategies [60], [61].

CONCLUSION

The chemical structure of lignin, cellulose, and hemicellulose in softwood and hardwood strongly influences the properties of resulting biochar. Softwood's high lignin content yields more aromatic and stable biochar, while hardwood-derived biochar is shaped by the decomposition of cellulose and hemicellulose. Major production challenges include variability in biochar quality, lack of global standards, high production costs, contaminant risks, and insufficient guidelines factors that cause market uncertainty and regulatory barriers.

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