Valorization of pine needles to biochar production: An initiative towards sustainable agriculture and circular economy.

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Abstract

Forest litter accumulation, particularly pine needles (*Pinus roxburghii*), offers considerable environmental and ecological concerns in many mountainous regions due to recurring forest fires, air pollution and inefficient biomass utilization. Despite its abundance, lignocellulosic residue is largely underutilized as a renewable carbon source. Growing interest in sustainable biomass management has emphasized thermochemical conversion, specifically pyrolysis as a viable approach for converting such residue into value-added products within circular bioeconomy frameworks. This review focuses on current advances in biomass management and the sustainable use of pine needles, with a focus on developing large-scale biochar synthesis strategies and process optimization for effective biomass valorization. Furthermore, environmental significance of biochar is highlighted, including its use in pollutant remediation, soil regeneration and long-term carbon sequestration for climate change mitigation. Integrating sustainable biomass consumption with scalable biochar technology for production is an intriguing approach to resource recovery, ecological restoration and the advancement of circular economy strategies.

Keywords: Pine needle, Biochar, Pyrolysis, Biomass valorization, Soil restoration, Environmental remediation.

Introduction

The growing production of forest biomass residues has become a major environmental concern, especially in mountainous areas where unmanaged litter accumulation can disturb ecological balance and raise the risk of natural disasters. The productivity of pine needles (*Pinus roxburghii*) is estimated to be 6.3 t ha^{-1} $year^{-1}$, making them one of the most prevalent forest wastes in the Himalayan region (Choudhary et al., 2020). The sluggish rate of decomposition of this lignocellulosic litter produces thick layers on the forest floor, which may impede the proliferation of vegetation, reduce the replenishment of groundwater and greatly increase the frequency and severity of forest fires (Li et al., 2017). Thermochemical conversion technologies have become a potential way to turn underused biomass into products with additional value in the past few years (Li et al., 2020). Pyrolysis is one of these technologies that has drawn a lot of interest as it can turn organic waste into biochar, a stable carbon-rich material with a variety of application in agriculture and the environment. The potential of biochar to improve soil quality, increase nutrient retention, immobilize pollutants and contribute to long-term carbon sequestration has been widely recognized (Leng et al., 2021). These benefits can help mitigate climate change and support sustainable management practices (Lateef et al., 2019). Furthermore, converting forest wastes into biochar adheres to circular bioeconomy concepts by converting waste biomass into useful carbon-based materials while minimizing environmental impacts associated with open burning and unmanaged decomposition. With the quantity of pine needle biomass and its related environmental impacts, converting it into biochar appears to be a feasible strategy for long-term forest residue management (Lal, 2015). This review explores the latest advances in the use of *Pinus roxburghii* needle biomass for biochar production, emphasizing its potential significance in environmental remediation, soil restoration and climate mitigation within circular economy frameworks. This work seeks to provide insights into increasing sustainable biomass valorization and supporting integrated forest waste management strategies by synthesizing recent advancements and highlighting critical research gaps.

Biomass management and sustainable utilization

In Indian Himalayan region biomass management is a critical environmental and socio-economic challenge due to the large-scale accumulation of forest residues, particularly pine needles, which contribute to recurrent forest fires, nutrient depletion and atmospheric pollution (Gupta et al., 2022). The large-scale accumulation of forest residues, especially pine needles, which contribute to frequent forest fires, nutrient depletion and atmospheric pollution, makes biomass management a crucial environmental and socio-economic challenge (Mandal et al., 2018). Substantial greenhouse gas emissions and inappropriate use of lignocellulosic resources are the results of conventional disposal practices like open burning and uncontrolled decomposition (Chausali et al., 2021). The conversion of such remainders into value-added products is emphasized by sustainable biomass management that is consistent with the principles of the circular bioeconomy, decreasing waste whilst optimizing resource efficiency (Bhandari et al., 2023). The conversion of biomass into biochar, a stable carbon-rich substance with numerous environmental applications is rendered possible by thermochemical processes, particularly pyrolysis as shown in fig.1 (Kumar et al., 2020).

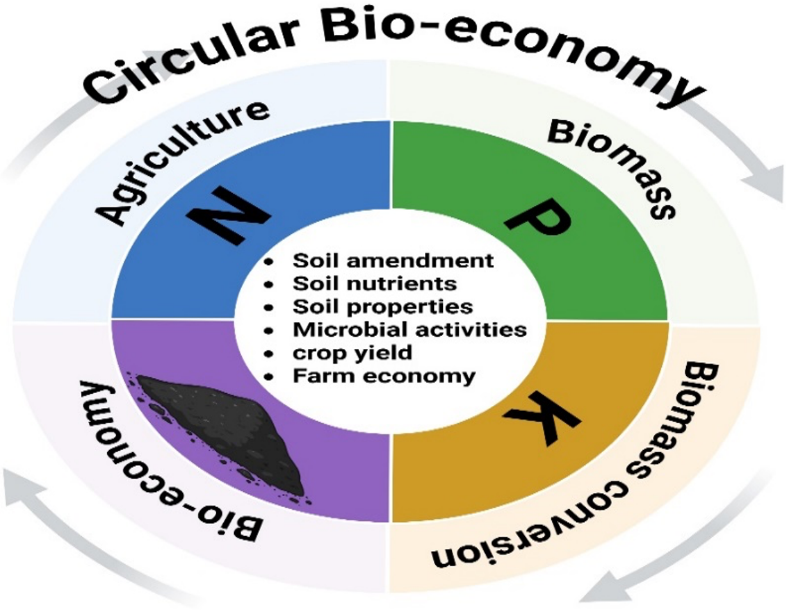

Fig. 1 Use of biomass within the circular bioeconomy concept.

According to recent study, biochar improves the physicochemical characteristics of soil, increases nutrient retention and fosters microbial activity, all of which help soil regeneration and crop production (Chaubey et al., 2024). It is also useful for environmental remediation because of its porous structure and surface functionality, which promote the adsorption and immobilization of both organic and inorganic pollutants (Sharma et al., 2023). By facilitating long-term carbon absorption and lowering greenhouse gas emissions from soils, biochar significantly aids in the mitigation of climate change (Kaushik & Mathur, 2025). Decentralized biomass valorization methods can be integrated into regional frameworks to improve resource circularity, reduce transportation obstacles and promote rural livelihoods (Kumar et al., 2025). In the Himalayan and larger Indian location, using circular bioeconomy-driven biomass management techniques provides a sustainable route for ecological restoration, climatic resilience and effective resource exploitation (Ahmad et al., 2013).

Comparative evaluation of pine needle derived biochar with other feedstocks

The unique physicochemical properties and potential for valorization of pine needles biomass are brought out by contrasts with other typical feedstocks. As pine needle biomass is rich in lignin, resinous components and aromatic elements, the resulting biochar offers a higher stable carbon content and enhanced thermal stability (A. Gupta et al., 2023; Y. Li et al., 2020). The long-term carbon sequestration capacity and structural stability of biochar are enhanced by this lignin-rich composition, which encourages the formation of stable aromatic carbon structures during pyrolysis (NAIN, 2023). Agricultural residues, including crop straw and stover usually have higher ash and silica contents, which lead to lesser carbon stability and a smaller production of biochar. In addition, when compared to other feedstocks like soybean stover, comparative study has shown that biochar produced from pine needles exhibits effective pollutant immobilization and carbon stability (Ahmad et al., 2016). Pine needles offer advantages in terms of quantity, simplicity of pyrolytic conversion and substantial environmental benefits, especially in fire-prone places, even though woody biomass frequently yields biochar with larger surface area and rigidity (A. Gupta et al., 2023).

Process optimization for effective biomass valorization

Process optimization in biomass valorization is governed by several critical parameters that directly influence biochar yield, physicochemical properties and overall process efficiency (Tripathi et al., 2016). The most influential factor is pyrolysis temperature, where higher temperatures (500–700 °C) enhance aromaticity, surface area and carbon stability while lower temperatures (300–400 °C) promote higher biochar yield (Junior et al., 2025). Product distribution is determined by heating rate; biochar formation is facilitated by slow pyrolysis at moderate heating rates (~5–10 $°C\ min^{-1}$), while the production of syngas and bio-oil is favored by fast heating (Junior et al., 2025). Residence time also play a significant, as higher vapor residence times can impact carbon structure, boost secondary reactions and lower volatile content. Heat transfer and conversion efficiency are greatly affected by feedstock characteristics such as moisture content (<10%), particle size (<2 mm) and lignocellulosic composition (Subramaniam et al., 2026). Drying and grinding are instances of pre-treatment processes that improve process consistency and energy efficiency (Qambrani et al., 2017). Controlling thermal deterioration pathways and ensuring consistent product quality are also dependent on the type of reactor and operating parameters (such as an inert environment and a restricted oxygen supply) (Mengesha et al., 2024). For circular bioeconomy systems to maximize biochar yield, improve carbon sequestration potential and enable scalable biomass valorization, these parameters must be precisely controlled and optimized (Bridgwater, 2012).

Improving large-scale production strategies for biochar

One of the most important challenges in biomass valorization is the shift from laboratory-scale research to industrial-scale biochar production. Pyrolysis has shown great promise for turning lignocellulosic wastes into stable carbon compounds, but in order to scale up the process and ensure reliability and economic viability, reactor design, feedstock handling and process optimization must be improved (Beesley et al., 2010; Inyang et al., 2016). To improve productivity, energy efficiency and product consistency, large-scale production technologies such fluidized bed reactors, rotary kilns and continuous pyrolysis reactors have been developed continuous biomass feeding, consistent heat transmission and improved residence time control are made possible by these technologies, all of which are critical for the industrial production of high-quality biochar as shown in table 1 (Hornung et al., 2024). Integrating biochar production with current biomass management and bioenergy systems is another crucial tactic for widespread implementation (Hirst et al., 2018). Utilizing plentiful remainders, such as forestry litter, agricultural waste and agro-industrial by-products, can guarantee a steady supply of fuel while minimizing disposal issues (Higashikawa et al., 2016). Additionally, by combining pyrolysis units with energy recovery systems, syngas and bio-oil produced during the process can be used, increasing total energy efficiency and decreasing running costs (Hamid et al., 2022). Enhancing the production and stability of biochar products also heavily depends on process optimization through temperature control, heating rate modification and feedstock pre-treatment (Guo et al., 2020). Promising prospects for handling biomass residue in inaccessible or wooded areas are also provided by innovations in decentralized pyrolysis units, modular reactor systems and grassroots production models (Aziz et al., 2023). In addition to improving biomass consumption, these tactics support sustainable waste management and the growth of the circular bioeconomy (Goswami et al., 2022).

Table 1. Large-Scale production strategies for biochar

S.No.	Technology	Key Features	Advantages	Limitations	References

1.	**Continuous Pyrolysis Reactors**	Continuous feeding of biomass with controlled residence time and heating	Consistent biochar quality, large production capacity and suitable for industrial scale	Complex process control and high initial investment	(Hoekstra et al., 2009)
2.	**Rotary Kiln Reactors**	Rotating cylindrical reactor permitting uniform heating of biomass	Handles large amount of biomass, good blending and heat transfer	Higher energy consumption	(S.-Q. Li et al., 2004)
3.	**Fluidized Bed Reactors**	For rapid heat transfer, biomass particles are suspended in a hot gas stream.	Uniform temperature distribution, high conversion efficiency and scalable	Requires complex operation and uniform particle size	(Kersten et al., 2005)
4.	**Modular / Decentralized Pyrolysis Units**	Modules of small to medium size deployed near biomass sources	Suitable for rural or forest area and minimize transportation cost	Reduce throughput compared to centralized units	(Nobre et al., 2026)
5.	**Integrated Bioenergy Systems**	Coupling biochar production with bio-oil and	Enhance energy efficiency and economic feasibility	Requires advanced process integration	(Kersten et al., 2005)

		syngas energy recovery		and infrastructure	
6.	**Feedstock Pre-treatment**	Drying, grinding, and size reduction before pyrolysis	Increases biochar yield, improves thermal efficiency and uniformity	Additional energy demand and operational cost	(Ippolito et al., 2020)

Environmental remediation, soil restoration and climate mitigation

As a multipurpose carbon material, biochar has shown great promise in soil recuperation, environmental restoration and climate change mitigation (Ghosh et al., 2023). Biochar has a strong adsorption the ability for a variety of environmental contaminants, such as heavy metals, pesticides and organic pollutants in soil and water systems, owing to its extremely porous structure, vast surface area and abundance of functional groups (Fiore et al., 2018). These characteristics make it possible to effectively immobilize harmful compounds and enhance the quality of the environment (Anupama & Khare, 2021). It has been widely reported that adding biochar to agricultural soils improves soil structure, increases water-holding capacity and improves nutrient retention through increased cation exchange capacity, all of which boost microbial activity and overall soil fertility (Farzad et al., 2016). As a result, using biochar promotes better agricultural yield and sustained soil rejuvenation. Additionally, by transforming unstable biomass carbon into stable aromatic carbon compounds that can endure in soils for hundreds to thousands of years, biochar contributes significantly to the mitigation of climate change (Amalina et al., 2022; Enaime et al., 2020). In light of its capacity to sequester carbon over an extended period of time and its ability to reduce greenhouse gas emissions from soils, including methane and nitrous oxide, biochar is a viable approach to sustainable land management and environmental preservation table 2 (Alfares et al., 2025; Deshoux et al., 2023).

Table 2. Role of biochar in environmental remediation

S.No.	**Application**	**Mechanism**	**Environmental Benefits**	**Findings**	**References**

1.	**Environmental Remediation**	Ion exchange, adsorption, pore entrapment of contaminants and surface complexation	Removal of heavy metals, organic pollutants and pesticides from soil and water	High surface area of biochar, functional groups enhance adsorption of contaminants such as Pb, Cd and organic dyes	(Das et al., 2023b)
2.	**Carbon Sequestration**	Conversion of biomass into stable aromatic carbon structures	Reduced atmospheric CO_2 levels and long-term carbon storage in soil	Biochar stays stable in soil for thousands of years	(Das et al., 2023a)
3.	**Waste Biomass Valorization**	Thermochemical conversion of forest and agricultural residues	Minimization of waste aggregation and environmental pollution	Biochar production supports sustainable waste management and circular bioeconomy	(Das & Ghosh, 2023)
4.	**Greenhouse Gas Mitigation**	Reduction of nitrous oxide (N_2O) and methane (CH_4) emissions from soil	Reduce agricultural greenhouse gas emissions	Biochar improves nitrogen use efficiency and modifies soil microbial processes	(Chen et al., 2020)

5.	**Soil Restoration**	Improvement of nutrient retention, soil structure and microbial activities	Increased crop productivity, enhanced soil fertility and improved water holding capacity	Biochar amendments increase cation exchange capacity, soil organic carbon and nutrient availability	(Chen & Zhou, 2022)

Circular bioeconomy potential of biochar

By transforming low-value biomass residue into marketable carbon products and lowering waste management expenses, biochar production within a circular bioeconomy framework offers substantial economic benefits. Depending on the type of feedstock, pyrolysis process and operational scale, the cost of producing biochar usually ranges from $300 US to 1,200 per ton (Campion et al., 2023). As transportation and feedstock procurement costs are lower in decentralized systems that use locally accessible residues like pine needles, costs can be significantly reduced. Crucially, by balancing operating energy costs and boosting overall system efficiency, integrating biochar production with energy recovery systems (bio-oil and syngas usage) can enhance process economics (X. Li et al., 2024). From the standpoint of the circular economy, biochar helps reduce waste management costs, study indicates that when wastes are valorized in lieu of burned or landfilled, biomass disposal costs are reduced by 30-50% (IEA Bioenergy, 2025). Also, applying biochar to agriculture can cut the amount of fertilizer needed by 10-30%, which lowers input costs while promoting soil productivity (Lehmann & Joseph, 2024). While biochar-based carbon sequestration has been expected to produce $30–120 per ton of CO_2 equivalent through carbon credit mechanisms, carbon markets further improve economic feasibility (Woolf et al., 2010). Global estimates indicate that turning crop residue into biochar could enable large-scale carbon dioxide reduction by stabilizing biomass carbon that would otherwise flow back to the atmosphere (Karan et al., 2023). Biochar has significant carbon sequestration potential in terms of climate impact. likewise, it has been proven that using biochar improves nutrient cycling (N, P, and K) and lowers nitrous oxide (N_2O) emissions, increasing resource efficiency in agricultural systems (Jindo et al., 2020).

From the perspective of the circular economy, biochar solutions may significantly reduce waste streams as thermochemical conversion processes employing forestry residue alongside producing co-products like syngas and bio-oil, which help create biorefinery models with almost zero waste (Carvalho et al., 2022).

Conclusion

Transforming abundant organic residue into valuable resources while reducing environmental impacts require sustainable consumption and effective biomass management. To ensure economic viability and industrial scalability, developments in large-scale biochar production such as enhanced feedstock management, continuous pyrolysis technologies and optimum reactor systems are crucial. These techniques make it possible to effectively transform biomass into stable, carbon-rich materials that have many benefits for the environment. The pine tree, which is well known to be associated with forest fire in most of the developed and developing economy is not readily biodegradable to the toxic phytocompounds consortia and need to be efficiently managed. The review provided valuable insight into the scarce reports on the use of environmental niches as a potential source of biochar, paving the way for better utilization of the resulting biochar along with other by-products. Applications of biochar have shown great promise in soil restoration by enhancing nutrient retention and soil structure, environmental remediation through pollutant adsorption , and climate mitigation through long-term carbon sequestration and a reduction in greenhouse gas emissions. With the urgent need to remove pine needle waste from higher altitudes, the existing studies have provided insight into the advancement of using the waste as a potential source of biochar. When combined, scalable biochar production and sustainable biomass management offer feasible options for ecosystem restoration, resource recovery and advancement of circular bioeconomy endeavours.

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