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REVIEW

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# Role of biochar made from low-value woody forest residues in ecological sustainability and carbon neutrality

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**Abstract**

Forest management activities that are intended to improve forest health and reduce the risk of catastrophic fire generate low-value woody biomass, which is often piled and open-burned for disposal. This leads to greenhouse gas emissions, long-lasting burn scars, air pollution, and increased risk of escaped prescribed fire. Converting low-value biomass into biochar can be a promising avenue for advancing forest sustainability and carbon neutrality. Biochar can be produced either in a centralized facility or by using place-based techniques that mitigate greenhouse gas emissions and generate a high-carbon product with diverse applications. This review explores the multifaceted roles of biochar produced from low-value biomass during forest restoration activities in the context of the United Nations Sustainable Development Goals and carbon sequestration for climate change mitigation. First, the ecological benefits are evaluated, including soil restoration, nutrient cycling, and vegetation enhancement, which are pivotal for restoring post-disturbance forest health and enhancing resilience to future disturbance. Second, we evaluate the role of biochar in carbon sequestration and carbon neutrality objectives, which also foster sustainable soil practices and sustainable forest management. In addition, we highlight biochar markets, commercialization, and carbon credit interactions as emerging mechanisms to incentivize biomass utilization for biochar. The integration of biochar made from low-value woody residues from forest restoration can enhance restoration strategies, engage stakeholders in sustainable land management practices, and mitigate environmental problems while enhancing the resilience of forest ecosystems to future disturbances. The findings underscore the importance of leveraging low-value woody biomass for biochar production as a strategic resource for achieving comprehensive forest restoration goals and fostering sustainable development in forested landscapes.

## 1 | INTRODUCTION

Forests play a major role in the global carbon cycle and are pivotal in mitigating climate change by sequestering carbon dioxide (Pan et al., 2011). In addition, forest ecosystems store more than 80% of the aboveground carbon and greater than 70% of all soil organic carbon (Batjes, 1996). The combined above- and belowground forest ecosystem can remove approximately 2 Pg year$^{-1}$ of carbon from the atmosphere which

**Abbreviation:** SDG, sustainable development goals.

is nearly 30% of anthropogenic $CO_2$ emissions (Bellassen & Luyssaert, 2014; Kohl et al., 2015). The amount of carbon sequestered each year is dependent on the interactions of soil properties (chemical, physical, and biological), climate, topography, vegetation, parent material, and land management practices (Ameray et al., 2021; Jackson et al., 2017; Wiesmeier et al., 2019).

Meeting the demand for wood, fiber, and other ecosystem services necessitates active forest management, including harvesting, which increases the amount and extent of disturbance leading to rapid changes in biogeochemical processes (Noormets et al., 2015). Forest harvest operations such as clearcutting, thinning, partial cutting, or salvage logging result in removal of aboveground and belowground carbon. The belowground carbon, which comprises the litter, soil carbon, and the root biomass carbon, are often uprooted by the movement of heavy equipment during the forest operation activities. In temperate forests, soil carbon losses after harvesting are usually related to reduced carbon inputs from litter and faster decomposition rates (Mayer et al., 2020). The woody biomass remaining on site after silvicultural treatments and other vegetation management activities is called forest residues, and is comprised of a mixture of foliage, twigs, branches, bark, and low-quality or small-diameter stems. Forest residues generated by timber harvest are often called harvest residues or logging residues, but some treatments, such as precommercial thinning and some fuel treatment, can generate large amounts of forest residues without a concurrent harvest of roundwood. Although there is increased demand for using this biomass for bioenergy, much of this material is left on-site in piles, scattered, or left unused because it is expensive to collect and transport to facilities that can use it for bioenergy and bioproducts (Sahoo et al., 2019). Even under the most rigorous sustainability standards, it is common practice in many places to burn post-harvest forest residues to create growing space for regeneration and manage risks associated with wildfire, insects, and diseases. Pile burning, however, leads to missed opportunities for both carbon sequestration and sustainable resource utilization (Evans et al., 2013; Kizha & Han, 2016). In recent years, the United Nations introduced 17 Sustainable Development Goals (SDGs) for industrial forests that form a framework for creating a more environmentally friendly and sustainable future worldwide (United Nations, 2015). These SDGs are related to timber and nontimber forest products and include the successful integration of forest biomass utilization into strategies that align with multiple SDGs, including those related to energy access, climate change mitigation, biodiversity conservation, and economic development.

One key SDG is the improvement of soil health (Xiong et al., 2022). Biochar derived from forest residues is a nature-based solution and a promising avenue for realizing the principles of sustainability while contributing to carbon neutrality efforts (Agyei et al., 2024; Q. Hu et al., 2021; Jindo et al., 2020). Biochar has the potential to significantly enhance soil fertility by increasing the organic matter content in soils, akin to the fertile *Terra preta* soils found in the Brazilian Amazon, which displayed a threefold acceleration in crop growth compared to adjacent soils (Glaser et al., 2001). Biochar added to soil enhances soil quality and health while building and retaining carbon, which consequently plays a significant role in climate change mitigation (Lal, 2016; Lehmann, 2007; Obour et al., 2023). The multi-functionality of biochar creates a comprehensive framework that integrates a method to valorize low-value woody biomass, which could be a crucial component for effectively executing the sustainability model (Ghosh et al., 2020; Lehmann et al., 2003; Rodriguez Franco et al., 2024; Singh et al., 2022).

**Core Ideas**

- Biochar production from unmerchantable forest biomass is an alternative to open pile burning.
- Application of biochar restores degraded forest soil and promotes healthy forest vegetation.
- Biochar from low-value woody residues can promote ecological sustainability and carbon neutrality in forestry.

Biochar has been widely reported to be an excellent material for achieving sustainability in forest soil that has been degraded by wildfire, mining, and other catastrophic soil disturbances (Dubey et al., 2021; Ghosh & Maiti, 2021). For example, Guayasamín et al. (2024) reported an increase in 23%–19% tree growth by biochar produced from forest waste biomass on tropical Amazonian Ecuador forest soil. Further, Li et al. (2024) reported the long-term effect of pine wood biochar application on the Australian subtropical native forest soil, indicating that biochar reduced mineral N loss and promotes plant growth for more than 3 years. In a suburban native forest in Australia, biochar combined with fuel reduction prescribed burning improved water and nitrogen use efficiency in understory acacia growth and soil C and N pools (W. Sun et al., 2024). However, in some locations, the responses to biochar are inconsistent. In subtropical China, Zhu et al. (2024) reported that biochar altered microbial physiological processes, inhibited microbial metabolic quotient ($qCO_2$) and hydrolase activities, and decreased $CO_2$ emission in a relatively fertile soil, but in the relatively barren soil, biochar promoted $CO_2$ emissions by stimulating microorganisms to enhance $qCO_2$ and oxidase activities. In a warm-temperate broadleaved forest in Japan, woody feedstock biochar reduced N mineralization and nitrification rates (Yasuki et al., 2024). Hence, geographically speaking, soil and vegetation responses in varying climatic regimes and forest ecosystems can be strikingly different. In this context, the role of biochar created from woody residues in forest ecosystem sustainability is relatively understudied compared to biochar in agricultural systems and needs attention as an important emerging opportunity.

This review explores the potential of biochar created from low- or no-value woody biomass as a crucial resource within the framework of sustainability, offering multifaceted benefits that extend beyond waste reduction. By converting forest residues into biochar using place-based conversion technologies, organic material is diverted from a carbon intensive disposal pathway (e.g., decomposition, composting, or burning) to a carbon sequestering pathway with additional local environmental benefits (Bruckman & Pumpanen, 2019). This reduces open burning impacts on soil and minimizes wildfire risk while also creating a valuable product with numerous applications (Kumar et al., 2022). Converting woody biomass into biochar could be particularly beneficial in the western United States and other regions prone to wildfire, where wildfire seasons are longer and generate more severe fires compared to the previous decades (Rodriguez Franco & Page-Dumroese, 2021). Local use of wood-based biochar could be a method to increase forest resilience for better adaptation to climate change by increasing water storage and availability to increase forest health by decreasing insect and disease outbreaks. It is important to point out that the local production of biochar is based on using woody residues that would otherwise be burned in piles or left to decompose rather than specifically harvesting living forest biomass for biochar production (Rodriguez Franco & Page-Dumroese, 2021). In general, sustainable forest-based bioenergy and biochar production practices utilize biomass residues and waste materials, such as branches, wood chips, and other biomass not suitable for other purposes, rather than healthy trees harvested to use as feedstock. By using this approach, biochar production can help reduce the environmental impact of waste biomass disposal while also providing a valuable soil amendment and carbon sequestration tool. The goal is to ensure that biochar production is sustainable and does not contribute to deforestation or forest degradation.

The application of biochar in agriculture and mining for sustainability purposes is well-documented (e.g., Ghosh & Maiti, 2021; Glaser et al., 2001; Kammann et al., 2017), but there is a notable gap in the literature for using woody residues to create biochar and its application to forest soil. Agricultural soil research highlights the advantages of using biochar to improve soil health attributes (e.g., nutrient retention and carbon sequestration). Biochar has been noted to be a climate-smart tool during forest management activities to mitigate climate change, increase soil carbon, and reduce greenhouse gases (GHGs) (Rodriguez Franco et al., 2024), but there is a lack of exploration in the role of biochar derived from forest biomass and the pursuit of carbon neutrality. Thus, we aim to highlight the research gaps and explore the potential of converting forest residues into biochar. The review emphasizes the sustainable use of resources and minimizing waste in a closed-loop system, thereby addressing the problems associated with excess hazardous fuels left after harvest operations, which can increase wildfire risk. In essence, forests, forest soils, and forest residues are interdependent and there is a need to understand the role that biochar can play in managing residues and as a strategic tool in advancing sustainability principles and contributing substantively to global efforts for carbon neutrality.

## 2 | WOODY BIOMASS SOURCES AND UTILIZATION

The growing demand for wood fiber presents a dilemma with contrasting perspectives. On one hand, there is a demand to remove all available fiber from forest sites to reduce the risk of wildfire and meet other management objectives, while the counterargument suggests retaining a portion of the woody residues for the preservation of ecological functions and biodiversity (Harvey et al., 1981; Sandström et al., 2019; Schnepf et al., 2009). However, during harvest operations, all woody material cannot physically be removed (Kizha & Han, 2016). Normally, some large-diameter wood, surface organic horizons, and some small-diameter wood is retained on-site for ecological functioning, nutrient cycling, or erosion control, but the remainder is piled within or near the harvest unit. Woody residues that are piled can be considered “waste” biomass when there are no markets and they incur a disposal cost, such as the cost of burning or removal. In practice, woody residues have low value and cannot be sold for products like sawlogs or pulpwood, though they can be used for fuel for energy in some areas. In the United States, low-value woody residues are generated through several different harvesting methods (US Energy Information Administration, 2023):

1. *Mature tree harvesting*: Trees are cut for wood products such as lumber and paper. When harvested, not all of the tree is used for the final products. Branches, bark, foliage, twigs, and other residues are left on-site and generally scattered across the harvest unit to decompose, are broadcast burned, or are piled for later burning.
2. *Stand thinning*: In the absence of natural disturbance or active management, unmanaged forests can become dense compared to managed forests. For example, many forests in the western United States that were once subjected to frequent, low-intensity fire are overstocked due to fire suppression and other land management practices (Polagye et al., 2007). Although there are a wide variety of silvicultural thinning options, stand thinning generally involves

removing small-diameter, subdominant or unhealthy trees, trees with poor form, and trees of undesirable species to reduce competition for resources and improve the health and growth of the remaining trees. Generally, thinned trees are unmerchantable (i.e., precommercial), and all of this biomass is generally piled and burned or left to decompose. Tree pruning removes the lower branches to improve the quality of wood and reduce the risk of fire spread, diseases, or insects and typically takes place in plantation and arboriculture settings, such as urban communities. Pruned branches are also considered unmerchantable biomass and is often destined for a landfill or piled.

3. *Fuel reduction thinning*: This practice is a specific kind of thinning focused on removing understory vegetation and subdominant trees to reduce the risk of wildfire by altering fire behavior. The removed vegetation, including small trees, branches, and other woody material, often has no market value, and is generally piled. In some cases, fuel reduction thinning includes the harvest of merchantable logs.
4. *Forest restoration*: Similar to thinning operations, forest restoration activities aim to restore natural ecosystem processes, enhance biodiversity, and to restore forest stand structure and composition to some desirable reference condition. Restoration might involve planting native species, removing invasive species, and creating conditions that support healthy forest growth such as reducing the number of trees per hectare in forests under drought stress. As part of these activities, excess unmerchantable woody residues are generated and piled.
5. *Salvage logging after wildfire and natural disturbances*: After wildfires or large-scale natural disturbances (e.g., insect outbreaks and hurricanes), there is a large number of dead trees left on-site. Salvage logging removes merchantable material, leaving behind biomass like a normal timber harvest. However, if harvest operations are delayed, the dead trees may have little or no market value and larger amounts of biomass are piled and later burned for disposal to reduce a hazard to infrastructure like power lines, roads, campgrounds, and trails.

In practice, many of these activities can occur simultaneously on the same site. For example, the harvest of merchantable sawlogs and pulpwood can be incorporated into fuel reduction thinning or forest restoration that also removes nonmerchantable vegetation from the forest. The foremost priority for efficient utilization of forest biomass from any of these activities is meeting management objectives. Often those include reducing the cost of forest operations and wildfire risk or improving post-harvest site conditions and ecosystem services (Huffman et al., 2020; Stephens et al., 2020).

Interest in removing low-grade wood from forests has increased because of rising fossil fuel costs, concerns about carbon emissions from fossil fuels, and the risk of catastrophic wildfires (Evans et al., 2013). In many places, forest residues are underutilized because the costs involved in collection and transportation are higher than their market value or there is no market (Ghaffariyan et al., 2017). Piling and burning slash continues to be a forest management practice because it is a rapid method to reduce pile size at a low cost (Nance, 2023). For example, in British Columbia, 69%–80% of the residues generated during harvesting are delivered to the roadside, piled, and burned (Nance, 2023). This biomass disposal option causes air pollution, adds carbon dioxide to the atmospheric carbon sink, can produce burn scars that last for decades (Rhoades & Fornwalt., 2015), and often stagnates the process of plant succession (Huffman et al., 2020). Utilization of woody biomass to create biochar or bioenergy can help mitigate the negative effects of open pile burning.

## 3 | CURRENT TRENDS IN FOREST BIOMASS UTILIZATION

Low-value biomass can play a significant role in achieving sustainability through forest management activities for its utilization and the development of forest biomass derived industry (Figure 1).

### 3.1 | Forest biomass utilization

Woody residues can be utilized in various ways within a sustainability framework:

1. *Bioenergy*: Forest biomass can be converted into heat, electricity, and fuel through a variety of conversion pathways, including combustion, gasification, pyrolysis, and biological conversion (Huang et al., 2020). Renewable bioenergy reduces reliance on fossil fuels and contributes to a more sustainable energy mix. The bioenergy potential of logging residues is dependent on many variables such as tree species, harvest system, or recovered residues and it depends on demand for roundwood, plantation establishment rates, and wood supply (Smeets & Faaij, 2007). Nevertheless, by 2050, logging residues can be a significant source of bioenergy. Thus, technology development for the utilization of woody residues can help reduce the amount of biomass that could be treated within the forest.
2. *Bioproducts*: Forest biomass can be used to create a wide range of bioproducts, including bio-based materials, chemicals, and textiles. For example, wood can be transformed into sustainable building materials, such as engineered wood products and bio-based plastics (Ghaffariyan et al., 2017). It can also be pyrolyzed to make a useful byproduct like biochar. Biochar, for example, can be an additive to cement to sequester carbon and extend

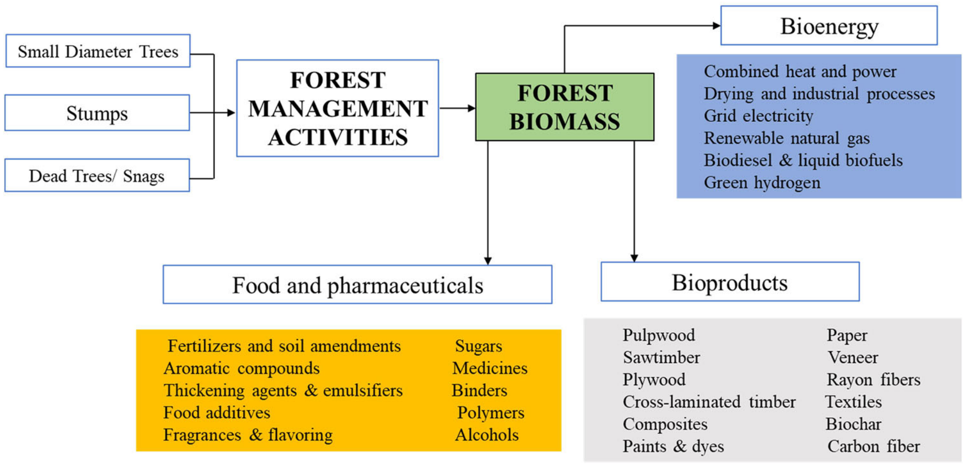


**FIGURE 1** The current trends of forest biomass utilization.

the life of the composite (Tan et al., 2021). Biochar can also improve soil physical, chemical, and biological properties such as nutrient and water retention, and carbon sequestration (Kumar et al., 2022).

3. *Food and pharmaceuticals*: Non-timber uses for forest biomass include medicines, crafts, and food. Often, small-diameter biomass is used in cook stoves, but forests are also sources of non-timber, non-fiber forest products such as aromatic spices, fruits, roots, seeds, nuts, bark, and fungi (Shanley et al., 2015). Pharmaceuticals and botanical medicines are other non-timber forest biomass uses (Laird & Wynberg, 2005). Extracting these compounds sustainably from forest biomass, especially foliage and bark, can reduce the need for synthetic alternatives.

## 3.2 | Scope of biochar production from forest biomass

Forest residues generated during forest management activities offer an excellent source of biomass feedstock for biochar production. The 2023 Billion-Ton Report indicates that the harvest for conventional forest products is about 198.67 million dry metric tons per year, leaving about 1270 million metric tons of tree biomass unharvested on timberland across the United States annually (US Department of Energy, 2024). In terms of biomass production potential, this report projects that depending on price, potentially 19 million dry tons per year and 35 tons per year could be available from forest residues and harvest of small diameter trees, respectively, in the United States, in a mature market biomass supply scenario (US Department of Energy, 2024). In this context, sustainability of this biomass supply is tied closely to regeneration of the forest stands (i.e., keeping land in forested land use), as well as objectives of maintaining site productivity, maintaining habitat, controlling erosion, maintaining nutrients, and mitigating nutrient deficiencies on harvested sites. Recently, the US Department of Agriculture, Forest Service implemented a wildfire crisis strategy that highlights the federal government plans to treat up to 20 million acres on the National Forest System in the West, and also treating up to an additional 30 million acres on other Federal, State, Tribal, and private lands in the West (USDA Forest Service, 2022). This is expected to generate additional amounts of unmerchantable wood that can be used for bioproducts, including biochar, especially from small-diameter trees.

Woody biomass generally has higher cellulose, hemicellulose, and lignin content than crop residues, herbaceous plants, or grasses (Ippolito et al., 2020; Kloss et al., 2012). In particular, trees have a higher lignin content that promotes carbonization and leads to increased biochar production rates (Demirbas, 2004). Several resources provide detailed information and data comparing the physical and chemical characteristics of a wide range of biomass feedstocks, including forest and mill residues (Cai et al., 2017; Emerson et al., 2016; Hartley et al., 2020), which have implications for biochar production from these feedstocks. Previous studies have shown that feedstock species may also strongly influence biochar surface characteristics (surface area, pH, and functional groups), thereby affecting their potential environmental applications (Ippolito et al., 2020; Sandhu & Kumar, 2017). Moreover, biochar derived from wood biomass generally exhibits a greater surface area compared to that derived from grass biomass, as indicated by studies such as Mukherjee et al. (2011). A review conducted by Rodriguez Franco and Page-Dumroese (2021) reported that wood-based biochar has low or no polyaromatic hydrocarbon or dioxins/furans contaminants and, if present, the levels are generally lower than current cleanup levels required by law.

Thomas and Gale (2015) reported that the biochar derived from woody residues possess distinctive properties that make them suitable for application in forest restoration. These include high durability and the ability to retain cations, anions, and water, and provide a refugia for beneficial soil microorganisms (Sheng & Zhu, 2018) within the surface and subsurface soil profile (Lorenz & Lal, 2014). Additionally, their sorptive properties enable the reduction of bioavailability for various toxic materials with the greatest biochar benefits found on low fertility, contaminated, (Rodriguez Franco & Page-Dumroese, 2021), or low organic matter soils (El-Naggar et al., 2019; Shaaban et al., 2018). Furthermore, the relative ease of production from locally available feedstocks using place-based technologies to create biochar adds to the appeal for creation and use in forest restoration efforts. Wood-based biochar has a significant potential to address several environmental issues including remediation of pollutants in soil, water, and gaseous media (Rodriguez Franco & Page-Dumroese, 2021; Thomas & Gale, 2015), with subsequent improvement in soil health, water and air quality, carbon sequestration, GHG emissions, vegetation establishment, erosion, and bioavailability of contaminants, and, thus, promote vegetation establishment.

### 3.3 | Placed-based production systems

Biochar production can occur at a variety of scales ranging from fixed bioenergy facilities to small-scale conservation burned hand piles. Because the generated forest biomass is often left in the forest at roadsides and log landings, much of the work to create biochar uses place-based production methods when transportation to a fixed plant is not feasible. This means that controlling for temperature, moisture content, and tree species will be limited, but it also means that locally produced biochar is used on local soils to avoid additional handling and transportation costs. For carbon sequestration and climate change mitigation, adding biochar to forest soils at the production site also decreases transportation emissions.

When creating biochar in or near forest harvest operations, there are various methods that can be used, including conservation hand piles and machine piles, kilns of various sizes and configurations, and air curtain burners. For details on all place-based technologies, see Wilson et al. (2024). In general, there are three general categories of place-based technologies:

1. *Kilns*: Traditional kilns involve the use of bricks or metal drums for creating an oxygen limiting environment for biochar production (Shamim et al., 2015). Traditional brick kilns are relatively inexpensive but may not be very efficient and are difficult to move. Metal drum kilns are often repurposed oil drums or similar containers. They are relatively easy to build and use, making them accessible for small-scale biochar production. However, they may not provide as much control over the pyrolysis process as more advanced kiln designs and have relatively low production throughput. Larger kilns (e.g., Ring of Fire Kiln [Wilson Biochar, LLC] and Big Box Kiln [Utah State University]) can be made or purchased and these provide greater capacity for biochar production. Retort kilns depend on external heating and come in a wide variety of sizes, some of which are suitable for place-based production of biochar.
2. *Rotary kilns*: These continuous pyrolysis systems rotate the biomass during the heating process, which ensures the biomass is heated uniformly, leading to consistent biochar quality (Moser et al., 2023). They are often used for large-scale production and can yield biochar with specific physical characteristics, such as the porosity, depending on the design and residence time, but are generally more difficult to mobilize than kilns. This type includes drum, auger, and some hearth-based systems.
3. *Air curtain burners*: Air curtain burners, also known as air curtain incinerators, are industrial devices that are sometimes used for biochar production. These machines are primarily designed for the controlled combustion of biomass, which harness the heat generated by the combustion process to pyrolyze biomass into biochar efficiently (Oyier et al., 2024). Air burners work by forcing air at high velocity through a series of nozzles into a combustion chamber (Page-Dumroese et al., 2024). This creates an air curtain that contains the flames and ensures complete combustion of the organic material. Air curtain burners are suitable for handling larger volumes of biomass quickly compared to kilns, making them suitable for large-scale biochar production.

Designer biochars are for specific purposes and can be created for specific needs, such as remediating contaminated soils. However, to take advantage of the large volume of easily accessible woody residues in slash piles for carbon sequestration and soil health, then selecting the appropriate place-based biochar production method is essential for a successful biochar based restoration of a degraded land. Considerations of available crews, amount of water needed, the size of the area available for safely deploying equipment, and if an excavator or other equipment is needed to load the kiln or air burner (Wilson et al., 2024).

## 4 | BIOCHAR APPLICATION AND SUSTAINABILITY IN DEGRADED SOILS

Biochar applications to degraded soils offer a sustainable solution to enhance soil health and productivity. By incorporating biochar into degraded soils, we can restore soil fertility, enhance vegetation yields, and promote sustainable land management practices that contribute to long-term environmental health and resilience.

### 4.1 | Abandoned mine sites within forested landscapes (low contaminants)

Surface mining causes the complete destruction of vegetation, soil structure, and biodiversity. This leads to huge overburden dumps, which change the topography and drainage and causes ecosystem pollution (Maiti, 2013). Mine spoil dumps generally have high rock-fragment contents, impoverished soil conditions, extremely low water holding capacity, no organic carbon and nutrients, acidic pH, and low cation exchange capacity, which pose difficulties in biological reclamation (Fellet et al., 2011; Ghosh et al., 2020; Jain et al., 2016; Peltz & Harley, 2015). Williams and Thomas (2023) studied the impact of wood ash biochar for mine tailing restoration and its impact on planted tree performance and metals uptake. The study showed that the survival and growth of saplings peaked at mid-range dosages of 3–6 t $ha^{-1}$, also the ion supply of P, K, and Ca in tailings increased in response to wood ash biochar. Reverchon et al. (2015) studied the impact of eucalyptus biochar on the growth and nutrient status of a native legume, *Acacia tetragonophylla*, grown in a mixture of topsoil and mine spent. Biochar increased soil pH, C content, and C/N ratio. The study concluded that the revegetation of mine sites with acacia in combination with biochar amendment constitutes a plausible alternative to the wide use of N fertilizer. Similarly, Ghosh et al. (2020) reported that biochar produced from an invasive weed growing on coal mining sites significantly improved the mine spoil properties and promoted plant growth. By supporting vegetation, biochar helps restore ecosystems and promote biodiversity in reclaimed mine lands (Rodriguez Franco & Page-Dumroese, 2021). Furthermore, its long-term carbon sequestration capabilities contribute to climate smart strategies, while its production from waste biomass adds an element of cost-effectiveness and resource efficiency to mine restoration efforts. Hence, by linking silvicultural practices, place-based biochar production, and mine reclamation practices, it is possible to restore soil health, promote plant growth, and enhance the overall sustainability of mined lands, thereby transforming them into functional ecosystems.

For the widespread implementation of biochar, it is crucial that the production process is simple, cost-effective, and readily accessible at reclamation sites during plantation. Particularly in the regions where the reclamation areas for mining projects can span from 50 to 200 hectares, there exists a significant potential for the application of biochar in these regions (Ghosh & Maiti, 2020). The current scenario presents an opportunity for substantial biochar utilization. Envisioning the large-scale adoption of biochar, this approach holds the promise of spurring technological advancements, increasing its application, and gaining acceptance within the mining industry. Since many active and abandoned mine sites occur near or on National Forests, one avenue for creating the biochar used to remediate these soils is from local harvest operations where biochar can be made near- or on-site (Page-Dumroese et al., 2024). In addition, as new mine areas are opened, biomass generated could be converted into biochar for ecorestoration of these mines. At present, the utilization of biochar in mine spoil reclamation is in its initial stages. Over time, as the mining sector recognizes the advantageous outcomes of employing biochar for sustainable mine spoil reclamation, the technology for producing biochar will inevitably progress. This progression, in turn, will naturally facilitate the expansion of large-scale biochar production and its widespread application. Ultimately, the seamless integration of biochar into mine spoil reclamation stands to contribute significantly to sustainable practices, technological advancement, environmental well-being on a broader scale, and promoting sustainability.

### 4.2 | Abandoned mine sites within forested landscapes (with contaminants)

Soils act as a repository for various contaminants, both organic and inorganic, as they can bind or form complexes with organic matter, such as humus (Brockamp & Weyers, 2021). Once contaminants enter the soil, they can disrupt biogeochemical processes, be transported through eroded sediments and water, be absorbed by plants leading to phytotoxicity, and pose various environmental risks to human and animal health. Heavy metal contamination due to mining activities can range from single metal contamination to a multitude of metal(oid) contamination, tailing ponds and the peripheral soil near the mining operation site requires a remediation technology, which is sustainable and effective. The alkaline nature of the organic components in biochar reduces the bioavailability of heavy metals in soil (Paz-Ferreiro et al., 2017). A meta-analysis on 74 studies by Chen et al. (2018) indicated a substantial reduction in the average concentrations of available Cd, Pb, Cu, and Zn in soil by 52%, 46%, 29%, and 36%, respectively, after the application of biochar. Lu et al. (2017) reported that the addition of bamboo biochar at a rate of 5% (w $w^{-1}$) led to a decrease in extractable Cd, Cu, Pb, and Zn concentrations in contaminated soil. This effect can be attributed to the interaction between surface functional groups on the biochar and the heavy metals, resulting in immobilization (Table 1). Similarly, Fellet et al. (2014) reported that the biochar produced from the pruning residues from orchards has the potential to remediate the bioavailability of Cd, Pb, Tl, and Zn in a contaminated soil. In summary, utilizing biochar for heavy metal remediation aligns with the sustainability principles by repurposing waste materials, promoting resource efficiency, and minimizing environmental impact. It not only addresses pollution issues but also can contribute to sustainable agricultural practices.

**TABLE 1** Impact of biochar application on degraded soil in mining, heavy metal contaminated and wildland sites.

| Biochar type | Soil type and crop/test plant | Role of biochar | References |
|---|---|---|---|
| **1. Mine degraded soil** | | | |
| *Lantana Camara* 450˚C for1 h 0–30 g $kg^{-1}$ | Coal mine degraded soil/corn | Significant ameliorative effects were observed with increase in organic carbon content (2.9 times), cation exchange capacity (two times), water holding capacity (0.13 times), and decrease in bulk density (0.5 times) in the mine spoil. The seedling vigor index and germination also increased significantly at 30 g $kg^{-1}$ biochar treatment compared to control. | Ghosh et al. (2020) |
| Lemongrass (*Cymbopogon flexuosus*) | Metal contaminated coal mine spoil/*Cymbopogon martini* | Biochar amendment @ 4% (w $w^{-1}$) reduced the bioavailability of toxic metals present in the mine spoil and increase heavy metal immobilization. | Jain et al. (2016) |
| Invasive weeds 450˚C 10–20 t $ha^{-1}$ | Coal mine degraded soil | Soil properties such as moisture content (+27%), available-N (+3%), exchangeable-K (+15%), and cation exchange capacity (+35%) improved at 20 t $ha^{-1}$ compared to control. Additionally, the total C-stock increased by 13 and 91% at 10 t $ha^{-1}$ and 20 t $ha^{-1}$, respectively. | Ghosh and Maiti (2023) |
| Orchard prunings 500˚C 10% (v $v^{-1}$) | Abandoned metal mine soil | Biochar application reduced Cd (50%), Cu (51%), and Zn (86%) concentrations in the sampled pore water of the mine spoil. | Beesley et al. (2014) |
| Holm oak wood (*Quercus ilex*) 400˚C for 8 h 4% (w $w^{-1}$) | Mine tailing pond | Biochar in combination with compost and *Brassica juncea* L. was effective in reducing the phytoavailable contents of Cu, Pb, Ni, and Zn. | Forján et al. (2017) |
| Wood biomass 500˚C 5% (w $w^{-1}$) | Former Gold mine | Biochar @5% (w $w^{-1}$) reduced the As (24%), Pb (44%), and Sb (54%) concentration in the pore water. | Lomaglio et al. (2017) |
| Oak, beech, and charm @2% (w $w^{-1}$) 500˚C for 3 h | Technosol from a former tin mine extraction site | Biochar could be applied only at the upper 30 cm of the soil when plants with a shallow root system. | Simiele et al. (2020) |
| **2. Heavy metal contaminated soil** | | | |
| Pruning residues from orchards, fir tree pellets 500˚C @10% (w $w^{-1}$) | Mine tailings | Biochar @10% (w $w^{-1}$) decreased the bio-availability of Cd, Pb, Tl and Zn of the mine tailings. | Fellet et al. (2014) |
| Corn cob | Metal mine trailing, *Jatropha curcas* | Biochar @5% (w $w^{-1}$) decreased the Cu, Zn, Cd, and Pb content by 33%, 41%, 70%, and 53%, respectively. | González-Chávez et al. (2017) |
| *Arundo donax* 600˚C and for 2 h | Non-ferrous metal tailing, Wheat | Biochar @5% (w $w^{-1}$) decreased the phytotoxicity of Cu, Cd, and Pb but increased phytotoxicity of As and Sb. | Gu et al. (2020) |
| Bamboo 500˚C for 30 min | Cd, Cr, Ni, Cu, Pb, Zn contaminated soil, and *Brassica napus* | Bamboo biochar @ 2% (w $w^{-1}$) reduced the exchangeable fraction of Cu, Pb, and Zn by 71%, 84%, and 53%, respectively. | Munir et al. (2020) |
| Hardwood 0%, 2%, or 5%; w $w^{-1}$ | Soil of historic hydraulic gold mine sites | Biochar can be an effective remediation agent for metal mine-contaminated water, soil, and sediment. | Brandt et al. (2021) |
| British oak, ash, sycamore, and birch @20% (v $v^{-1}$) | Copper-contaminated soil | Biochar effectively reduced pore water Cu concentrations. Shoot Cu and Pb levels were also reduced. | Karami et al. (2011) |
| Oak, Beech, and Charm 500˚C @ 10% (w $w^{-1}$) | Pb- and As-contaminated soil | Biochar lower soil pore water Pb concentration (0.0047 mg $kg^{-1}$). | Benhabylès et al. (2020) |

(Continues)

**TABLE 1** (Continued)

| Biochar type | Soil type and crop/test plant | Role of biochar | References |
|---|---|---|---|
| Birch and pinewood<br>500°C for 3 h<br>@2% or 5% (w $w^{-1}$) | Pb and As, *Phaseolus vulgaris* | Biochar application reduced pore-water Pb concentration while having no effect on the As concentration. | Lebrun et al. (2018) |
| 3. **Degraded forest soil** | | | |
| Common reed<br>300°C<br>1% (w $w^{-1}$) | Forest soil and bamboo | Soil water content increased to 15%, available nitrogen decreased, and pH increased. It also altered the keystone taxa during the intermediate phases of the treatment, thereby enhancing the stability of the ecological network. | Wu et al. (2023) |
| Oak pellet-derived<br>550°C<br>0%–20% | Forest Haplic or Albic Luvisol | A decreased abundance of arbuscular mycorrhizal fungi (AMF) was observed shortly after the addition of biochar to soil and attributed to a temporary increase in nutrient availability. | Hardy et al. (2019) |
| Oak pellet-derived<br>550°C<br>0%–20% | Luvic Phaozem and Haplic Luvisol | Biochar addition proportionally increased microbial abundance in all soils and altered the community composition, particularly at the greatest addition rate, toward a more gram-negative bacteria-dominated community. | Gomez et al. (2014) |
| Chinese fir (400°C)<br>12.5 g charcoal/kg soil | Chinese fir plantation soil | Reduced the soil bulk density due to high porosity, large surface area of biochar, and irregular and fluffy granular structure. | Meng (2014) |
| Sugar maple wood<br>500°C at a rate of 30°C $min^{-1}$<br>5, 10, and 20 t $ha^{-1}$ | Phosphorus-limited forest soil | The cumulative soil $CO_2$ respired was higher for biochar-amended samples relative to controls indicating improved soil microbial activities. | Mitchell et al. (2015) |
| Spruce<br>500°C and 650°C<br>0, 5, and 10 t $ha^{-1}$ | *Pinus sylvestris* forests | Biochar amendment rates of 5–10 t $ha^{-1}$ to boreal forest soil do not cause large or long-term changes in soil $CO_2$ effluxes or reduction in native soil C stocks. | Palviainen et al. (2018) |
| *Cunninghamia lanceolata* leaf or woodchip<br>1% or 3% w $w^{-1}$<br>300 °C or 600 °C | Mountain acidic red loam soil | Biochar soil treatments improved the P-solubilizing bacteria in soil which can indirectly improve P availability in soil. Biochar application also improved the growth of vegetation in forest soil. | Zhou et al. (2020) |
| Douglas-fir slash<br>30 min at 420°C<br>0%, 1%, and 10% biochar | Humo-ferric podzol with a gravelly sandy-loam texture | Biochar application at high (10%) application rates increased $CO_2$ and $N_2O$ emissions when applied without urea-N fertilizer. | Hawthorne et al. (2017) |

## 4.3 | Application of biochar for sustainability of wildland soils

Although the use of biochar in wildland soils may pose more logistical challenges than in agricultural systems, these environments offer substantial opportunities to improve soil quality through the application of biochar (Page-Dumroese et al., 2016; Zhang et al., 2022). For example, the pattern, distribution, and severity of forest fires may result in large-scale impacts on species diversity and regeneration. Biochar offers the prospect of mitigating fire risks by effectively managing the presence of highly combustible excess woody biomass materials within forest sites (Anderson et al., 2013). Furthermore, it has the capacity to enhance soil water retention, nutrient availability, and promote improved vegetation growth by augmenting soil physical and chemical characteristics (Blanco-Canqui, 2017; Thomas & Gale, 2015). Moreover, considering the significant role of charcoal in fire-maintained ecosystems following natural and prescribed fire, the application of biochar is anticipated to closely resemble the soil attributes associated with naturally regenerated charcoal (Page-Dumroese et al., 2016). Wu et al. (2023) reported that the application of common reed biochar in forest soil improved the water content by 15% and it also altered the keystone taxa during the intermediate phases of the treatment, thereby enhancing the stability of the ecological network. Sujeeun and Thomas (2023) reported that the application of biochar helps mitigate the allelopathic effect of the black walnut (*Juglans nigra*) and Norway maple (*Acer platanoides*) in the native plant species. A meta-analysis of recent studies on biochar responses of woody plants indicates a potential for large tree growth responses to biochar additions, with a mean 41% increase in biomass (Thomas & Gale, 2017).

The porous nature of the biochar holds the potential to enhance various crucial physical attributes of the degraded wildland soils. Its application yields significant benefits, especially concerning the reduction of soil bulk density on skid trails and log landings in forestry operations (Page-Dumroese et al., 2016). The restoration of ecosystem processes on National Forests and Grasslands or on rangelands in the United States often involves the removal of roads. In this context, roads are frequently decompacted using mechanized equipment (i.e., "ripped") to alleviate soil surface compaction. This practice typically employs equipment such as bulldozers with plows or grapplers to lift the roadbed. Once the process of decompaction is achieved, soil amendments can be introduced either by surface application or through mixing. The removal of outdated or unused roads presents a valuable opportunity to employ biochar as an organic addition (Mitchell et al., 2015). This serves the dual purpose of incorporating organic matter and contributing to the maintenance of lower bulk density through the formation of micro-aggregates, which further facilitates vegetation establishment (F. Sun & Lu, 2014), thus aligning with the goal of sustainability by improving post-harvest forest and soil health.

Wildland soils can be a GHG sink or source, by either contributing to the atmospheric levels of $CO_2$, $CH_4$, and $NO_X$ or storing them. Adding biochar to wildland soils has a long-term impact on the physical, chemical, and biochemical attributes of the soil, thereby exerting both direct and indirect influence on the emission of GHGs (Table 1). A study conducted in the coastal region of Dongtai, China, on poplar (*Populus*) plantations reported that the addition of biochar (80–120 t $ha^{-1}$) displayed an inhibitory effect on the emissions of $CH_4$ and $N_2O$ from saline soil (G. B. Wang et al., 2019). Meanwhile, when applied to a pine forest soil, biochar exhibited a dual positive impact by alleviating $N_2O$ and $CO_2$ emissions, with a significant (31.5%) $CO_2$ emission reduction (L. Y. Sun et al., 2014). Thus, the application of biochar can play an active role in the reduction of GHG emissions and help ensure the goals of sustainability.

Biochar application contributes to the development of sustainable land management practices with continuous improvement and resource optimization. In summary, biochar application in forest and range soils supports soil health, carbon sequestration, and promote sustainability. It offers a holistic approach to sustainable land management that addresses environmental challenges and promotes resilient ecosystems.

## 5 | BIOCHAR, CARBON NEUTRALITY, AND INDIRECT EMISSIONS

### 5.1 | Biochar application and carbon fixation

The stability of the biochar is due to its high recalcitrance, that is, resistant to microbial decomposition. This resistance is due to the loss of functional groups such as -OC and C-O-C during the pyrolysis of the biomass, which often rearrange itself to form more aromatic rings that become more condensed by bond formation amongst the rings (Bird et al., 2015; Tomczyk et al., 2020). Due to the biomass devolatilization during pyrolysis, the biochar is enriched with carbon and other inorganic nutrients. H and O are removed due to the heat of pyrolysis and the predominant remaining element is C, which cause the decrease in the H/C and O/C ratios. A decreasing H/C ratio in biochar indicates an increasing aromatic structure in the biochar, providing enhanced stabilization than biomass (Ghosh et al., 2020). The mean residence time (MRT) of biochar in soil is influenced by factors such as pyrolyzing temperature, O/C ratios, and soil clay content. Biochar produced at temperatures exceeding 800°C have lower O/C ratios (~0.2) and exhibit a longer MRT of ~1000 years in the soil. Despite yielding less biochar, it is more resistant to weathering and degradation, primarily due to its recalcitrant carbon pool constituting approximately 97% of its composition (J. Wang et al., 2016). The decomposition rate of biochar in soil is notably slower when the soil has a clay content ranging from 40% to 70%. Although there is a potential for biochar decomposition in soils, the recalcitrant carbon content contributes to an extended MRT, lasting well beyond 600 years. Microbial decomposition of biochar is limited due to its high stability, impacting soil microorganisms by modifying the soil environment (Zhang & Shen, 2022). The study conducted by Sarauer et al. (2019) reported that biochar application in forest soil increased soil C content by 41% and can be an agent for carbon sequestration in forest soils. In conclusion, while there exists a possibility of biochar decomposition in soils, its gradual rate and the persistence of the recalcitrant carbon pool contribute to an extended MRT. The influence of biochar on soil microbial communities suggests potential benefits for soil health and fertility, with ongoing research expected to provide further insights into its dynamics in diverse soil environments.

### 5.2 | Indirect impacts of biochar on GHG emissions

Methane ($CH_4$) is a potent GHG with a global warming potential of approximately 25 times that of carbon dioxide over a 100-year period (IPCC, 2007). The application of biochar in soil management can result in both positive and negative impacts on soil $CH_4$ emissions. Some studies suggest that biochar application has the potential to reduce methane emissions due to its high surface area, which limits the release of GHGs into the atmosphere (Nguyen & Van Nguyen, 2023). Furthermore, biochar has been observed to foster the growth of methanotrophic bacteria, leading to decreased methane emissions. The study by Karhu et al. (2011) also indicates that biochar amendment can enhance $CH_4$ uptake in soil by improving soil aeration and increasing $CH_4$ diffusion through the soil. The increased porosity of biochar may contribute to higher soil water holding capacity, stabilizing fluctuations in $CH_4$ flux caused by changes in water content.

Conversely, biochar application has been associated with instances of increased methane emissions. Biochar application can add a carbon-rich substrate that boosts microbial activity, including processes like methanogenesis. Furthermore, under specific conditions, biochar may alter soil aeration, water dynamics, and temperature, creating environments favorable for methanogenesis and subsequently raising methane emissions. Spokas and Reicosky (2009) observed varied effects on methane emissions when different types of biochar were added to soils. Similarly, Yu et al. (2013) noted that in soils with low moisture content, biochar enhanced $CH_4$ emissions due to its impact on soil pH and microbial activity. Conversely, in moister soils, biochar increased $CH_4$ emissions consistently over the incubation period. The addition of organic carbon from biochar provided a substrate for methanogens and promoted anaerobic conditions, which facilitated $CH_4$ emissions.

Biochar has been reported to aid in the reduction of nitrous oxide ($N_2O$) emissions, another potent GHG with a global warming potential of 298 times that of carbon dioxide (IPCC, 2007). Soil microbial processes, including nitrification, denitrification, and nitrate ammonification, are significant contributors to $N_2O$ emissions (Baggs, 2011). Studies indicate that biochar application decreases $N_2O$ emissions by 38%–54% on average (Borchard et al., 2019; Bruun et al., 2011; Cayuela et al., 2014). The observed reductions in $N_2O$ emissions are associated with changes in pH affecting the $N_2O$-to-$N_2$ ratio during denitrification, alterations in microbial abundance, increased adsorption of $NH^{4+}$ or $NO^{3-}$, and improvements in soil aeration and porosity, affecting soil water dynamics and leading to lower denitrification rates. The impact of biochar on microbial activity is a key driver of these changes. The influence of biochar on soil $N_2O$ emissions varies depending on the specific soil type to which it is added. The potential mitigation of $N_2O$ by biochar can differ due to various factors, including environmental conditions, soil characteristics, and crop management practices (Baggs, 2011). Therefore, the outcomes of studies evaluating the effects of biochar on $N_2O$ emissions might show variability, emphasizing the need for region-specific research to understand the role of biochar in mitigating GHG emissions and promoting sustainable soil and crop management practices.

The biochar production techniques itself can also be a carbon negative technique for carbon neutrality. The relationship between MRT and the carbon efficiency of biochar production centers on a trade-off: biochar with longer MRTs (more stable in soil) are often produced at higher pyrolysis temperatures, which reduce carbon efficiency by releasing more carbon as gases. In contrast, optimizing carbon efficiency (retaining more carbon in the biochar) might result in shorter MRTs because the biochar contains more labile, less stable carbon. Balancing these factors is key to maximizing both production efficiency and long-term carbon sequestration potential. With the emergence of the new carbon removal economy, this line of applied research would be of great value for entrepreneurs, investors, financiers, policymakers, and various potential market participants to better understand the dynamics behind commercial carbon removal projects via biochar production.

### 5.3 | Plant yield and C-sequestration improvements

Biochar application in forest soils can lead to improvements in plant yield and carbon sequestration through several mechanisms tailored to the specific conditions and needs of forest ecosystems:

1. *Increased nutrient availability*: Biochar amendments enhance soil nutrient retention and availability (Y. L. Hu et al., 2018; Lehmann et al., 2003). This improvement facilitates the availability of essential nutrients such as nitrogen, phosphorus, and potassium for the plant uptake. The enhanced nutrient availability better plant growth and biomass accumulation, leading to increased carbon sequestration within the plant tissues of the forest vegetations.
2. *Enhanced plant growth and root development*: Biochar can improve soil structure, water retention, nutrient availability, and microbial activity (Ghosh et al., 2020). These factors collectively create a more favorable environment for root growth, leading to healthier and more vigorous plants. Additionally, biochar can help reduce nutrient leaching and enhance soil fertility over the long term. The porous structure of biochar provides a conducive habitat for beneficial soil microbes, enhancing soil health and nutrient uptake. With stronger root systems, plants can access more nutrients and water, leading to higher biomass production and increased carbon sequestration potential.
3. *Improved water use efficiency*: Biochar-amended soils have improved water retention due to enhanced soil structure, increased water retention capacity, and reduced water drainage (Basso et al., 2013; F. Sun & Lu, 2014). These factors collectively help maintain adequate soil moisture levels for plant uptake, thereby promoting more efficient use of water resources by vegetation in forest ecosystems and contributing to increased carbon sequestration.
4. *Reduced GHG emissions*: Biochar application in forest soils offers a promising strategy for reducing GHG emissions (Nguyen & Van Nguyen, 2023). Lower GHG emissions led to fewer carbon losses, allowing more carbon to be retained and sequestered in the plant biomass. These effects contribute to a net decrease in overall GHG emissions from forest ecosystems where biochar is

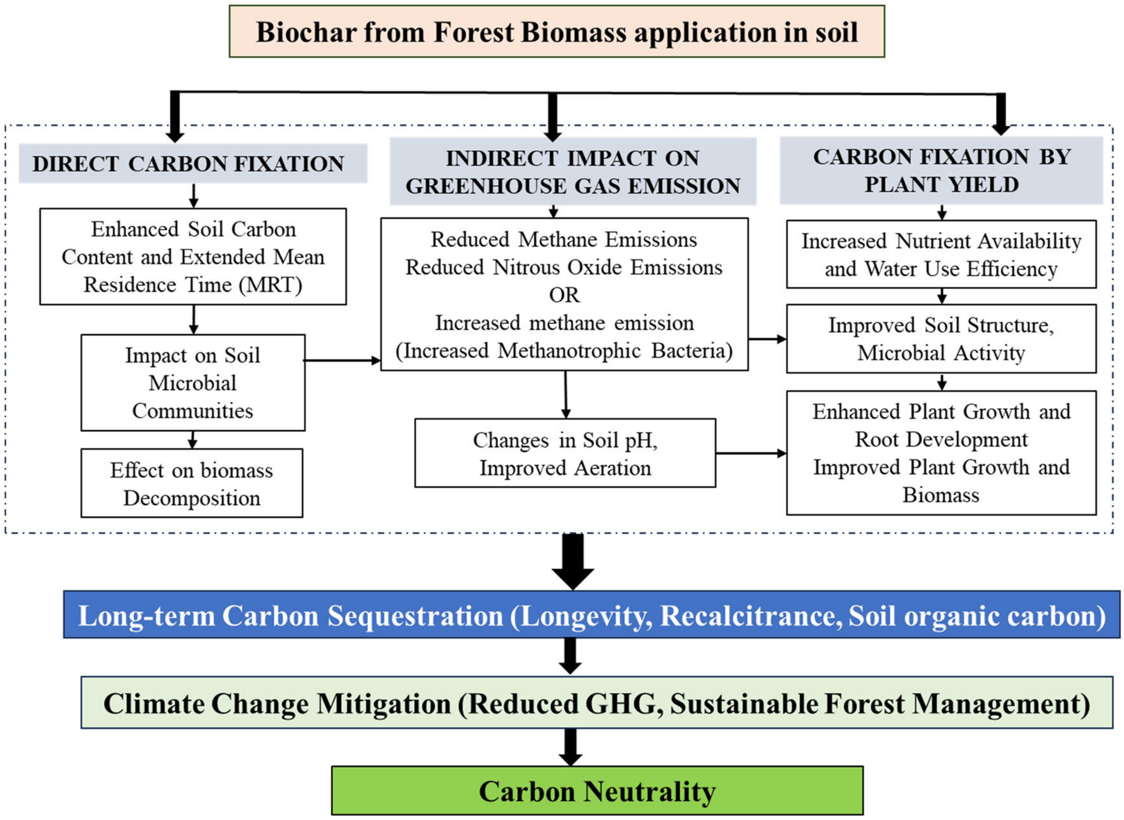


FIGURE 2 Biochar application in forest soil can promote carbon neutrality by direct and indirect pathways. GHG, greenhouse gas.

applied, making it a valuable tool in efforts to combat climate change.

5. *Recalcitrance of biochar-derived carbon*: Biochar, produced through pyrolysis of organic materials, undergoes structural changes that render its carbon content less susceptible to microbial breakdown compared to original biomass. This recalcitrance results in biochar-derived carbon persisting in soil for extended periods, potentially centuries, thereby sequestering carbon and contributing to long-term soil carbon storage. This characteristic makes biochar a valuable tool for enhancing soil carbon stocks and mitigating GHG emissions in forest ecosystems (Lal, 2016).

By enhancing soil fertility, nutrient availability, water use efficiency, and overall plant growth, biochar application in forest soils can create ideal conditions for increased carbon sequestration in vegetation (Figure 2). This dual impact—directly stimulating plant biomass growth and indirectly influencing soil carbon dynamics—positions biochar as a valuable tool for enhancing carbon storage in forest ecosystems. However, the effectiveness of biochar application in forests can vary due to factors such as biochar characteristics, soil composition, forest type, and management strategies. Therefore, careful consideration and optimization are crucial to achieve desired outcomes and maximize the potential of biochar in fostering sustainable forest management and mitigating climate change impacts.

## 6 | BIOCHAR AND SUSTAINABILITY

Biochar can play a significant role in promoting sustainability principles by creating sustainable and value-added cycles within environmental systems (Figure 3). Sustainability is an approach that focuses on minimizing waste, optimizing resource use, and fostering a closed-loop system; application of biochar can effectively align with sustainability principles:

1. *Waste utilization*: Biochar can be produced from forestry residues such as branches, leaves, and wood chips that are typically left on forest floors or burned post forest operations. By converting these residues into biochar, forest waste can be transformed into a valuable resource rather than being disposed of by open burning, contributing to air pollution, or acting as a fuel for wildfires. This promotes a cyclical waste utilization and opens the scope for soil remediation by the biochar produced from the forest biomass.
2. *Carbon sequestration*: Biochar serves as a stable form of carbon, effectively sequestering carbon from forest waste

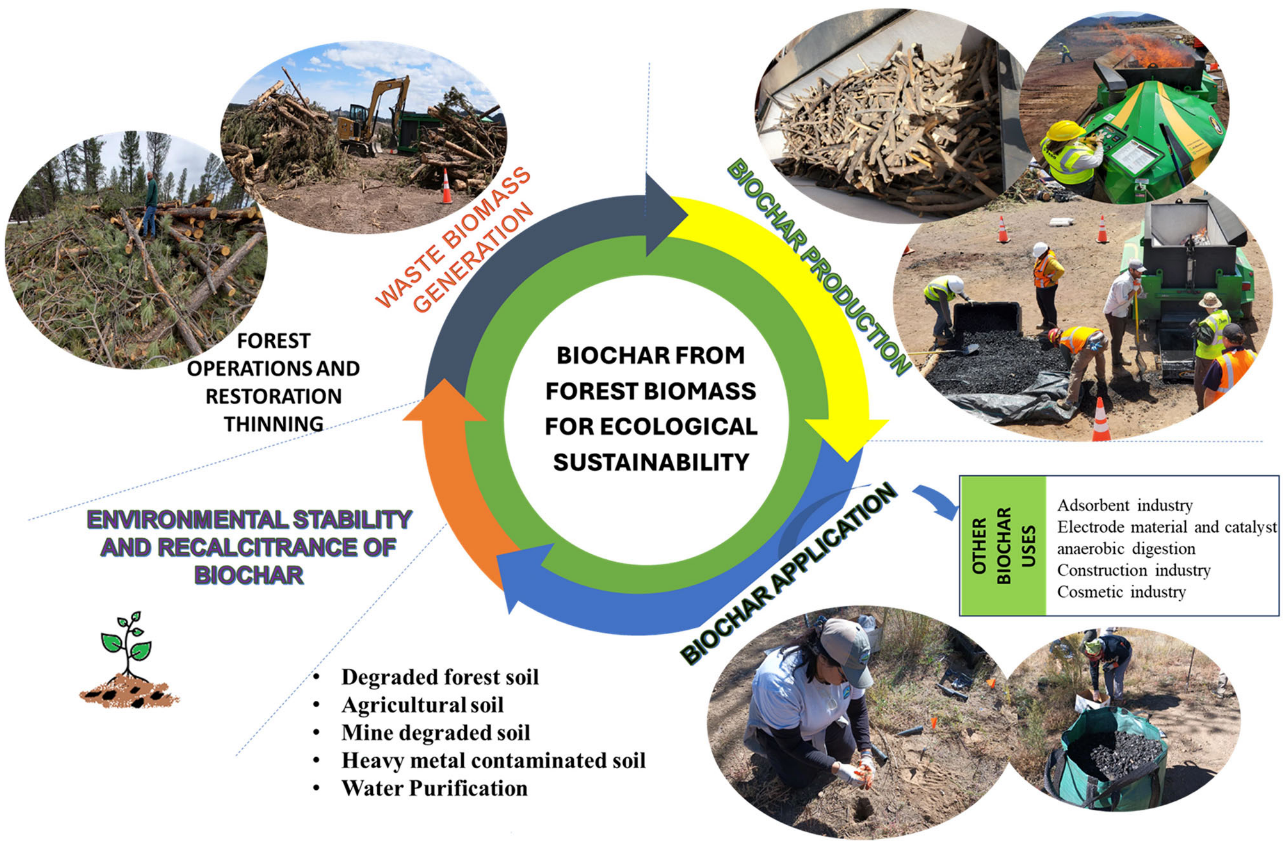


**FIGURE 3** Biochar produced from forest waste biomass as a resource for sustainability.

in soil for long periods. This helps mitigate GHG emissions and contributes to climate change mitigation efforts and contributing to a closed carbon cycle.

3. *Nutrient cycling*: Biochar can facilitate nutrient cycling in forest ecosystems by improving the retention and availability of nutrients in soils. The use of the forest biomass for biochar production keeps the nutrient loop in the forest ecosystem intact. This supports sustainable forest management practices by reducing the need for synthetic fertilizers and enhancing nutrient uptake by vegetation.
4. *Soil health and productivity*: Application of biochar improves soil structure, water retention, and microbial activity. Biochar derived from forest waste can be applied to forest soils to enhance soil fertility, water retention, and nutrient availability. This can help promote healthier tree growth and improve overall ecosystem resilience. Additionally, it can also help forest soils in reducing erosion caused by rainfall and wind. This is particularly beneficial in steep, highly disturbed, or degraded forested areas where erosion control is critical for maintaining ecosystem health.
5. *Reduced wildfire risk*: Removing biomass residues from the surface organic horizons and converting them into biochar can reduce the accumulation of combustible material, thereby lowering the risk of wildfires. Biochar application can also improve soil conditions in fire-prone areas, potentially mitigating the impact of wildfires on forest ecosystems.
6. *Renewable energy and heat*: The pyrolysis process used to produce biochar can generate bioenergy and heat. This energy can be harnessed to power the pyrolysis system itself or other processes, further closing resource loops and reducing reliance on non-renewable energy sources.
7. *Bio-based products*: Biochar can be incorporated into composite materials for construction, such as biochar-infused wood composites or biochar-enhanced concrete. These materials offer improved thermal properties, durability, and sustainability compared to traditional construction materials. This supports the development of sustainable alternatives to conventional products, contributing to sustainability principles.
8. *Sustainable land management*: Biochar application can rehabilitate degraded forest soils, making land suitable for forest regeneration post degradation due to wildfire and so on. This supports sustainable land use and minimizes the need for deforestation or expansion into new areas.
9. *Localized solutions*: Biochar production and application can often be implemented on a local scale, reducing the need for long transportation chains and associated

emissions. This supports community-level sustainability and resource management.

By integrating biochar into forest restoration practices, sustainability principles can be achieved, contributing to resource efficiency, reduced waste, and more sustainable land and resource management. However, it is important to carefully consider factors such as feedstock selection, production methods, and application practices to ensure that the benefits of biochar are realized in an environmentally and socially responsible manner.

## 7 | BIOCHAR COMMERCIALIZATION

Although biochar fits well in the sustainability concept, economic viability and market competitiveness are necessary to facilitate broader scale biochar production and its adoption in sectors like forestry, ranching, and agriculture. Commercializing biochar from forest biomass involves establishing production facilities near biomass sources, optimizing pyrolysis processes, and developing markets for biochar products. However, not all biochar uses require a market; for example, in situ biochar production and application for soil remediation does not depend upon an independent biochar market, but rather a market for remediation services. However, to advance greater production and use, further development of the biochar market is needed. The global biochar market size was valued at USD 184.90 million in 2022 and is projected to grow from USD 204.69 million in 2023 to USD 450.58 million by 2030 exhibiting a compound annual growth rate (CAGR) of about 12% during the growth period (Market Research Report, 2023a). The US biochar market size was estimated at USD 125.3 million in 2020 and is expected to expand a CAGR of 16.8% from 2021 to 2028 (Market Analysis Report, 2023b). This can be due to the overutilization of fertilizers in the agricultural sector owing to the increasing demand of crop production. The increased acidity due to fertilization abuse has popularized the use of carbon-based additives such as compost, lime, or biochar, which can neutralize the low pH of these soils. Additionally, the accessibility of equipment and the user-friendly nature of the process have been pivotal in driving its widespread acceptance. Particularly, smaller production facilities find the pyrolysis technology attractive due to its low up-front capital cost and simplified setup in comparison to alternative techniques.

According to Nematian et al. (2021), the final cost of biochar is a function of costs of feedstock purchase, transportation, production, labor, and storage. Achieving a better understanding of production costs helps entrepreneurs to develop a competitive advantage in biochar production, and eventually drive demand for the bioeconomy. Fear of failure is an obstacle to entrepreneurship and new product adoption; and the lack of cost data leads to uncertainty when branding the biochar. However, technological innovation that can help shorten production time, leading to cost competitiveness and higher profit.

Carbon credits are a tradable commodity that represents a certain amount of carbon dioxide equivalent ($CO_2$e) emissions reduced or sequestered. They are often used as a tool to incentivize actions that mitigate climate change. Organizations or individuals that reduce their carbon emissions or sequester carbon can earn carbon credits, which can then be sold or used to offset their own emissions. Forest biomass biochar projects can generate carbon credits through carbon offset programs or carbon markets (see Climate Action Reserve, 2023, for example). These credits represent the amount of $CO_2$e that is avoided or sequestered by using biochar instead of releasing biomass carbon through decay or burning. The concept of biochar-based carbon crediting involves utilizing biochar as a tool to sequester carbon from the atmosphere and then receiving carbon credits for carbon stored in the biochar. This can provide financial incentives for forest practitioners or businesses to adopt biochar practices, which in turn can lead to increased adoption of sustainable land management practices and reduced GHG emissions. It is important to note that the effectiveness of biochar-based carbon crediting depends on factors such as the type of biomass used for pyrolysis, the production process, the characteristics of the soil in which biochar is applied, and the monitoring and verification mechanisms in place to ensure that the carbon remains sequestered over time. However, while the concept has potential, there are also challenges to consider, such as accurately quantifying carbon sequestration, addressing potential unintended environmental impacts, and establishing robust methodologies for monitoring and verifying the carbon stored in biochar. Biochar-based carbon crediting is an evolving concept and its implementation and recognition in various carbon credit markets is growing each day.

Despite its promising potential, several factors could contribute to setbacks and hindered growth in the biochar market:

1. *Lack of awareness and education*: Many people, including forest practitioners and policymakers, might not fully understand the benefits and applications of biochar. This lack of awareness can hinder adoption and investment in this technology.
2. *High production costs*: The production of biochar often involves specialized equipment and processes, which can be costly to set up and maintain. These high costs might deter potential producers from entering the market, leading to limited supply. This can make biochar less competitive compared to other soil amendments or forest and agricultural practices. However, low-tech kilns or air

curtain burners require little technical knowledge to create high-quality biochar.

3. *Regulatory and policy challenges*: Depending on the region, the biochar industry might face regulatory hurdles or lack of supportive policies. Unclear regulations regarding the use and production of biochar could discourage potential investors and users. The biochar market may face regulatory hurdles related to the use of biochar in agriculture or other sectors. Additionally, establishing standardized certification processes for biochar products can be complex and time-consuming.
4. *Limited research and development*: Further research is needed to understand the long-term impacts of biochar on soil health, carbon sequestration, and other potential benefits. Limited research could lead to uncertainty about its effectiveness and hinder widespread adoption.
5. *Market competition*: Biochar faces competition from other soil amendments and carbon sequestration methods. If other alternatives are more widely accepted or economically viable, biochar adoption could be limited.
6. *Infrastructure and supply chain issues*: Developing a robust supply chain and distribution network for biochar products can be challenging, particularly in regions with limited infrastructure.
7. *Perception and acceptance*: Some potential users may be skeptical about the benefits of biochar or might not view it as a viable solution for their needs. Overcoming these perception barriers is important for market growth.
8. *Scaling challenges*: Transitioning from small-scale production to large-scale commercial production can be difficult. Scaling up production while maintaining consistent quality and adhering to environmental standards can pose challenges.
9. *Variable product quality*: The quality and characteristics of biochar products can vary widely based on the feedstock used, production methods, and processing conditions. Inconsistent product quality can make it challenging for consumers to trust and adopt biochar. Although agencies such as the International Biochar Initiative, U.S. Biochar Initiative, and European Biochar Certificate are putting forth efforts to standardize biochar systems that are safe and economically viable, yet it still needs a lot of effort.

### 7.1 | Other biochar markets

Biochar has several other notable uses and applications beyond its role in soil improvement and carbon sequestration, which makes it a substance suited for sustainability. Fixed plants can make large volumes of biochar suitable for a variety of commercial products. These nonconventional markets for biochar can help bridge the gap between the issues of its commercialization and promote the biochar industry:

1. *Construction industry*: The utilization of biochar for enhancing the characteristics of mortar and concrete has gained popularity over the years. Addition of biochar has been reported to improve strength, durability, enhance thermal properties, and the potential for carbon sequestration. These properties make biochar a better material than silica fume, a common additive known for its performance benefits (Schmidt, 2013)
2. *Additives for anaerobic digestion and composting*: Anaerobic digestion is a promising bioprocess used to convert organic materials into biomethane-rich gas. Biochar has emerged as an effective strategy to enhance anaerobic digestion.
3. *Adsorbent industry*: The adsorption ability of the biochar is extensive and versatile, allowing it to adsorb a wide range of substances from various mediums, including water, air, and soil. Some of the common types of substances that biochar can adsorb include heavy metals, organic pollutants, dyes and pigments, gases, odors, and pharmaceuticals.
4. *Electrode material and catalyst*: In recent years, researchers have explored its potential in fields like electrode materials and catalysis, showing its versatility and adaptability.
5. *Cosmetic industry*: Biochar has a porous structure, which gives it a large surface area capable of adsorbing substances (Ghosh & Maiti, 2020). In skincare, this property could be harnessed to develop products like facial masks or cleansers that are designed to pull impurities, excess oil, and toxins from the skin's surface. The cosmetic industry has been moving towards natural and sustainable ingredients.
6. *Livestock industry*: In the United States, biochar can be used in livestock pens to reduce odor, and enhance composting and disease transmission. Biochar has been effectively employed in livestock operations both as a feed additive and as a manure management tool. While the use of biochar as a feed additive is well-established in Europe, it has been less common in the United States, primarily due to the regulations set by the FDA governing feed additives. However, current research efforts and approvals at the state level have initiated pilot projects and opened the door to broader production use in the United States (Groot et al., 2021).

## 8 | CONCLUSIONS

The utilization of biochar produced from forest waste biomass produced from forest management plays a pivotal role in advancing ecological sustainability and contributing to carbon neutrality. Excessive biomass in forests not only poses a fire hazard but also jeopardizes long-term ecosystem health.

Biochar production allows repurposing of woody residues from fuels management, thinning, harvesting, or restoration activities, which not only addresses the challenge of waste fuels but also creates economic opportunities. Instead of burning residues in slash piles, which harms soils and emits pollutants, biochar production offers a more sustainable and environmentally friendly alternative. Forest waste biochar enhances soil quality and promotes long-term ecological benefits. Also, by sequestering carbon in the soil, it not only aids in mitigating climate change but also reduces the bioavailability of toxic materials, thereby fostering a healthier environment. The relative ease of production from locally available feedstocks further underscores its potential as a sustainable solution which addresses multifaceted challenges for achieving the SDGs.

## AUTHOR CONTRIBUTIONS

**Dipita Ghosh**: Conceptualization; data curation; methodology; writing—original draft; writing—review and editing. **Deborah S. Page-Dumroese**: Investigation; supervision; validation; writing—review and editing. **Han-Sup Han**: Funding acquisition; investigation; project administration; supervision; validation; writing—review and editing. **Nathaniel Anderson**: Supervision; validation; writing—review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

The data are available on request from the corresponding author.

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