



# Acorn review: Biochar and its applications in US forestry

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## ABSTRACT

Biochar derived from woody feedstocks is typically high in carbon, low in ash, and relatively low in nutrients compared with agricultural biochar, making it especially suitable for long-term carbon storage. Current evidence indicates that key functional properties for forestry applications include biochar yield, fixed carbon, pH, nutrient content, and porosity. Across studies, there is broad agreement that these properties are shaped by both feedstock and production conditions, particularly pyrolysis temperature and residence time. Yield and fixed carbon appear to be driven mainly by pyrolysis conditions, whereas pH, nutrient content, and porosity are more strongly linked to feedstock, though still influenced by processing temperature. At the same time, disagreement remains over how consistently wood-based biochar improves tree growth and productivity in forest systems. Reported outcomes range from positive to neutral to negative, reflecting differences in site conditions, application method and rate, and the interaction of biochar traits with forest soil ecosystems. Taken together, the literature suggests that biochar performance is highly context dependent and that benefits are most likely when biochar properties are matched to target species, site conditions, and the time horizon over which responses are evaluated. Overall, woodbased biochar should be viewed as a value-added use of low-value woody biomass rather than a universal solution. Its long-term role in forestry will depend on better alignment between biochar properties and site-specific management needs, expansion of end uses beyond soil amendment, improved production and distribution economics, and stronger policy support to facilitate broader adoption.

Biochar is a solid material derived by thermochemical conversion of biomass under oxygen-limited conditions (International Biochar Initiative, 2012). It lies along the black carbon continuum (Spokas et al., 2012) and can be analogous to *in situ* charcoal found in fire-prone ecosystems (DeLuca and Aplet, 2008) but is distinguished from conventional charcoal by its intentional production for use as a soil amendment (Lehmann et al., 2011) or for niche industrial applications. Experimental work on biochar – typically derived from crop residues, manures, and poultry litter – has largely focused on agrarian systems, evaluating its effects on plant growth and soil processes (Biederman and Harpole, 2013; Jeffery et al., 2011; Liu et al., 2013; Spokas et al., 2012). In parallel, studies examining the potential of biochar for restoring abandoned mines are also well-documented (Brandt et al., 2021; Ghosh et al., 2025; Page-Dumroese et al., 2018; Rodriguez-Franco and Page-Dumroese, 2021a; Rodriguez-Franco and Page-Dumroese, 2021b). By contrast, applications of biochar in managed forest systems remain relatively limited, although recent years have seen rapid growth in studies examining tree responses to wood-based industrial biochar.

Given that biochar is increasingly heralded as a climate-smart tool for forest management as a soil amendment that can improve carbon retention (Franco et al., 2024), and because traditional markets for adjacent forest products that rely on small diameter roundwood are declining, this brief review examines the key properties of wood-based biochar, synthesizes current evidence on its effects on forest sites, and identifies critical research gaps that warrant immediate attention to better understand its potential for broader, commercial adoption, particularly in the southeastern US.

## 1. Current consensus among scientists

There is a broad agreement that biochar sourced from woody feedstocks are high-carbon, low-ash, highly aromatic materials that are relatively meager in nutrient but strongly recalcitrant, making them particularly suited for long-term carbon storage. The physical and chemical properties are highly tied to the feedstock material and production conditions, particularly pyrolysis temperature and residence

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time (Page-Dumroese et al., 2016a; Page-Dumroese et al., 2016b). Literature suggests some of the important functional properties of biochar from an application standpoint are biochar yield, fixed carbon, pH, nutrient content (N, P, K), and porosity. Biochar yield and fixed carbon seems to be largely determined by pyrolysis temperature (and residence time) whereas pH, nutrient content, and porosity are tied to the feedstock to a larger extent (Ippolito et al., 2020), but these feedstock dependent properties can also be influenced by pyrolysis temperature (Enders et al., 2012).

### 1.1. Biochar yield

As the pyrolysis temperature increases, the yield of biochar decreases (Spokas, 2010). This is because heightened temperature increase the release of volatile compounds during pyrolysis, converting a greater fraction of biomass into gaseous and liquid products and leaving less solid material behind (Jamal and Fletcher, 2023). Most studies have shown that the optimum temperature of 400–600°C generates biochar yields between 20% and 30% for wood-based feedstock (Enders et al., 2012; Spokas et al., 2012). While the biochar yield may not be considerably different between hardwoods and softwoods, biochar yield may vary based on preprocessing condition (such as moisture content), production technology (burning rate/technology), and the size/forms of wood feedstocks (logs/chips). Enders et al. (2012) illustrated that at the optimum temperature of 400–600°C, the biochar from oak and pine generates similar yield of about 30%. A recent study by Usha et al. (2026) reported that biochar from loblolly pine chips generated the highest yield of 23% at 450°C. Mašek et al. (2013) reported relatively higher (30–40%) biochar yield from all three feedstocks i.e., pine chips, mixed larch and spruce wood chips, and softwood pellets. Using a CharBoss (a mobile unit) for biochar production from ponderosa pine, Oyier et al. (2024) illustrated that medium and mixed diameter classes have the highest biochar yield per unit of biomass burned at 17.2%, followed by small diameter (13.2%), large diameter (10.7%), and green biomass (8.8%); these results suggest that lower burning rate associated with larger-sized woods and higher moisture content of green biomass could potentially reduce the amount of biochar recovered, indicating that small-diameter roundwood may be better suited for biochar systems.

### 1.2. Fixed carbon

The ability of biochar to hold stable carbon i.e., recalcitrance, is arguably the most useful property of biochar – and by that virtue, the most important, especially from a carbon dioxide removal (CDR) standpoint. Enders et al. (2012) reported fixed carbon content of about 60–70% for pine and oaks pyrolyzed between 400 and 600°C. Usha et al. (2026) also reported similar estimates of fixed carbon for biochar derived from loblolly pine chips (about 65% at 450°C to 75% at 650°C). However, yield of the stable carbon fraction of biochar might be more important than a mere stable carbon concentration as the former informs the discussion around maximum carbon storage per unit of feedstock. Mašek et al. (2013) shows that despite the concentration of the stable fraction in biochar derived from wood chips dramatically increasing with temperature (from nearly 70% at 350 to nearly 90% at 550), the pyrolysis temperature affects the yield of the stable fraction (% of feedstock) to a much smaller extent, at least for pine chips and mixed larch and spruce wood chips. Their findings suggest that the yield of the stable biochar fraction is nearly independent of the pyrolysis temperature. It is also important to note that stability of the carbon is likely to be contingent upon the degradation processes and conditions that it is exposed to, most commonly the soil ecosystem (Mašek et al., 2013). Nevertheless, biochar derived from wood is a stable carbon reservoir possessing a half-life in excess of 100 years (Spokas, 2010).

### 1.3. pH

The pH of wood-based biochar is typically lower than that of agricultural residues but still generally alkaline. pH generally correlates positively with ash content (Enders et al., 2012). While pH is dependent upon the parent feedstock, it can be substantially augmented through pyrolysis temperature (Li et al., 2023; Mukherjee et al., 2011). For instance, biochar from loblolly pine wooden chips ranged from 6.29 at 450 to 8.39 at 650 (Usha et al., 2026); pH increased from loblolly pine to laurel oak to grass at all production temperatures of 250, 400, and 650 (Mukherjee et al., 2011). It is important to note that pH value might be markedly different at a species level, and not just at a mere hardwood/softwood distinction. For instance, pH of biochars produced under similar conditions were similar for mixed conifer and Oregon white oak at about 8 but has considerably lower for Pacific madrone at about 4.5 (Page-Dumroese et al., 2016a; Page-Dumroese et al., 2016b).

### 1.4. Nutrient content

Wood-based biochar is a relatively poor soil amendment in terms of NPK content and fertilization potential. Nutrient content for wood-based biochar is substantially lower than animal-based biochar (Li et al., 2023; Spokas et al., 2012). However, there can be considerable variation based on species and pyrolysis temperature. Freitas et al. (2020) reported higher P and K content for mixed hardwood (maple, oak, and pine feedstock) followed by maple (*Acer* spp.) than for Douglas-fir based biochar. A meta-analysis (Ippolito et al., 2020) reported that softwood supply higher percent of P whereas hardwood supply higher K. Under similar production conditions of biochar derived from commonly occurring tree species in the western US, Page-Dumroese et al., 2016a; Page-Dumroese et al., 2016b found considerably higher NPK content from Oregon white oak than mixed conifer (predominantly Douglas fir). Nutrient content, especially N, can increase as temperature increases but decreases beyond a certain temperature threshold. For instance, upon further heating from 300 to 600 °C, oak and pine biochar showed N enrichment (Enders et al., 2012); N content decreased as temperature increases over 500 (Li et al., 2023); N content increased from 450 to 550 but decreased at 650 for loblolly pine-based biochar (Usha et al., 2026).

### 1.5. Porosity

Porosity is a primary factor affecting water retention ability of biochars; however, secondary parameters such as cation exchange capacity (Batista et al., 2018) and post-processing activation of biochars are also important (Anderson et al., 2021; Sajjadi et al., 2019; Thomas, 2021). Literature suggest that both feedstock and production process influence biochar porosity – the former responsible for inherited macropore (Rasa et al., 2021; Srocke et al., 2021) and the latter responsible for the development of micro/mesoporosity and associated surface area (Barszcz et al., 2024; Elnour et al., 2019; Tomczyk et al., 2020). For instance, Werdin et al. (2020) reported that biochar made from lower density Eucalyptus wood had up to 35% greater water holding capacity and up to 45% greater plant available water than biochar made from higher density Eucalyptus wood. Multiple studies report monotonic increase in surface area and pore volume with increasing pyrolysis temperature over common operating ranges (Elnour et al., 2019; Tomczyk et al., 2020). For example, biochar produced between 400 and 600 °C generally has the least amount of hydrophobicity and highest water holding capacity, while those created under higher temperatures have much stronger hydrophobic tendencies (Kinney et al., 2012).

Forest managers and biochar producers must navigate several trade-offs when selecting biochar production conditions. Increasing pyrolysis temperature generally enhances fixed carbon content and stability, thereby increasing its carbon sequestration potential, but often reduces biochar yield. Consequently, managers pursuing carbon dioxide removal (CDR) objectives may favor higher pyrolysis temperatures, whereas

those seeking to maximize biochar production for large-scale soil amendment or restoration may prefer lower temperatures. Pyrolysis temperature can also influence biochar pH, with higher temperatures often linked to alkaline biochar. Because many oak/pine forest ecosystems are naturally acidic, highly alkaline biochar may not always be desirable; however, their liming effect can facilitate vegetation establishment on heavily contaminated abandoned mine lands and other degraded acidic sites.

## 2. Contrasting evidence from literature on the topic

While biochar itself possess a number of beneficial traits as discussed above, its effectiveness in forest systems is, however, context-dependent as application outcomes depend heavily on matching biochar properties to site characteristics, method/rate of application, evaluation period, and how their specific properties interact with the soil ecosystem. Consequently, evidence on wood-based biochar effects on trees growth and productivity is mixed, ranging from positive responses under some conditions to neutral or even negative outcomes (for tabulated summary and detailed description, see [Supplemental Table 1](#)).

Across field trials in forest ecosystems, growth responses are often modest or inconsistent and appear to vary by forest type and region. Available evidence generally supports the observation of [Thomas and Gale \(2015\)](#) that biochar-induced growth responses tend to be greater in boreal and tropical forests than in temperate forests. For example, in young boreal Scots pine forests (< 20 years old) in southern Finland, spruce-derived biochar increased diameter growth of dominant trees at higher amendment rates yet did not increase nitrogen over three years ([Palviainen et al., 2020](#)). In a long-term study (over 9 growing seasons) in young managed Scots pine forest in northern Sweden, surface application of biochar promoted the survival of Scots pine; biochar also enhanced overall growth but did not alter overall nitrous oxide and the supply rates of the main soil nutrients ([Grau-Andrés et al., 2021](#)). Both study sites were located in nutrient-poor, xeric boreal forest soils. In subtropical Japanese oak systems, higher application rates increased canopy-tree dbh growth and acorn production, but net primary production in foliage and wood did not respond to biochar application ([Ohtsuka et al., 2021](#)). In contrast, several operationally oriented field studies report limited justification for field applications of biochar based on growth and survival outcomes. In temperate mixed forests of northern Minnesota, biochar application had only modest short-term influence on growth and survival of jack pine over 5 years – effects did not appear sufficient to justify application costs for seedling establishment ([Slesak et al., 2022](#)). The study attributed the low survival to a combination of soil conditions (low water holding capacity), low precipitation in the year of planting, and shorter evaluation period of the study (5 years). A subsequent study similarly reported no survival or growth gains on planted jack pine seedlings on sandy soils and observed alleviated foliage calcium concentration relative to controls, suggesting the possibility of nutrient immobilization or altered nutrient availability when biochar is added without a complimentary nutrient source ([Slesak and Windmuller-Campione, 2024](#)). However, this study suggested that greater benefits may be realized with higher application rates or alternative application methods.

In post-thinning stands of the western coniferous forests in Idaho, biochar neither diminished or improved basal area growth or residual tree growth, suggesting neutral stand-level responses under those site and management conditions ([Sherman et al., 2018](#)). Adding nitrogen to these nitrogen-limiting forests, however, increased forest growth. The study further suggested that higher biochar application rates may have produced stronger responses, although application rates commonly used in agricultural systems may be impractical in forestry operations given current technologies and fertilizer costs. Longer-term monitoring of over 6 years across managed forests sites in Idaho, Montana, and Oregon further indicates that biochar can considerably elevate soil C stocks without detectable detrimental effects on tree growth ([Sarauer et al.,](#)

2019).

In red and jack pine seedlings trials in temperate mixed forests of Lake States, biochar application produced lower diameter and heights after 2 years of biochar amendment indicating transient nutrient arrest; however, incorporation into the soil produced significant improvements in terms of reduced bulk density, increasing water volume and water holding capacity ([Richard et al., 2018](#)). The study highlighted the need for long-term monitoring, as shading and microsite variability may exert stronger influences on seedling establishment and growth than short-term improvements in soil properties. [Noyce et al. \(2017\)](#) reported no consistent seedling growth after biochar application, instead noticed that sugar maple and red pine seedlings often had opposing responses to the same amendment-soil combination, suggesting that the effects of soil amendment are more strongly associated with soil textural class and species traits than with amendment type *per se*. These findings underscore the critical importance of tailoring biochar and ash amendments to native soil conditions and target tree species to optimize improvements in tree nutrition. In a study of the application of biochar as a growing media component for containerized production of Douglas-fir, mixing biochar into peat-based media progressively reduced height and diameter growth rates, seedling biomass, and photosynthetic rate; biochar application was counterproductive as biochar also increased growing media pH to levels incompatible with conifer seedling requirements and decreased media extractable P concentration ([Sarauer and Coleman, 2018](#)). Biochar addition did not reduce fertilizer requirements for producing similarly sized seedlings, likely because elevated pH reduced phosphorus availability, suggesting that biochar pH may need to be adjusted for Douglas-fir seedling production.

In more disturbed or engineered substrates, where soil compaction or organic matter or nutrient deficits are key constraints, biochar amendments more frequently demonstrate measurable improvements in tree performance. In compacted urban soils, incorporating biochar amendments increased sapling dbh and canopy growth relative to tillage-only or unamended treatments, with no significant differentiation among the organic matter amendments ([Somerville et al., 2020](#)). Similar urban soil work also reported significant increase in sapling growth of sugar maple and honey locust with biochar treatments ([Scharenbroch et al., 2013](#)). In propagation and nursery contexts, biochar derived from red oak feedstock performed comparably to vermiculite as a potting-mix component for hybrid poplar cuttings: higher shoot K and significantly higher shoot and total biomass ([Headlee et al., 2014](#)). At the site level, short-term nutrient effects can also be consequential as biochar additions have been identified as increasing the supply of limiting nutrients, particularly phosphorus and calcium, in mixed hardwood systems in eastern Ontario ([Sackett et al., 2015](#)).

Because field trials of wood-based biochar in southeastern forests remain scarce, findings from other regions should be extrapolated cautiously. Some mechanisms may nevertheless be relevant: highly weathered, acidic Ultisols could benefit from biochar-induced changes in pH, cation exchange capacity, water retention, and nutrient availability. However, responses may differ from those observed in boreal Podzols, glacial soils of the Lake States, volcanic-ash and loess-derived soils of western forests, and volcanic soils in Japan because of differences in soil mineralogy, climate, stand composition, and management intensity. In loblolly pine plantations, competition control, fertilization, genetic improvement, and short rotations may alter or mask biochar effects. Additionally, although alkaline biochar may ameliorate soil acidity, its effects on phosphorus availability warrant attention where establishment fertilization is phosphorus-based. In Southern Appalachian forests, biochar-induced nitrogen immobilization could suppress nitrogen-demanding competitors such as tulip-poplar, potentially favoring more drought-tolerant oaks. Thus, although some underlying mechanisms may be transferable, growth responses, application rates, and operational feasibility require validation in southeastern pine and Appalachian hardwood systems.

### 3. Final remarks and key points where more evidence is needed

Overall, literature supports a consistent interpretation that biochar is a value-added product but its application in forests systems as a growth stimulant largely depend on (i) compatibility of biochar properties with target species and site conditions, especially soil texture, soil atmosphere, and nutrient availability; and (ii) the time horizon over which responses are assessed. This helps reconcile why some studies report increased diameter growth, survival, or reproduction at higher rates or in constrained soils, whereas others find neutral or negative outcomes. While some biochar properties such as pH may be inherently tied to feedstock, most properties can be largely enriched during the production process and to some extent, during post-processing (Anderson et al., 2021; Thomas, 2021). As such, feedstock differentiation, i.e., softwood vs hardwood, is perhaps not as substantial as production and processing conditions in producing biochar of desirable qualities for *in situ* application.

Beyond the clear need for additional regional field trials, numerous barriers and opportunities will shape the expansion and commercial adoption of biochar in southeastern forestry, particularly in the following areas:

#### 3.1. Techno-economic considerations

a) One of the operationally decisive questions for scaling forest-based biochar is the relative merit of mobile/portable/in-woods versus centralized/stationary production units. The optimal choice is context-dependent, influenced by feedstock availability and dispersion, desired throughput, local market demand, and the scope of intended application. In general, stationary facilities can provide higher and more consistent output, economies of scale, and scalable operations, but they often require sustained procurement of feedstock and can incur exceedingly higher transportation costs and utilization risk in low-demand markets (Ahmed et al., 2025). Portable systems, on the other hand, offers flexibility in accessing dispersed biomass, avoid additional emissions associated with hauling biomass over longer distances (Sahoo et al., 2021), and reduce upfront investment (still cost prohibitive); however, they may face lower throughput, higher unit costs, and possible deficit production relative to projected demand (Ahmed et al., 2025). Moreover, in-woods technique is not a single approach but a range of technologies for optimal production with distinct requirements and constraints – from feedstock specifications and moisture tolerance to water needs, handle crews and skills required, logistical considerations, and seasonality – allowing landowners and operators to match production systems to site conditions and operational objectives (Oyier et al., 2024; Wilson et al., 2024).

#### 3.2. Policy, spatial planning, and regulatory considerations

b) Biochar adoption in the US still remains constrained by limited market and cost structures, with minimum selling prices considerably higher than direct revenues from selling biochar as a stand-alone product (Ahmed et al., 2025; Bergman et al., 2022; Sahoo et al., 2019). Considerably higher application cost on plantation site seems to make biochar application unsustainable (Richard et al., 2018). Because biochar is a climate-smart tool that contributes to climate change mitigation through durable carbon sequestration and potential reductions in soil GHG emissions (Franco et al., 2024), while also improving overall soil health (Antonangelo et al., 2025), other sources of revenues via renewable energy or carbon credits (Johannesson et al., 2024) or disaster management can be tackled on to improve financial performance and offset operational costs. Until biochar markets broaden and become self-sustaining, a pragmatic bridge strategy is to align biochar application with international and national priorities. For example, biochar carbon removal is a

IPCC-recognized carbon dioxide removal technology (International Biochar Initiative); USDA-NRCS has recently launched a \$700 million Regenerative Pilot Program focused on outcomes in soil health, water management, and natural vitality; Fix Our Forests Act (H.R. 471) includes biochar-focused demonstration projects intended to advance development and commercialization while supporting forest health and carbon sequestration goals.

- c) Suitability map that integrates biomass availability and forest conditions with disaster risk (e.g., hurricane and wildfire exposure), physiography and terrain constraints, and infrastructure and market access can help identify optimal locations for stationary biochar production hubs, thereby improving the feasibility of scaling biochar facilities across the region (Adhikari et al., 2024; Sharma and Khanal, 2026).
- d) A patchwork of air-permitting requirements across state, district, and county jurisdictions increases compliance uncertainty and transaction costs, making it challenging, especially for mobile or multi-state operators, to plan investments and scale operations (Rodriguez Franco et al., 2024). Besides, documented misrepresentation in similar forest-product markets (e.g., charcoal) underscores the need for clear standards and verification throughout the supply chain, thereby building buyer confidence and support credible biochar commercialization (Costa et al., 2025).

#### 3.3. Market development and diversification

- e) In the US, scientists from the USFS-RMRS have advanced biochar research not only through field trials, but also by developing deployment-ready technologies. Notably, an in-woods biochar machine *CharBoss* (Oyier et al., 2024) was developed through collaboration with a private company; the station has also developed and tested a high-capacity biochar spreader that can be used in challenging terrains across skid trails and log landings (Page-Dumroese et al., 2016a; Page-Dumroese et al., 2016b). Together, these efforts emphasize the importance and value of public-private partnerships in translating forest management needs into market solutions. Hence, strengthening coordination among private industry, state agencies, and federal partners, especially around product development, standardization, and implementation logistics, could accelerate technology refinement and enable broader, more consistent application of biochar beyond public lands.
- f) Expanding biochar into nonconventional markets can help further commercialize and accelerate industry growth. For instance, biochar is being explored in construction to improve mortar and concrete performance, as an adsorbent to capture heavy metals, odors, and pharmaceuticals, in cosmetics as a high-surface area ingredient in masks and cleansers, and in livestock systems as a feed additive and manure management tool (Ghosh et al., 2025).

#### 3.4. Novel research needs

- g) Biochar can be tested as a component of integrated *Phytophthora* management in Christmas tree systems, as the root rot remains one of the most consequential diseases of Fraser fir and other Christmas trees in North Carolina. While the evidence is not yet systematized for Fraser fir specifically, Zwart and Kim (2012) reported that biochar amendment increases resistance to stem lesions caused by *phytophthora* spp. in red oak and red maple seedlings.
- h) Another promising research direction is to evaluate the potential of biochar to mimic the ecological functions of wildfire-derived charcoal and fire-burned residues, thereby helping counteract mesophication in historically fire-adapted, oak-dominated forests.
- i) Further research should assess biochar for reducing salinity (Wang et al., 2024) in coastal ghost forests and explore its interactions with plant growth-promoting fungi (Hammer et al., 2014) in southeastern pine plantations.

While biochar is not a silver bullet for offsetting the shock of declining markets for small-diameter roundwood, it nevertheless represents a promising pathway for utilizing stranded “low-value” woody biomass. Its long-term role and relevance in forestry will depend on aligning biochar properties to site-specific management needs, expanding end uses beyond soil amendment, improving the economics of production and distribution, and strengthening policy support that enables broader adoption.

### CRedit authorship contribution statement

**Gaurav Dhungel:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Justin Baker:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Jesse D. Henderson:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Rachel Cook:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Appendix A. Supporting information

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### Data availability

No data was used for the research described in the article.

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