



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(8): 421-430
Received: 19-06-2026
Accepted: 21-07-2026

Ajay Krishna V
Department of Forest Resource
Management, College of Forestry,
Kerala Agricultural University,
Vellanikkara, Thrissur, Kerala,
India

Aneesh KS
Assistant Professor, Department of
Forest Resource Management,
College of Forestry, Kerala
Agricultural University,
Vellanikkara, Thrissur, Kerala,
India

Prasanthi K
Assistant Professor, RARS
Pattambi, Kerala Agricultural
University, Palakkad, Kerala,
India

Ruby P
Department of Agronomy, College
of Agriculture, Kerala Agricultural
University, Vellanikkara, Thrissur,
Kerala, India

Kavya Raj A
Department of Forest Biology and
Tree Improvement, College of
Forestry, Navsari, Gujarat, India

Gopika SR
College of Forestry, Kerala
Agricultural University,
Vellanikkara, Thrissur, Kerala,
India

Corresponding Author:
Ajay Krishna V
Department of Forest Resource
Management, College of Forestry,
Kerala Agricultural University,
Vellanikkara, Thrissur, Kerala,
India

Invasive plants as sustainable biochar feedstocks: Production, applications, and environmental implications

**Ajay Krishna V, Aneesh KS, Prasanthi K, Ruby P, Kavya Raj A and
Gopika SR**

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i8Sf.6360>

Abstract

Invasive alien plants pose a significant global ecological challenge, threatening biodiversity, ecosystem functioning, and human health, while generating substantial biomass waste during management. This systematic review synthesises current knowledge on converting invasive plant biomass into biochar via pyrolysis, examining production parameters, physicochemical characteristics, and applications across agriculture, environmental remediation, carbon sequestration, and emerging technologies. Pyrolysis temperature emerges as the most critical factor shaping biochar properties, with temperatures of 300-700 °C yielding materials with varied surface areas, functional groups, and carbon stability suitable for diverse applications. Agricultural applications demonstrate enhanced crop productivity, improved soil health, increased nutrient availability, and disease suppression, with biochar application rates of 5-20 t/ha yielding optimal benefits. Environmental remediation applications show significant potential for heavy metal adsorption, with maximum capacities reaching 38.10 mg•g⁻¹ for cadmium and 358.7 mg•g⁻¹ for lead, alongside effective removal of organic pollutants and municipal wastewater treatment. Carbon sequestration studies confirm biochar's climate change mitigation potential, with applications in reclaimed mine soils increasing total carbon stock by up to 91%. Emerging applications in geotechnical engineering, constructed wetlands, and slow-release fertilisers expand the utility of invasive plant-derived biochar. Risk assessment studies identify potential contaminants, including persistent free radicals, polycyclic aromatic hydrocarbons, and heavy metals, that require mitigation strategies. Integrating invasive plant management with biochar production offers a promising circular economy approach that simultaneously addresses ecological restoration, waste valorisation, and sustainable resource utilisation. Future research priorities include assessing long-term field performance, optimising economic feasibility, standardising properties, evaluating ecotoxicological risks, and developing regulatory frameworks to support widespread adoption and commercialisation.

Keywords: Biochar, invasive plants, sustainability, pyrolysis, remediation, soil amendments, wastewater treatment

1. Introduction

Invasive plants are non-native species that spread rapidly into new environments, threatening local ecosystems, native plants, the economy, or human health (Weber, 2017). They often grow quickly and produce numerous seeds that accumulate in the soil (Marchante *et al.*, 2010) or spread vegetatively (You *et al.*, 2016). Typically, these plants lack natural predators in new locations, increasing competition with native species for light, water, and nutrients. Consequently, invasive alien plants (IAPs) represent one of the most significant ecological challenges globally, threatening biodiversity, ecosystem functioning, and human health (Klavins *et al.*, 2024). Their exceptional environmental tolerance, rapid reproduction, and spreading capabilities have led to their proliferation across diverse ecosystems, causing substantial economic and ecological damage (Feng *et al.*, 2021; Yang *et al.*, 2022). Managing and eradicating IAPs, while essential, generates substantial biomass waste that poses additional disposal challenges and incurs considerable costs (Ceriani *et al.*, 2024) [63, 41, 68, 32, 14, 65, 7]. This dual challenge-controlling invasions while managing waste biomass has prompted

researchers to explore sustainable valorization pathways that can transform this ecological liability into a resource.

Biochar, a carbon-rich material produced by pyrolyzing organic biomass under oxygen-limited conditions, has emerged as a promising solution for converting IAP biomass into value-added products (Feng *et al.*, 2021; Yang *et al.*, 2022). Pyrolysis not only enables the safe disposal of invasive plants but also produces a versatile material with applications in agriculture, environmental remediation, and energy production (Ahmed *et al.*, 2020; Lian *et al.*, 2020). Biochar characteristics including porous structure, high surface area, functional groups, and carbon stability depend on feedstock type and pyrolysis conditions, particularly temperature (Reza *et al.*, 2020; Li *et al.*, 2023). This variability enables the production of biochar tailored for specific applications, from soil amendment and carbon sequestration to wastewater treatment and heavy metal adsorption (Wang *et al.*, 2021; Ghosh and Maiti, 2021). The global imperative to achieve net-zero emissions and transition toward circular economies has further intensified interest in utilizing IAP biomass as a renewable resource (de Almeida Moreira *et al.*, 2025). Beyond biochar production, IAP biomass shows potential for bioenergy generation, pellet production, and extraction of bioactive compounds (Klavinš *et al.*, 2024). However, realizing this potential requires addressing challenges related to cost management, transportation logistics, and regulatory frameworks (Rawat *et al.*, 2024). This systematic literature review comprehensively synthesizes current knowledge on the utilization of invasive plant biomass, with particular emphasis on biochar production and its diverse applications, to identify research trends, knowledge gaps, and future directions for sustainable management of IAPs [10, 14, 65, 2, 35, 49, 34, 58, 20, 10, 32, 48].

2. Methodology: This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility. A comprehensive literature search was conducted across four major electronic databases: Google Scholar, PubMed, Scopus, and Web of Science. The search strategy employed a combination of keywords and Boolean operators including: ("invasive plants" OR "invasive alien species" OR "invasive weeds") AND ("biochar" OR "pyrolysis" OR "biocarbon") AND ("soil amendment" OR "heavy metal adsorption" OR "wastewater treatment" OR "carbon sequestration" OR "agricultural productivity" OR "environmental remediation"). Studies published between January 2013 and June 2026 were considered for inclusion. The search was limited to peer-reviewed journal articles, review papers, and conference proceedings published in English. Additional records were identified through manual screening of reference lists of included studies and relevant review articles to ensure comprehensive coverage of the literature. Studies were included if they (i) investigated biochar production from invasive plant species; (ii) evaluated biochar applications in agriculture, environmental remediation, or carbon sequestration; (iii) reported original experimental data or comprehensive reviews; and (iv) provided sufficient methodological details for data extraction. Studies were excluded if they (i) focused on non-invasive plant species; (ii) did not involve biochar production or application; (iii) were non-peer-reviewed publications such as book chapters, editorials, or conference abstracts without full-text availability; or (iv) were duplicate publications. After initial screening of titles and abstracts, we assessed full-text articles for eligibility. A total of 70 relevant

studies were included in this systematic review. Data extraction focused on: (i) biochar production parameters (feedstock type, pyrolysis temperature, residence time, yield); (ii) biochar physicochemical characteristics (pH, surface area, carbon content, functional groups); (iii) application areas (agriculture, environmental remediation, carbon sequestration, emerging applications); and (iv) reported outcomes and mechanisms.

3. Results and Synthesis

3.1. Biochar Production from Invasive Plants

The production of biochar from invasive plant species has been extensively investigated across diverse feedstocks and pyrolysis conditions. Liao *et al.* (2013) investigated Brazilian Pepper and Air Potato as feedstocks, comparing them to traditional materials (water oak and energy cane) across pyrolysis temperatures of 300, 450, and 600 °C, finding that Air Potato yielded high biochar while Brazilian Pepper produced high oil yields, with a mathematical model developed describing the relationship between feedstock weight and minimum residence time. Ahmed *et al.* (2020) investigated biochar production from invasive species biomass under varying temperatures (400-600 °C), reporting yields of 45.36-58.35 wt% at 400 °C decreasing to 22.68-29.42 wt% at 600 °C, with carbon content and heating values improving at higher temperatures. The heating values of feedstock biomass ranged from 18.65 to 20.65 MJ/kg, with volatile matter (61.54-72.04 wt%), fixed carbon (19.27-26.61 wt%), and ash content (1.51-1.86 wt%). Reza *et al.* (2020) examined *Pennisetum purpureum* biochar at 400-600 °C, finding heating values of 22.18-23.75 MJ/kg and alkaline pH ranging from 9.10 to 10.17, with enhanced porosity at higher temperatures confirmed by SEM imaging. Biochar yields decreased from 35.13% to 23.02% with increasing temperature, while O/C atomic ratios were 0.15, 0.08, and 0.06 for biochar at 400, 500, and 600 °C respectively. FT-IR analysis revealed functional groups including C-O, C=C, and C-H.

Lian *et al.* (2020) demonstrated that ragweed and horseweed biochars produced at 450 °C exhibited maximum adsorption capacities for Cd(II) (139 mg·g⁻¹) and Pb(II) (358.7 mg·g⁻¹), with immobilized fractions mainly attributable to acid soluble and non-available fractions. Wang *et al.* (2021) characterized biochars from five invasive species (*Bidens pilosa* L., *Praxelis clematidea*, *Ipomoea cairica*, *Mikania micrantha*, and *Lantana camara* L.) at 300-700 °C, concluding that all species were suitable feedstocks with temperature and species interacting to determine biochar properties. BBC500 (*Bidens pilosa* L.) and MBC500 (*Mikania micrantha*) exhibited higher metal equilibrium adsorption capacities (38.10 and 38.02 mg·g⁻¹ for Cd²⁺; 20.01 and 20.10 mg·g⁻¹ for Cu²⁺) and buffer abilities to pH. Adsorption kinetics were explained adequately by pseudo-second-order models, with Langmuir and Freundlich models fitting different biochar types. Lin *et al.* (2025) systematically analyzed pyrolysis characteristics of biomass components (cellulose, hemicellulose, lignin) and their mechanistic effects on biochar physicochemical properties, showing that lignocellulose composition and pyrolysis temperature synergistically controlled adsorption mechanisms. Qiu *et al.* (2023) studied co-pyrolysis of pig manure and Japanese knotweed at different mixture ratios (3:1, 1:1, 1:3) and temperatures (400-700 °C), finding that co-pyrolysis increased fixed carbon contents by nearly 1.5 folds compared with manure-derived biochar alone, significantly reducing heavy metals and transforming Cu and Zn into more stable forms. The combined feedstock biochar P1J1 generated at 600 °C was most effective in reducing environmental risk of heavy metal leaching while retaining most nutrients (P, Ca, Mg, and K).

Jiang *et al.* (2025) employed machine learning using deep neural

networks and LightGBM to predict biochar specific surface area based on plant characterization information, finding that plant organ information enhanced model performance with pyrolysis temperature identified as a key feature. The DNN model achieved R^2 improvement from 0.897 to 0.917 after incorporating plant organ characteristics. Tshikovhi *et al.* (2024) investigated biochar from water hyacinth synthesized via controlled pyrolysis (300-700 °C), with biochar at 500 °C (WHB500) exhibiting highest adsorption capacity attributed to high porosity and optimal carbon content (73.1%). FTIR analysis showed structural changes in functional groups (aliphatic C-H and carbonyl C=O), with WHB700 showing enhanced adsorption due to strong alkaline amine peaks. Overall adsorption efficiency followed the order WHB500 > WHB700 > WHB300 > Raw WH [37, 2, 49, 35, 58, 38, 46, 27, 54].

3.2. Agricultural Applications and Soil Improvement

Biochar derived from invasive plants has shown considerable promise for enhancing agricultural productivity and soil health. Fartyal *et al.* (2025) evaluated biochar from *Ageratina adenophora*, *Lantana camara*, and *Parthenium hysterophorus* applied at four rates (1, 3, 5, 7 g kg⁻¹ soil) to *Lens culinaris* crops, finding that *P. hysterophorus*-derived biochar outperformed others, though biochar application inhibited seed germination rates while stimulating growth parameters including shoot length, total plant length, shoot volume, total biomass, root moisture content, and seed vigour index. The study concluded that feedstock type significantly influences biochar characteristics and nutrient content. Khatri *et al.* (2025) reported that *A. adenophora* biochar produced at 500 °C increased germination rates, while 350 °C biochar at lower application rates (1 g/kg) yielded optimal growth and productivity in wheat, with interactive effects of temperature and application rate showing significant effects on germination rate, length, and biomass of roots in the initial growth period.

Choudhary *et al.* (2023) demonstrated that *Lantana camara* biochar (10 t/ha) combined with 75% recommended fertilizer increased oat fodder yield by ~8% and crude protein by ~6%, decreased acid detergent fibre and neutral detergent fibre by 5.70% and 6.04%, and significantly improved soil microbial populations including bacteria (7.33×10^8 CFU/g soil), alkaline phosphatase activity (19.56 µg pNP/g soil/h), microbial biomass carbon (156.67 µg/g soil), and dehydrogenase activity (12.59 µg TPF/g/24 h). Agbeshie *et al.* (2025) conducted a three-season field experiment in Ghana, finding that invasive aquatic plant biochar increased persistent soil organic carbon pools by 36-50% through greater accumulation of mineral-associated organic carbon, with the largest bulk soil organic carbon stock of 25.52 t ha⁻¹ observed at 0-15 cm depth. The B5 treatment increased particulate organic carbon and soil microbial biomass carbon concentrations by up to 300%. Leaf chlorophyll content, NPK uptake, and grain yield were significantly enhanced by amendments C4, C2, and B2.5 + C2, with value-cost ratios exceeding 2 indicating profitability.

Li *et al.* (2023) compared biochar from invasive plants (Blackjack, Wedelia, and Bitter Vine) with liming for acid rain-affected soils (pH 4.5 and 2.5), showing that biochar maintained neutral soil pH (6.5-7) while liming alkalized soil pH to 9.5. Biochar caused fourfold increases in available N and P compared to liming, while liming decreased available soil N, P, and K by 36.3%. BJ-biochar increased soil available P and K, while BV-biochar maximized soil available N. Biochar caused balanced increments in Ca²⁺ by threefold, cation exchange capacity by 45%, urease activity by 16%, and fungal diversity

by 10%, while having slight reduction in bacterial diversity by 2.5%. The study strongly recommended biochar from invasive plants instead of lime for sustainable improvements in soil properties under acid rain. Wang *et al.* (2024 - Wang S.) investigated *Solidago canadensis* L. biochar to control bacterial wilt in tomato, finding that application significantly reduced *Ralstonia solanacearum* abundance (16.8-32.9%) and wilt disease index (14.0-49.2%) while promoting tomato growth. The biochar treatment increased soil organic carbon, nutrient availability, soil chitinase, and sucrose activities under pathogen inoculation, and significantly increased relative abundance of beneficial organisms including *Bacillus* and *Sphingomonas*.

Karim *et al.* (2025) evaluated *Acacia auriculiformis* wood-waste biochar on germination and early growth of five major crops (rice, wheat, chili, eggplant, tomato) in Bangladesh, finding significant ($p < 0.001$) increase in germination with higher biochar application rates. In *Capsicum annuum* the 15 t/ha treatment resulted in 96% increase in germination compared to control (43.3% vs 85.1%). The linear mixed-effects model showed significant effect of biochar treatment on germination ($F = 57.33$, $p < 0.001$) and significant interaction with crop type ($F = 15.84$, $p < 0.001$). Shamim *et al.* (2018) assessed impact of biochar from *Albizia saman*, *Neolamarckia cadamba*, and *Albizia richardiana* on paddy germination and early growth, finding that 15 t/ha of Raintree biochar significantly increased root length, while 15 t/ha of Chambul biochar showed strongly significant ($p < 0.001$) increase of NPK compared to control. Luo *et al.* (2019) investigated co-application of poplar-derived wood vinegar and biochar on pepper and tomato, finding that wood vinegar promoted root and shoot lengths at low concentrations (0.002% and 0.02%), while co-application significantly increased root length, surface area, and volume of tomato by 98.0%, 66.7%, and 83.1% respectively, attributed to enhanced nutrient availability and slow-released active acid and phenol components adsorbed by biochar [13, 31, 9, 1, 34, 60, 29, 50, 40].

Fornes *et al.* (2025) evaluated raw biochar, nitrogen-enriched biochar, and urea on tomato cultivation, finding that raw biochar stimulated seed germination and early radicle growth possibly due to karrikins detected (0.039 and 0.044 mg kg⁻¹), while nitrogen-enriched biochar showed positive impact on plant growth and yield without releasing high ammonium or negatively affecting seed germination. Dziosa and Makowska (2025) investigated biochar from *Chlorella* sp. algae as seed growth stimulant for radish, finding average germination time of 1.12 for treated samples vs 1.87 for control, germination energy of 93% vs 88%, and germination capacity of 97% vs 92%. Gasco *et al.* (2016) reported seed germination and plant development for three biochars (wood, paper sludge plus wheat husks, sewage sludge) on five higher plant species, finding that seed germination was generally not affected except for inhibition caused by wood biochar and paper sludge biochar on lettuce, with results significant for advancing understanding of biochar impacts on vegetative growth.

Zhang *et al.* (2022) provided extensive overview on biochar-based seed coating, discussing promotion of seed germination and stand establishment, improvement of plant growth and nutrition, suitable carriers for microbial inoculants, and increase in herbicide selectivity. Tan *et al.* (2025) investigated biochar-based pelletized seed for late-sown rapeseed with functional agents including 6-benzylaminopurine, abscisic acid, salicylic acid, and trehalose, finding that Tre1 treatment increased yield by 9.75% in 2021-2022 and 5.88% in 2022-2023. The pelletizing treatments significantly improved emergence and germination, increased osmoregulatory capacity and enzymatic

antioxidant capacity, and reduced membrane lipid damage and reactive oxygen species damage during overwintering. Redundancy analysis revealed late-sown rapeseed yield was significantly and positively correlated with relative growth rate and cold resistance of seedlings. Amoroso *et al.* (2025) evaluated biochar-enriched coatings incorporating olive pomace, buffalo digestate, and microbial consortia for four crops, finding that biochar-based coatings mitigated phytotoxic effects of ammonia, salts, and polyphenols, enhancing germination and root elongation. *Trichoderma harzianum* addition further improved seedling establishment with increases exceeding 100% compared to control. Field trials confirmed biochar-*T. harzianum* combinations improved both shoot and root biomass, particularly in *Lactuca sativa* and *Solanum lycopersicum*.

Huang and Gu (2019) reviewed effects of biochar on container substrate properties and plant growth, finding that 77.3% of studies found certain percentages of biochar addition promoted plant growth, while 50% revealed plant growth decreased due to certain percentages. The review cautioned about toxic substances (heavy metals, polycyclic aromatic hydrocarbons, dioxin) in biochars and emphasized caution when selecting feedstocks and production conditions. Frenkel *et al.* (2017) reviewed biochar influence on plant disease, revealing that lower concentrations ($\leq 1\%$) often suppressed diseases while higher concentrations ($\geq 3\%$) were mostly ineffective or induced disease, recommending standardization of feedstocks and concentrations for consistent and reproducible effects. Poveda *et al.* (2021) presented comprehensive review of pathogen-suppressive effects of biochar, describing modification of root exudates, soil properties, nutrient availability, induction of systemic plant defenses, activation of stress-hormone responses, and changes in active oxygen species. The review highlighted biochar's potential for controlling root or foliar fungal pathogens, nematodes, and insect pests through changes in soil microbial community diversity, release of nematicidal compounds, and induction of plant defenses [15, 12, 17, 69, 53, 3, 25, 16, 45].

Murtaza *et al.* (2023) reviewed biochar-soil-plant interactions for sustainable agriculture under changing climate, highlighting role in transforming soil physicochemical and biological properties, improving seed germination and seedling growth, altering crop physiological attributes, enhancing crop resistance against biotic and abiotic stresses, improving crop productivity, curtailing GHGs, and controlling nutrient leaching losses. Wang *et al.* (2019) conducted meta-analysis on co-composted biochar (COMBI) effect on plant productivity, finding application rates of <20 t/ha and >30 t/ha significantly increased plant productivity by 48.3% and 15.7% respectively, with greatest increase at acidic soil pH (4-5), and cereal grasses yielding significantly higher grain yields (39.7%). Liu *et al.* (2018) reviewed migration and transformation mechanisms of nutrient elements (N, P, K) within biochar in straw-biochar-soil-plant systems, noting that pyrolysis conditions vital in regulating nutrient characteristics, with appropriate conditions (400 °C in CO₂ atmosphere) reducing migration of nutrients to liquid and gaseous products and increasing retention rate of nutrient elements (biochar-N: 64.94%; biochar-P: 100%; biochar-K: 100%) [42, 62, 39].

3.3. Environmental Remediation: Heavy Metals and Organic Pollutants: The adsorption capacity of invasive plant-derived biochars for heavy metals and organic contaminants has received substantial research attention. Wang *et al.* (2021) reported that biochars pyrolyzed at 500 and 700 °C exhibited

high metal adsorption capacity, with BBC500 (*Bidens pilosa*) and MBC500 (*Mikania micrantha*) showing equilibrium adsorption capacities of 38.10 and 38.02 mg·g⁻¹ for Cd²⁺ and 20.01 and 20.10 mg·g⁻¹ for Cu²⁺. The Langmuir model fit IBC500, MBC500, and LBC500 better than the Freundlich model, while the opposite was true for BBC500 and PBC500, suggesting monolayer adsorption for some and chemical adsorption for others. Wang *et al.* (2024 - Wang X.) demonstrated that biochar mixtures from multiple invasive species improved Cd-contaminated soil remediation, with effects increasing with species richness (from ~22% to ~38% reduction in Cd bioavailability). Biochar application significantly increased both the concentration (~126%) and pool size (~59%) of Cd in roots of native plant communities, although it significantly decreased biomass (~25%). The study identified a novel biodiversity-mediated ecosystem service using multiple invasive plant species for biochar production. Yang *et al.* (2024) developed *Mikania micrantha* biochar for bacterial immobilization and adsorption of contaminants, embedding *Proteus terrae* ZQo2-MB within polyvinyl alcohol-sodium alginate gel to create biochar-modified bacterial microspheres. Taking chlorothalonil as example, field experiments demonstrated removal efficiency of 59.8% by the third day, while improving richness and diversity of soil bacteria and enhancing microbial community structure by the seventh day. The study validated the adsorption capacity of MB, the biofilm growth-promoting ability of BBM, and the CHT mineralisation ability of strain ZQo2 as a joint mechanism.

Li *et al.* (2020 - Li S.) functionalized invasive plant-derived biochar with CaAl-LDH at five mass ratios for Eu(III) adsorption, finding that sorption affinities were strongly affected by solution pH, contact time, temperature, and mass ratio. The CaAl-LDH/IPB composite with high ratio of IPB had higher sorption capacity due to larger porosity. Three mechanisms—ion exchange between Al and Eu ions, surface complexation with carboxyl- and oxygen-containing functional groups, and precipitation were involved, with dominant mechanism differing with mass ratio. In composites with more IPB, both ion exchange and surface complexes dominated, while in high LDH composites, ion exchange dominated. Poonia *et al.* (2025) investigated biochars from invasive weeds *Calotropis gigantea*, *Crotalaria burhia*, and *Tephrosia purpurea* for municipal wastewater treatment in Jodhpur, India. Untreated wastewater showed high pollutant loads including COD (369 mg/L), BOD (58 mg/L), turbidity (66 NTU), color (175 Hazen), SAR (13.07), and coliform count (177.5 MPN/100 mL). *C. burhia* exhibited highest efficiency reducing COD and BOD by 89% and 88.27%, followed by *C. gigantea* (65.85%, 63.41%) and *T. purpurea* (66.39%, 60.34%). Dissolved oxygen increased by 51.35% with *C. burhia*, and total coliform counts decreased by up to 73.33% with *C. burhia*. Invasive weed-derived biochars with high fixed carbon (64-81%) proved sustainable, low-cost alternatives for wastewater remediation while addressing invasive species management.

Nguyen *et al.* (2021) investigated methyl orange dye adsorption using three biochars from wattle bark (BA), mimosa (BM), and coffee husks (BC), finding adsorption efficiency stable at pH 2-7 (95-96%) with maximum adsorption capacity of 12.3 mg/g. BA (393.15 m²/g) and BM (285.53 m²/g) had higher specific surface area compared to BC (2.62 m²/g). Underlying mechanisms were governed by electrostatic adsorption and pore diffusion, with highest efficiency occurring with BM. Chen *et al.* (2018) conducted meta-analysis of 1298 independent observations from 74 published papers on biochar effects on heavy metal

accumulation in plants. Results showed average decreases of 38%, 39%, 25%, and 17% in accumulation of Cd, Pb, Cu, and Zn respectively. Manure-derived biochar was most effective for reducing Cd and Pb concentrations, and biochar with high pH and high application rates resulted in greater decreases in plant heavy metal uptake. Zhao *et al.* (2025) used hierarchical meta-analysis of 237 datasets from 59 studies to evaluate co-application of biochar and plant growth-promoting bacteria, finding combined treatment increased root and shoot biomass by 84% and 116% respectively, while reducing heavy metal concentrations in roots (33%), shoots (45%), and soil (44%). The biochar and *Pseudomonas* combination exhibited optimal biomass enhancement, while Proteobacteria and biochar consortium had most significant effect on decreasing heavy metal content in plant and soil [58, 61, 66, 33, 44, 43, 8, 70].

Wang *et al.* (2023) characterized heavy metal and antibiotics contamination in Pearl River water and sediment samples, finding that heavy metals and antibiotics increased toward downstream region of Pearl River Delta. Invasive plant-derived biochars showed high antibiotic removal capacity but failed to reduce most water heavy metals since these invasive plants are potential heavy metal hyperaccumulators. Su *et al.* (2025) explored nanosilica modification of biochar from terrestrial (*Sonchus oleraceus* L.) and aquatic (*Myriophyllum verticillatum* L.) invasive plants for mitigating heavy metal stress in *Allium hookeri*. Silicon modification increased silicon mass fraction by 9.10% and 4.67% respectively. Terrestrial Si-KBC significantly increased chlorophyll A, chlorophyll B, and chlorophyll T compared to aquatic Si-HBC. Si-HBC was most suitable for yellow soil contaminated by Cd, Cu, and Pb, while HBC was best suited for remediation of Fe and Zn contaminated brown soil. Rajapaksha *et al.* (2014) investigated burcucumber biochar (BBC700) for sulfamethazine uptake by lettuce, finding that with 5% BBC700, uptake was reduced by 86% in soil spiked with 5 mg kg⁻¹ SMT compared to control, with 63% reduction observed in soil spiked with 50 mg kg⁻¹ SMT. Vithanage *et al.* (2014) examined sorption and transport of sulfamethazine in agricultural soils amended with burcucumber biochar produced at 300 and 700 °C, finding that biochar-700 had high degree of SMZ retention, achieving up to 89% and 82% increase in SMZ retention in sandy loam and loamy sand soils respectively. Mechanisms included π - π electron donor-acceptor interaction and electrostatic cation exchange at pH 3, while cation exchange was main mechanism at pH 5 and 7 [52, 47, 57].

Dong *et al.* (2024) [11] reviewed application of invasive plant-derived biochar in controlling plant invasion by removing its own allelochemicals, noting that research on biochar prepared by invasive plants to adsorb their own allelochemicals is still scarce, which may limit application in invasion prevention and control. Kamyab *et al.* (2025) [28] examined biochar as carrier for plant growth-promoting bacteria in phytoremediation of pesticides, highlighting biochar's suitability due to porous structure, surface chemistry, and ability to create microbial habitats, with interactions between biochar, PGPB, and plants enhancing phytoremediation efficiency. Hasnain *et al.* (2026) [24] comprehensively reviewed adverse biochar effects including contaminants (persistent free radicals, metal cyanides) posing risks like phytotoxicity, cytotoxicity, and neurotoxicity, emphasizing significance of designing pyrolysis units that ensure separation of pyrolysis liquids from solids, minimizing organic contaminant condensation, and reducing PTE levels through co-pyrolysis and higher pyrolysis temperatures.

3.4. Carbon Sequestration and Climate Change Mitigation

The potential of invasive plant-derived biochar for carbon sequestration has been explored in multiple contexts. Ceriani *et al.* (2024) carried out in-depth characterization of biochar produced at 550 °C from 10 widespread IAPS (five woody and five herbaceous) in the central-southern Alps region. IAPS-derived biochars exhibited relevant properties in different fields, with coordinated variation and trade-offs from biochars with high stability to biochars with high soil amendment potential (PC1), while soil remediation potential represented independent axis of variation (PC2). Herbaceous IAPS were more suitable for soil amendment due to greater pH, macronutrient content, and macropore area, while woody IAPS showed greater surface area, smaller pores, and higher lead adsorption potentials from aqueous solutions, with higher fixed carbon content indicating higher carbon stability preferable for carbon sequestration. Ghosh and Maiti (2023) applied invasive weed biochar at 10 t/ha and 20 t/ha to 8-year-old reclaimed mine spoil, finding that BC20 significantly improved moisture content (+27%), available-N (+3%), exchangeable-K (+15%), and cation exchange capacity (+35%). Geometric mean of enzymatic activities index increased in BC10 (8) and BC20 (10.2) compared to control (5.8). BC20 had significantly high recalcitrant carbon, total carbon stock increased by 13% and 91% at BC10 and BC20 respectively, and CO₂ sequestered increased by 13% at BC10 and 91% at BC20. In-situ production and surface application of biochar at 20 t/ha cost 239 USD/ha. Ghosh and Maiti (2021) conducted 6-month incubation study on effect of biochar amendment (2% and 3%) on mine spoil enzymatic activities, finding significant improvement in dehydrogenase (83%) and cellulase activity (78%) at 3% amendment. Geometric mean of enzymatic activities increased from 1.87 in control to 4.51 at 2% and 3.25 at 3%. Mine spoil physio-chemical properties such as soil organic carbon (65%), cation exchange capacity (54%), bulk density (25%), and water holding capacity (19%) improved significantly. Biochar amendment reduced CO₂ flux at 2% (2.85 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and 3% (2.60 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) compared to control (4.92 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). Cost of biochar production and application in pit plantation during reclamation estimated at 844 USD t ha⁻¹. Simmons *et al.* (2021) examined clearing invasive native scrub in southern Australian rangelands and pyrolysing residues to produce biochar, assuming syngas used for electricity generation and biochar applied to soils for wheat production. The pyrolysis scenario provided mitigation benefits from reduced N₂O emissions from fertiliser use and reduction in lime use to ameliorate soil acidity. Yin *et al.* (2024) explored effects of invasive-plant biochar on established invaded plant communities in Tianjin coastal saline-alkaline wetland, adding biochar derived from *Amaranthus palmeri* and *Spartina alterniflora* at 0%, 1%, 3%, and 5% addition rates. Biochar addition significantly decreased performance measures of invaded plant community, with decrease in abundance of *A. palmeri* and increase in native plants. *S. alterniflora* biochar exhibited more pronounced effect compared to *A. palmeri* biochar. At 5% addition rate, *A. palmeri* and *S. alterniflora* biochar had contrasting effects on complexity of interspecific relationships within plant community. Phylogenetic β -diversities were significantly correlated with biochar addition rate and stochastic processes primarily governed plant community assembly [7, 21, 20, 51, 67].

Feng *et al.* (2021) reviewed current research status of invasive plants, focusing on potential for biochar productions and

applications, noting that invasive plant-derived biochar showed significant differences in structure, composition, and adsorption performance compared to traditional biochar. Yang *et al.* (2022) summarized progress of preparing and using invasive plant biochar, including production, modification, merits and demerits, application in improving soil quality, adsorption of pollutants, application in energy storage, and climate change mitigation potential. Viswanathan *et al.* (2023) investigated agronomic properties of biochars derived from selected invasive wetland weeds and effect on soil organic carbon dynamics and stability of tropical Ultisol soil. Agbeshie *et al.* (2025) suggested that biochar from IAP serves as climate-smart technology offering potential to increase crop productivity and contribute to "recarbonizing global soils" initiative for sustainable agro-ecosystems. Carson *et al.* (2018) assessed Laurentian Great Lakes coastal wetlands, finding that three invasive plants dominated 76,825 ha (36%) of approximately 212,000 ha of wetlands. A single growing season's biomass of these invasive plants was estimated at 659,545 metric tons, containing 10,805 and 1,144 metric tons of nitrogen and phosphorus respectively. One-time harvest and utilization for energy would provide gross equivalent of 1.8 million barrels of oil if combusted, or 0.9 million barrels of oil if converted to biogas. de Almeida Moreira *et al.* (2025) examined conversion of invasive environmental weeds into market-grade pellets, finding that non-woody species such as Brazilian Nightshade and Climbing Asparagus produced durable pellets (97-98%) with high energy density (up to 3.9 GJ/m³) and low ash (<5.1%). Response surface modelling revealed optimal pelletizing parameters, while principal component analysis underscored lignin content, ash chemistry, and particle size distribution as factors influencing pellet performance [56, 1, 6, 10].

3.5. Emerging Applications and Future Directions

Recent research has expanded the application domains of invasive plant-derived biochar. GuhaRay *et al.* (2019) investigated *Prosopis juliflora* biochar for stabilizing expansive black cotton soil at 5% and 10% w/w, reporting increased shear strength and California bearing ratio while decreasing free swell index. Microstructural (XRD, FTIR, SEM, EDX) and physicochemical (CEC, pH, specific gravity) as well as geotechnical characterizations (consistency limits, free swell, permeability, CBR, shear strength) were carried out, revealing that biochar-amended soils possess excellent geotechnical properties for stabilizing expansive soils. Kasak *et al.* (2018) assessed effect of wood-derived biochar amendment (10% v/v) on purification efficiency of pretreated municipal wastewater in planted (*Typha latifolia*) horizontal subsurface flow constructed wetlands filled with lightweight expanded clay aggregates. Biochar addition significantly increased plant biomass production (aboveground 1.9-fold, belowground 1.5-fold) and enhanced wastewater treatment efficiency. Efficiencies of TN and TP removal were highest in LBP filters (20.0% and 22.5%), followed by LP (13.7% and 16.2%) and LB (9.5% and 15.6%). More N and P were incorporated into plant biomass from wastewater in presence of biochar. Jayathilake *et al.* (2024) evaluated potential utilization of biochar as efficient filter medium made by invasive aquatic plants *Salvinia* spp. and *Eichhornia* spp. for treating rubber-manufactured wastewater. OH stretching (3,550-3,200 cm⁻¹), C=C aromatic stretching (1400-1660 cm⁻¹), and Phenol-O-H bending (1,300-1,400 cm⁻¹) were recorded in all biochar samples. Filter unit incorporated with activated *Eichhornia* spp. gave best treatment efficiency, with activated biochar-incorporated filters showing no

mortalities in toxicity assay, suggesting green approach using invasive aquatic plants for sustainable wastewater treatment.

Cai *et al.* (2024) investigated effects of biochar from water hyacinth on soil erosion under varying compaction and slope conditions using flume tests. Biochar addition reduced soil erosion by 10-69% and improved rainwater storage by 20-59%, with 5% biochar amendment achieving best efficiency due to enhanced formation of water-stable macroaggregates. Biochar content was most important factor for water retention (33% contribution) and erosion reduction (40% contribution). The study broadened understanding of water erosion and hydrologic responses under biochar influence and provided sustainable perspective for hydrologic management practice. Liang *et al.* (2026) systematically explored key advances in multifunctional capacity of biochar-based slow-release fertilizers, structured around four interconnected pillars: environmental intelligence and responsive nutrient management, closed-loop nutrient cycling, carbon-fertilizer synergy, and rhizosphere micro-regulation. The review assessed underlying nutrient release mechanisms, effects on soil characteristics and plant physiology, economic evaluations, and outlined challenges and prospective research directions for incorporating BSRFs into precision agriculture frameworks. Ghorbani *et al.* (2025) investigated combined effects of pyrolysis temperature (350 and 450 °C) and post-production hydrogen peroxide oxidation on soil nutrient dynamics and plant performance using wheat straw and wood residue biochars. Pristine biochars increased soil pH from 6.82 to 8.73-9.12 and EC from 2.15 to 3.06-4.71 dS m⁻¹, while oxidized biochars decreased soil pH to 5.62-5.93 due to introduction of oxygen-containing functional groups. All biochars reduced NO₃⁻-N, NH₄⁺-N, and PO₄³⁻-P leaching, with most pronounced reductions in oxidized wheat straw biochar at 450 °C (O-BWS450). Fava bean plants grown in O-BWS450-amended soil achieved greatest N (6.71%) and P (3.89%) uptake, significantly higher than control [22, 30, 26, 22, 36, 19].

Ghani *et al.* (2026) investigated pyrolysis temperature-dependent biochar strategy for improving nutrient retention by integrating urea with biochar produced at 300, 500, and 700 °C using water spinach. IB500 (biochar at 500 °C impregnated with urea) was most effective, improving CEC and availability of Ca²⁺, Mg²⁺, and K⁺ while increasing microbial biomass carbon and nitrogen. IB500 resulted in 56% increase in root length, 81% increase in surface area, 91% increase in root tip formation, 33% increase in leaf number, 59% increase in leaf area index, 44% increase in chlorophyll content, 12% higher photosynthetic rate, 13% increase in stomatal conductance, and 79% increase in nitrogen uptake. Vega *et al.* (2025) evaluated effects of eucalyptus wood biochar (0-40 Mg ha⁻¹) on soil properties and sugarcane productivity over five years under tropical conditions. Maximum sugarcane stalk productivity of 154 and 146 Mg ha⁻¹ was obtained with application of 37.71 and 31.00 Mg ha⁻¹ biochar in treatments with and without NPK fertilizer respectively. Biochar doses increased nutrient availability, cation exchange capacity, soil organic carbon, number of arbuscular mycorrhizal fungal spores, and glomalin, with no effect on total N and diazotrophic bacteria. Xue *et al.* (2025) investigated impacts of biochar derived from *Juglans regia*, *Spartina alterniflora*, and *Flaveria bidentis* on microbial communities in coastal saline wetland soils at rates of 1%, 3%, and 5%. Biochar application led to reduction in microbial community diversity, particularly evident in 5% SBC and FBC treatments. Addition of biochar enhanced overall complexity of community, with 5% SBC boosting complexity of microbial network and encouraging cooperative relationships. However,

community became more vulnerable to environmental changes. The study emphasized importance of carefully selecting biochar types during soil remediation with particular attention to high concentrations.

Azman *et al.* (2025) investigated the effects of biomass type, pyrolysis temperature, time, and heating rate on biochar traits, thoroughly examining porosity, surface area, pH, CEC, and labile carbon in relation to soil microbial community and biochar-microbe interaction to soil nutrient dynamics. Haider *et al.* (2020) investigated plant accessibility of captured nitrate in field-aged biochar, finding that biochar-captured N was as plant available as mineral nitrate except for highest dosage, suggesting N captured by biochar may improve N use efficiency in agriculture. Rawat *et al.* (2024) examined current political situation in South Africa seeking opportunities to promote sustainable development using renewable resources, proposing long-term options for optimizing costs and benefits of IAP biomass and meeting rising energy demand. Biomass from approximately 300 "Working for Water Projects" might be used for bioenergy, firewood, charcoal, and value-added forest products. The study implied that for competitive biomass-to-energy conversion, cost management particularly for transportation and significant regulatory incentives are essential, along with effective policy instruments promoting innovative systems and knowledge generation [18, 55, 64, 4, 23, 48].

4. Discussion

4.1. Research Trends and Synthesis

Analysis of the reviewed literature reveals several discernible research trends. First, studies have progressively shifted from characterizing biochar properties to optimizing production parameters for specific applications, with pyrolysis temperature consistently identified as the most critical factor influencing biochar characteristics (Ahmed *et al.*, 2020; Reza *et al.*, 2020; Lian *et al.*, 2020; Wang *et al.*, 2021; Lin *et al.*, 2025; Ghani *et al.*, 2026). Second, research has expanded from single-feedstock studies to comparative analyses across multiple species and mixed feedstocks, showing the potential to tailor biochar properties (Ceriani *et al.*, 2024; Qiu *et al.*, 2023; Wang *et al.*, 2024). Third, applications have diversified from primarily soil amendment to encompass water treatment, constructed wetlands, geotechnical engineering, advanced functional materials, and biochar-based fertilizers (Kasak *et al.*, 2018; GuhaRay *et al.*, 2019; Liang *et al.*, 2026; Ghorbani *et al.*, 2025; Tshikovhi *et al.*, 2024; Cai *et al.*, 2024). Fourth, there is growing emphasis on understanding mechanisms including adsorption kinetics, microbial interactions, nutrient dynamics, and plant-pathogen interactions rather than merely documenting effects (Yang *et al.*, 2024; Wang *et al.*, 2024; Poveda *et al.*, 2021; Zhao *et al.*, 2025; Frenkel *et al.*, 2017). Fifth, recent studies have begun integrating advanced analytical approaches, including machine learning, meta-analysis, and comprehensive characterization techniques, to predict biochar performance and synthesize findings across studies (Jiang *et al.*, 2025; Chen *et al.*, 2018; Wang *et al.*, 2019; Zhao *et al.*, 2025). Sixth, risk assessment and environmental safety have emerged as critical considerations, with studies identifying potential contaminants including persistent free radicals, polycyclic aromatic hydrocarbons, and heavy metals, emphasizing need for comprehensive contamination control strategies (Hasnain *et al.*, 2026; Huang and Gu, 2019; Gasco *et al.*, 2016) [2, 49, 35, 58, 38, 18, 7, 46, 61, 30, 22, 36, 19, 54, 5, 66, 60, 45, 70, 16, 27, 8, 62, 70, 24, 25, 17].

4.2. Knowledge Gaps and Future Directions

Despite significant progress, several knowledge gaps remain. The long-term field performance of IAP-derived biochar across diverse environmental conditions requires further investigation. The economic feasibility and scalability of production need comprehensive assessment, including cost-benefit analysis across different contexts. Standardization of biochar properties and quality control measures remains insufficient. Potential ecotoxicological risks, particularly persistent free radicals and heavy-metal accumulation in food chains, require systematic evaluation. Regulatory frameworks for biochar application and IAP management need to be developed and harmonised. Integrating invasive plant management with biochar production offers a promising circular-economy approach that addresses ecological restoration, waste valorisation, and sustainable agriculture. Future research should focus on developing tailored biochar products for specific applications, optimising production parameters for maximum efficiency, assessing long-term environmental impacts, and establishing regulatory frameworks to facilitate commercialisation. Combining IAP management with biochar production represents a win-win strategy that addresses both ecological restoration and sustainable resource utilisation.

5. Conclusions

This systematic review synthesizes current knowledge on invasive plant-derived biochar production and applications across 70 studies identified from Google Scholar, PubMed, Scopus, and Web of Science. Pyrolysis temperature emerges as the most critical factor influencing biochar characteristics, with temperatures ranging from 300-700 °C producing biochars with varied properties suitable for different applications. Agricultural applications demonstrate enhanced crop productivity, soil health, and disease suppression. Environmental remediation applications show significant potential for heavy metal adsorption, organic pollutant removal, and wastewater treatment. Carbon sequestration studies confirm biochar's climate change mitigation potential. Emerging applications in geotechnical engineering, constructed wetlands, and slow-release fertilizers expand the utility of IAP-derived biochar. Risk assessment studies identify potential contaminants requiring mitigation strategies. The integration of invasive plant management with biochar production offers a promising circular economy approach that simultaneously addresses ecological restoration, waste valorization, and sustainable agriculture. Future research should focus on long-term field performance, economic feasibility, standardization, ecotoxicological risks, and regulatory frameworks to facilitate widespread adoption.

References

1. Agbeshie AA, Ewusi-Mensah N, Amoah AA, Logah V, Jørgensen U. Invasive aquatic plant biochar increases soil organic carbon stocks and maize productivity in tropical climate. *Soil Use Manag.* 2025;41(4):e70142.
2. Ahmed A, Bakar MSA, Hamdani R, Park Y, Lam SS, Sukri RS, *et al.* Valorization of underutilized waste biomass from invasive species to produce biochar for energy and other value-added applications. *Environ Res.* 2020;186:109596.
3. Amoroso G, Idbella M, Motti R, Gemini A, Cozzolino A, Bonanomi G. Biochar, beneficial microbes, and agro-industrial byproducts in seed coatings: improving germination and biomass in multiple crops. *Horticulturae.* 2025;11(5):554.

4. Azman NANM, Asmadi M, Zainol MM. Investigation into pyrolysis impact on biochar traits, soil microbial community interaction, and nutrient dynamics: emission and leaching implications. In: *Biochar Ecotechnology for Sustainable Agriculture and Environment*. Elsevier; 2025. p. 443-467.
5. Cai W, Huang H, Chen P, Huang X, Gaurav S, Pan Z, *et al*. Effects of biochar from invasive weed on soil erosion under varying compaction and slope conditions: comprehensive study using flume experiments. *Biomass Convers Biorefin*. 2024;14(5):5771-5790.
6. Carson B, Lishawa SC, Tuchman N, Monks AM, Lawrence B, Albert D. Harvesting invasive plants to reduce nutrient loads and produce bioenergy: an assessment of Great Lakes coastal wetlands. *Ecosphere*. 2018;9(6):e02320.
7. Ceriani A, Dalle Fratte M, Agosto G, Beatrice P, Reguzzoni M, Bettucci L, *et al*. Woody and herbaceous invasive alien plant species-derived biochars are potentially optimal for soil amendment, soil remediation, and carbon storage. *GCB Bioenergy*. 2024;16(2):e13117.
8. Chen D, Liu X, Bian R, Cheng K, Zhang X, Zheng J, *et al*. Effects of biochar on availability and plant uptake of heavy metals a meta-analysis. *J Environ Manage*. 2018;222:76-85.
9. Choudhary P, Prasad M, Choudhary M, Kumar A, Kumar S, Srinivasan R, *et al*. Exploring invasive weed biochar as soil amendment: a study on fodder oats productivity and soil biological properties. *Environ Res*. 2023;216:114527.
10. de Almeida Moreira BR, Punde S, Hine D, Yadav S. From environmental invasive weeds to solid biofuels: assessing bioenergy potential through pelletisation and operational optimisation. *Sustain Energy Technol Assess*. 2025;80:104396.
11. Dong L, Zhang Y, Dong L. The application of invasive plant-derived biochar in controlling plant invasion by removing its allelochemicals. *J Sustain Civil Eng Technol*. 2024;3(2):158-166.
12. Dziosa K, Makowska M. Biochar from *Chlorella* sp. algae as a plant growth activator. *Sci Rep*. 2025;15(1):20700.
13. Fartyal A, Bhambra GK, Joshi V, Joshi C, Bargali K, Bargali S. Assessing the potential of three invasive alien plants as possible feedstock for the production of biochar and crop productivity. *J Soil Sci Plant Nutr*. 2025;25(1):1234-1248.
14. Feng Q, Wang B, Chen M, Wu P, Lee X, Xing Y. Invasive plants as potential sustainable feedstocks for biochar production and multiple applications: a review. *Resour Conserv Recycl*. 2021;164:105204.
15. Fornes F, Castejón-del Pino R, Cayuela ML, Sánchez-García M, Lidón A, Belda RM, *et al*. Effects of biochar, N-enriched biochar and urea on tomato seed germination, vegetative growth, and fruit traits. *J Sci Food Agric*. 2025;105(4):2476-2485.
16. Frenkel O, Jaiswal AK, Elad Y, Lew B, Kammann C, Graber ER. The effect of biochar on plant diseases: what should we learn while designing biochar substrates? *J Environ Eng Landsc Manag*. 2017;25(2):105-113.
17. Gasco G, Cely P, Paz-Ferreiro J, Plaza C, Mendez A. Relation between biochar properties and effects on seed germination and plant development. *Biol Agric Hortic*. 2016;32(4):237-247.
18. Ghani MU, Gong Y, Lin T, Xu Y, Zeng T, Kamran M, *et al*. Pyrolysis temperature regulates biochar-soil interactions to enhance cation exchange capacity, plant growth, and photosynthetic performance. *BMC Plant Biol*. 2026;26:215.
19. Ghorbani M, Amirahmadi E, Bernas J, Bárta J. From feedstock to function: how pyrolysis and oxidation shape biochar performance in soil-plant interactions. *Plants*. 2025;14(21):3278.
20. Ghosh D, Maiti SK. Effect of invasive weed biochar amendment on soil enzymatic activity and respiration of coal mine spoil: a laboratory experiment study. *Biochar*. 2021;3(4):519-533.
21. Ghosh D, Maiti SK. Invasive weed-based biochar facilitated the restoration of coal mine degraded land by modulating the enzyme activity and carbon sequestration. *Restor Ecol*. 2023;31(3):e13744.
22. GuhaRay A, Guoxiong M, Sarkar A, Bordoloi S, Garg A, Pattanayak S. Geotechnical and chemical characterization of expansive clayey soil amended by biochar derived from invasive weed species *Prosopis juliflora*. *Innov Infrastruct Solut*. 2019;4(1):44.
23. Haider G, Joseph S, Steffens D, Müller C, Taherymoosavi S, Mitchell D, *et al*. Mineral nitrogen captured in field-aged biochar is plant-available. *Sci Rep*. 2020;10(1):13816.
24. Hasnain M, Hira I, Zainab R, Ali F, Fitzgerald M, Abideen Z. Hazards and mitigation measures of applying biochar in water, soil, plants, animals and atmospheric for environmental safety. *Environ Geochem Health*. 2026;48(3):132.
25. Huang L, Gu M. Effects of biochar on container substrate properties and growth of plants a review. *Horticulturae*. 2019;5(1):14.
26. Jayatilake KMPI, Manage PM, Idroos FS. Invasive aquatic plants as potential sustainable feedstocks for biochar production and as an innovative approach for wastewater treatment. *Nat Environ Pollut Technol*. 2024;23(2):991-1005.
27. Jiang Z, Xia Q, Lu X, Yue W, Chen A, Liu X, *et al*. Machine learning prediction of biochar-specific surface area based on plant characterization information. *Renew Energy*. 2025;243:122633.
28. Kamyab H, Chelliapan S, Khalili E, Rezanian S, Balasubramanian B, Taheri M, *et al*. Biochar as a carrier for plant growth-promoting bacteria in phytoremediation of pesticides. *J Hazard Mater Adv*. 2025;18:100673.
29. Karim MR, Biswas S, Halim MA, Ahmed R. Biochar enhances seed germination and crop early growth for sustainable agriculture in Bangladesh. *PLoS One*. 2025;20(3):e0320005.
30. Kasak K, Truu J, Ostonen I, Sarjas J, Oopkaup K, Paiste P, *et al*. Biochar enhances plant growth and nutrient removal in horizontal subsurface flow constructed wetlands. *Sci Total Environ*. 2018;639:67-74.
31. Khatri K, Bisht N, Negi B, Bargali K, Bargali SS. Transforming invasive Crofton weed into biochar: effects of pyrolysis conditions and application rates on wheat growth. *S Afr J Bot*. 2025;180:345-357.
32. Klavins M, Purmalis O, Klavinja L, Niedrite E, Ansone-Bertinja L. Biomass of invasive plants as a resource for the development of the bioeconomy. *BioResources*. 2024;19(3):6721-6745.
33. Li S, Dong L, Wei Z, Sheng G, Du K, Hu B. Adsorption and mechanistic study of the invasive plant-derived biochar functionalized with CaAl-LDH for Eu(III) in water. *J Environ Sci*. 2020;96:127-137.
34. Li Y, Abdo A, Shi Z, Merwad AMA, Zhang J. Biochar derived from invasive plants improved the pH, macronutrient availability and biological properties better than liming for acid rain-affected soil. *Biochar*.

- 2023;5(1):67.
35. Lian W, Yang L, Joseph S, Shi W, Bian R, Zheng J, *et al.* Utilization of biochar produced from invasive plant species to efficiently adsorb Cd(II) and Pb(II). *Bioresour Technol.* 2020;317:124011.
 36. Liang P, Wang Y, Wang Y, Tian F, Wu Z. Biochar-based slow-release fertilizers: from nutrient carrier to intelligent regulator in soil-plant systems—a review and perspective. *J Environ Chem Eng.* 2026;14(2):121720.
 37. Liao R, Gao B, Fang J. Invasive plants as feedstock for biochar and bioenergy production. *Bioresour Technol.* 2013;140:439-443.
 38. Lin H, Huang Y, Jin Q, Ma T, Dong Y. Effects of biomass components and pyrolysis temperature on the adsorption properties of biochar for heavy metals: a review. *J Anal Appl Pyrolysis.* 2025;188:107321.
 39. Liu L, Tan Z, Gong H, Huang Q. Migration and transformation mechanisms of nutrient elements (N, P, K) within biochar in straw-biochar-soil-plant systems: a review. *ACS Sustain Chem Eng.* 2019;7(1):22-32.
 40. Luo X, Wang Z, Meki K, Wang X, Liu B, Zheng H, *et al.* Effect of co-application of wood vinegar and biochar on seed germination and seedling growth. *J Soils Sediments.* 2019;19(12):3934-3944.
 41. Marchante H, Freitas H, Hoffmann JH. Seed ecology of an invasive alien species, *Acacia longifolia* (Fabaceae), in Portuguese dune ecosystems. *Am J Bot.* 2010;97(11):1780-1790.
 42. Murtaza G, Ahmed Z, Eldin SM, Ali B, Bawazeer S, Usman M, *et al.* Biochar-soil-plant interactions: a cross talk for sustainable agriculture under changing climate. *Front Environ Sci.* 2023;11:1059449.
 43. Nguyen XC, Nguyen TTH, Nguyen THC, Van Le Q, Vo TYB, Tran TCP, *et al.* Sustainable carbonaceous biochar adsorbents derived from agro-wastes and invasive plants for cation dye adsorption from water. *Chemosphere.* 2021;282:131009.
 44. Poonia P, Parihar S, Jadhav RTJ. Biochar from invasive weeds for enhanced removal of organic pollutants and pathogens from municipal wastewater. *Sci Rep.* 2025;15:8945.
 45. Poveda J, Martínez-Gómez A, Fenoll C, Escobar C. The use of biochar for plant pathogen control. *Phytopathology.* 2021;111(9):1490-1499.
 46. Qiu J, de Souza MF, Robles-Aquilar AA, Ghysels S, Ok YS, Ronsse F, *et al.* Improving biochar properties by co-pyrolysis of pig manure with bio-invasive weed for use as the soil amendment. *Chemosphere.* 2023;312:137229.
 47. Rajapaksha AU, Vithanage M, Lim JE, Ahmed MBM, Zhang M, Lee SS, *et al.* Invasive plant-derived biochar inhibits sulfamethazine uptake by lettuce in soil. *Chemosphere.* 2014;111:500-504.
 48. Rawat YS, Singh GS, Tekleyohannes A. Optimizing the benefits of invasive alien plants biomass in South Africa. *Sustainability.* 2024;16(5):2134.
 49. Reza MS, Afroze S, Bakar MS, Saidur R, Aslfattahi N, Taweekun J, *et al.* Biochar characterization of invasive *Pennisetum purpureum* grass: effect of pyrolysis temperature. *Biochar.* 2020;2(2):239-251.
 50. Shamim M, Saha N, Hye FB. Effect of biochar on seed germination, early growth of *Oryza sativa* L. and soil nutrients. *Trop Plant Res.* 2018;5(3):336-342.
 51. Simmons AT, Cowie AL, Waters CM. Pyrolysis of invasive woody vegetation for energy and biochar has climate change mitigation potential. *Sci Total Environ.* 2021;770:145278.
 52. Su M, Tian H, Guo Z, Luo G, Gong X, Li X, *et al.* Utilization of SiO₂-NP-modified biochar from invasive plants to mitigate heavy metal stress in *Allium hookeri*. *Environ Technol Innov.* 2025;37:104041.
 53. Tan X, Wang Z, Zhang Y, Wang X, Shao D, Wang C, *et al.* Biochar-based pelletized seed enhances the yield of late-sown rapeseed by improving the relative growth rate and cold resistance of seedlings. *Ind Crops Prod.* 2025;223:119993.
 54. Tshikovhi A, Mudzanani K, Phadi T, Daramola M, Masindi V. Biochar from water hyacinth: a promising sustainable alternative to activated carbon and solution for invasive species management. *Waste Biomass Valor.* 2024;15:5679-5695.
 55. Vega CF, Mota MFC, Lopes EMG, dos Santos Júnior JM, Colen F, Frazao LA, *et al.* Biochar from eucalyptus waste improves the chemical and biological properties of an Inceptisol and sugarcane yield over time under tropical conditions. *Pedosphere.* 2025;35(3):456-468.
 56. Viswanathan SP, Nizhakhannuha GV, Neelamury SP, Padmakumar B, Ambatt TP. Invasive wetland weeds derived biochar properties affecting soil carbon dynamics of south Indian Ultisol. *Environ Sci Pollut Res.* 2023;30:78901-78918.
 57. Vithanage M, Rajapaksha AU, Tang X, Thiele-Bruhn S, Kim KH, Lee SE, *et al.* Sorption and transport of sulfamethazine in agricultural soils amended with invasive-plant-derived biochar. *J Environ Manage.* 2014;141:95-103.
 58. Wang J, Zhao M, Zhang J, Zhao B, Lu X. Characterization and utilization of biochars derived from five invasive plant species *Bidens pilosa* L., *Praxelis clematidea*, *Ipomoea cairica*, *Mikania micrantha* and *Lantana camara* L. for Cd²⁺ and Cu²⁺ removal. *J Environ Manage.* 2021;280:111746.
 59. Wang J, Lu X, Jing Q, Zhang B, Ye J, Zhang H, *et al.* Spatiotemporal characterization of heavy metal and antibiotics in the Pearl River Basin and pollutants removal assessment using invasive species-derived biochars. *J Hazard Mater.* 2023;454:131409.
 60. Wang S, Wang L, Li S, Zhang T, Cai K. The win-win effects of an invasive plant biochar on a soil-crop system: controlling a bacterial soilborne disease and stabilizing the soil microbial community network. *Microorganisms.* 2024;12(3):447.
 61. Wang X, Zheng WL, Yuan HM, van Kleunen M, Yu FH, Li MH. Biochar produced from diverse invasive species improves remediation of cadmium-contaminated soils. *Biol Invasions.* 2024;26(8):2595-2606.
 62. Wang Y, Villamil MB, Davidson PC, Akdeniz N. A quantitative understanding of the role of co-composted biochar in plant growth using meta-analysis. *Sci Total Environ.* 2019;685:741-752.
 63. Weber E. Invasive plant species of the world: a reference guide to environmental weeds. CABI; 2017.
 64. Xue Q, He M, Meng Z, Lu X, Wang Z, Liang L, *et al.* Modulated use of high-concentration invasive biochar in waste-to-energy strategies: impact analysis on microbial communities. *J Environ Manage.* 2025;377:124547.
 65. Yang L, Deng Y, Shu Z, Chen Q, Yang H. Application of invasive plants as biochar precursors in the field of environment and energy storage. *Front Environ Sci.* 2022;10:940563.
 66. Yang L, Yang X, Guo J, Yang Z, Du Y, Lu Q, *et al.*

- Invasive plant-derived biochar for sustainable bioremediation of pesticide contaminated soil. *Chem Eng J.* 2024;485:149876.
67. Yin S, Wang X, Meng Z, Mo X, He M, Liu J. Mitigating invasive species using biochar derived from invasive plants in saline-alkaline wetland plant communities dominated by *Amaranthus palmeri*. *Appl Veg Sci.* 2024;27(3):e12801.
68. You WH, Han CM, Fang LX, Du DL. Propagule pressure, habitat conditions and clonal integration influence the establishment and growth of an invasive clonal plant, *Alternanthera philoxeroides*. *Front Plant Sci.* 2016;7:568.
69. Zhang K, Khan Z, Yu Q, Qu Z, Liu J, Luo T, *et al.* Biochar coating is a sustainable and economical approach to promote seed coating technology, seed germination, plant performance, and soil health. *Plants.* 2022;11(21):2864.
70. Zhao S, Zhao S, Wang B. Combined application of biochar and PGPB on crop growth and heavy metals accumulation: a meta-analysis. *Environ Pollut.* 2025;381:126626.