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THE SIGNIFICANCE OF USING ENGINEERED BIOCHAR IN THE RECLAMATION OF SALINE SOILS FOR CARBON SEQUESTRATION AND THE REDUCTION OF GREENHOUSE GAS EMISSIONS

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Abstract. Soil salinization is a major environmental and agricultural challenge that reduces soil productivity, disrupts nutrient cycling, and limits the sustainable use of land resources. Engineered biochar has emerged as a promising soil amendment for saline soil reclamation because of its porous structure, carbon-rich composition, and capacity to influence soil physical, chemical, and biological properties. This article examines the role of engineered biochar in enhancing soil organic carbon storage and mitigating greenhouse gas emissions during saline soil reclamation. Particular attention is paid to biochar production conditions, feedstock selection, salinity and sodicity management, carbon persistence, soil respiration, and nitrous oxide and methane fluxes. The article also discusses the importance of life-cycle assessment, field-scale validation, and context-specific application strategies. It argues that the climate benefits of engineered biochar depend on its stability, production technology, application rate, soil characteristics, irrigation regime, and potential effects on greenhouse gas fluxes. Integrating engineered biochar into saline soil reclamation may support soil restoration and climate-change mitigation when supported by appropriate agronomic practices and rigorous carbon accounting.

Keywords: engineered biochar, saline soil reclamation, carbon sequestration, greenhouse gas emissions, soil organic carbon, soil salinity, sodicity, climate mitigation, soil restoration, life-cycle assessment.

Introduction. Soil salinization is one of the major constraints on agricultural productivity and sustainable land management in arid and semi-arid regions. High concentrations of soluble salts can reduce soil water potential, restrict plant water uptake, disturb nutrient balance, and impair seed germination and plant growth. In sodic soils, excessive exchangeable sodium can additionally cause clay dispersion, soil crusting, reduced infiltration, and deterioration of soil structure. These processes can reinforce one another, particularly where irrigation water quality, inadequate drainage, high evaporation, and shallow saline groundwater contribute to salt accumulation. The reclamation of saline and sodic soils therefore requires an integrated approach that addresses salt balance, water movement, soil structure, nutrient availability, and biological recovery. Conventional measures

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include leaching soluble salts, improving drainage, applying suitable calcium amendments to sodic soils, and selecting salt-tolerant crops. Although these practices can improve soil conditions, their effectiveness depends on local hydrological characteristics, water availability, soil texture, and the chemical composition of the soil and irrigation water. In this context, engineered biochar has attracted increasing scientific attention. Biochar is a carbon-rich material produced by heating biomass under oxygen-limited conditions. Its properties vary according to feedstock composition, pyrolysis temperature, residence time, and post-production treatment. Unlike untreated organic residues, engineered biochar can be produced and modified to achieve specific properties, including enhanced porosity, controlled alkalinity, improved surface functionality, or reduced concentrations of undesirable constituents.

The potential contribution of biochar to climate mitigation is closely connected with its capacity to retain a portion of biomass-derived carbon in a relatively persistent form. Depending on its chemical composition and environmental conditions, biochar may remain in soil for decades to centuries or longer. At the same time, its effects on nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) emissions can vary considerably across soils and management systems. Consequently, biochar should not be regarded as an automatically carbon-negative material; its net climate benefit must be assessed across the production, transportation, application, and soil-use stages. The scientific relevance of this topic lies in the possibility of integrating soil reclamation with carbon management. When appropriately designed and applied, engineered biochar may help improve selected soil properties while storing persistent carbon and modifying greenhouse gas fluxes. However, these outcomes depend on the interaction between biochar characteristics, soil salinity and sodicity, irrigation practices, and local environmental conditions. The aim of this study is to analyze the scientific basis for using engineered biochar in saline soil reclamation, with particular emphasis on carbon sequestration, greenhouse gas emission mitigation, and the environmental conditions that determine the overall effectiveness of this approach.

Literature Review. Biochar is generally produced through pyrolysis, during which biomass is thermochemically converted under oxygen-limited conditions. The resulting material contains varying proportions of aromatic carbon, mineral ash, volatile compounds, and surface functional groups. Its agronomic and environmental performance depends on the original feedstock and the conditions under which it is manufactured. The term engineered biochar refers here to biochar whose properties are deliberately controlled through feedstock selection, pyrolysis optimization, physical processing, or post-production modification. Examples include washed biochar, mineral-enriched biochar, and biochar modified to improve particular sorption or nutrient-retention properties. Engineering does not automatically guarantee superior performance: each product must be evaluated for its intended soil and environmental application. A comprehensive review of biochar and nanobiochar applications in salt-affected environments identifies potential mechanisms involving ion interactions, nutrient retention, soil modification, microbial processes, and plant salt tolerance [1]. These mechanisms

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provide a basis for investigating biochar as part of integrated reclamation systems. Nevertheless, these effects are not universal. A highly alkaline biochar may be unsuitable for an already alkaline soil, while biochar with high soluble-salt content may aggravate salinity. Its effectiveness must therefore be established through chemical characterization and soil-specific testing.

Salinity and sodicity: implications for reclamation. Salinity and sodicity are related but distinct soil degradation processes. Salinity is commonly assessed using the electrical conductivity of a soil-water extract, whereas sodicity is evaluated using indicators such as the exchangeable sodium percentage (ESP) and, where appropriate, the sodium adsorption ratio (SAR). Biochar may improve selected physical and chemical properties of salt-affected soils, but it does not remove accumulated salts by itself. Effective reclamation requires the movement of soluble salts out of the root zone and, where sodicity is present, an appropriate strategy for replacing exchangeable sodium and managing the displaced salts. For saline soils, leaching with suitable-quality water and adequate drainage are often central to reclamation. For sodic soils, calcium amendments such as gypsum may be required, depending on soil chemistry and reclamation objectives. Biochar may complement these measures by modifying water movement, supporting soil structure, and influencing nutrient cycling. Its use must be designed carefully. If biochar increases water retention but drainage remains inadequate, salt removal may not improve. Similarly, increasing the pH of an already alkaline soil may reduce the availability of certain micronutrients. Thus, engineered biochar should be considered a complementary soil amendment rather than a universal substitute for conventional reclamation measures.

Biochar and the soil carbon cycle. Biochar can contribute to soil carbon sequestration by converting part of the carbon contained in biomass into a material that is generally more resistant to biological decomposition than fresh plant residues. Its aromatic carbon structures can persist in soil, although the actual residence time depends on chemical composition, temperature, soil environment, and other factors. A global rapid review and meta-analysis published in 2024 examined 75 studies comprising 250 observations. It reported a 61% average increase in the soil-carbon-sequestration measure used in the included studies, with a 95% confidence interval of 36–90%. The same analysis found an average increase of 11% in total soil CO_2 flux, with uncertainty extending to the no-effect boundary, and no statistically clear change in total microbial respiration [2].

These findings demonstrate an important distinction: an increase in soil CO_2 flux does not necessarily mean that biochar-derived carbon storage has failed. Measured CO_2 can originate from several sources, including decomposition of native soil organic matter, decomposition of fresh organic inputs, and root respiration. Carbon accounting must distinguish these sources wherever possible and assess them alongside the quantity and persistence of biochar carbon. A defensible estimate of biochar's climate benefit must also consider emissions generated during biomass collection, transport, drying, pyrolysis, product processing, and application. The net benefit depends on the production technology, the alternative fate of the feedstock, the energy recovered during production, and the durability of the stored carbon.

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Results and Discussion. The literature indicates that engineered biochar can influence several soil properties relevant to reclamation, but the magnitude and direction of these effects depend on the characteristics of both the biochar and the soil. First, the porous structure of biochar may alter soil bulk density, pore-size distribution, and water retention. In coarse-textured soils, appropriately selected biochar may increase water-holding capacity, potentially reducing irrigation frequency and improving water availability to plants. In finer-textured soils, its effects on infiltration and hydraulic conductivity depend on particle size, application rate, soil aggregation, and the interaction between biochar particles and the mineral matrix. Second, biochar may affect the retention and movement of nutrients and selected ions. Its surface functional groups and mineral constituents can influence cation exchange and sorption processes. However, the retention of sodium does not necessarily constitute effective desalination. Sustainable reclamation requires a measurable reduction in root-zone salinity and, for sodic soils, an improvement in exchangeable sodium status. These outcomes must be demonstrated through soil testing rather than inferred from biochar application alone. Third, biochar can alter the soil pH and electrical conductivity. This is particularly important in arid regions, where saline soils may already be alkaline and irrigation water can introduce additional dissolved salts. Biochar with excessive ash or soluble-salt content may be unsuitable unless it is processed appropriately. Washing or other post-production treatments may reduce soluble salts in selected materials, although treatment effectiveness and the environmental consequences of wastewater disposal must also be evaluated. The practical implication is that the selection of engineered biochar should be based on a target soil profile rather than a generalized assumption that all biochars improve saline soils.

Carbon sequestration potential during soil reclamation. Carbon sequestration is one of the principal reasons for considering biochar as a climate-oriented soil amendment. Pyrolysis converts a portion of biomass carbon into relatively persistent forms, allowing carbon that might otherwise return rapidly to the atmosphere through decomposition to be retained in soil for longer periods.

The magnitude of this benefit depends on four principal factors:

1. Feedstock composition. Woody biomass, crop residues, and manure-derived materials can produce biochars with different carbon contents, ash fractions, and mineral characteristics.

2. Pyrolysis conditions. Temperature and residence time influence carbon concentration, aromaticity, porosity, and the proportion of volatile compounds.

3. Application rate and persistence. A higher application rate generally increases the initial carbon input, but it does not guarantee a proportionally higher net climate benefit.

4. Soil and management conditions. Soil moisture, temperature, pH, microbial activity, and land-management practices can affect biochar transformation and interactions with native soil organic matter.

The 2024 meta-analysis by Bekchanova and colleagues supports the potential for biochar to increase soil carbon storage, while also demonstrating that soil CO_2 flux and microbial respiration do

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not necessarily respond in the same way [2]. For saline soil reclamation, the carbon-storage benefit may be particularly relevant where the amendment is incorporated into a long-term soil restoration program. Nevertheless, the amount of persistent carbon must be estimated from biochar properties and an appropriate stability model, rather than treating the entire applied carbon stock as permanently sequestered. The distinction between gross carbon addition and net carbon removal is essential for credible climate reporting. If biochar production relies on unsustainable biomass harvesting, fossil-intensive processing, or feedstocks that would otherwise provide valuable long-term carbon storage, the net benefit may be substantially reduced.

Effects on carbon dioxide emissions. Biochar can influence soil CO_2 flux through several competing processes. On the one hand, the persistence of biochar carbon may reduce the fraction of biomass carbon that returns rapidly to the atmosphere. On the other hand, biochar may alter soil moisture, aeration, nutrient availability, and microbial activity, thereby changing the decomposition of organic matter. A rise in measured soil CO_2 flux after application does not automatically indicate a net climate penalty. Some of the additional flux may originate from short-term microbial activity or root respiration, while a separate portion of the applied biochar carbon remains stored in the soil. Conversely, it would be incorrect to assume that all increases in soil respiration are harmless simply because biochar has been added. A global meta-analysis published in 2026, based on 542 paired field observations, reported an average reduction of 15.6% in soil N_2O emissions, while CO_2 responses varied with soil, climate, biochar properties, and management [3]. These findings reinforce the need to assess soil carbon stocks and gas fluxes together. In saline soils, particular attention should be paid to irrigation-related changes in moisture and aeration, because these can influence both microbial carbon turnover and greenhouse gas production.

Potential mitigation of nitrous oxide emissions. Nitrous oxide is a potent greenhouse gas associated with soil nitrogen transformations, particularly nitrification and denitrification. Agricultural N_2O emissions are influenced by mineral nitrogen availability, soil moisture, oxygen status, temperature, pH, and microbial activity.

Biochar may reduce N_2O emissions through several mechanisms:

- Retention of selected mineral nitrogen forms, potentially reducing the availability of substrates for loss pathways.
- Changes in soil aeration and water distribution that affect nitrification and denitrification.
- Modification of soil pH and microbial community activity.
- Alteration of nitrogen-use efficiency and the timing of nitrogen availability to plants.

The evidence is promising but not uniform. Kaur and colleagues evaluated published meta-analyses and estimated an overall reduction of approximately 38.8% in soil N_2O emissions following biochar application, while noting substantial differences among studies [4]. A later field-based synthesis reported a smaller average reduction of 15.6% [3]. These estimates should not be treated as contradictory measurements of a single universal response. They are based on different evidence sets,

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study designs, and aggregation methods. Differences in soil type, experimental duration, biochar characteristics, and nitrogen management can substantially affect the measured outcome. In saline soils, the interaction between salt stress and microbial nitrogen cycling may further complicate the response. Reclamation can change soil moisture and microbial activity, potentially altering N_2O emissions independently of biochar. Therefore, a valid experiment should compare biochar-treated soil with an appropriate reclamation control rather than attributing all observed changes to biochar.

Relevance to arid and semi-arid regions. In arid and semi-arid regions, soil salinization, water scarcity, high evaporative demand, and limited drainage capacity frequently occur together. These conditions make the integration of soil restoration and carbon management particularly relevant. Engineered biochar could contribute to this integrated approach when it is produced from suitable agricultural residues and applied in combination with efficient irrigation, drainage, nutrient management, and salt-leaching practices. Local availability of crop residues may reduce transportation requirements and create an opportunity to manage biomass waste more productively. However, the use of agricultural residues must account for competing needs. Some residues are required for livestock feed, soil cover, erosion control, or the maintenance of soil organic matter. Removing excessive quantities for biochar production may create unintended environmental costs. In Uzbekistan and other water-limited agricultural regions, future research should therefore focus on the interaction between biochar characteristics, irrigation-water quality, soil texture, salt balance, and drainage performance. Long-term field trials would help determine whether soil improvements and carbon storage persist under local climatic conditions.

Limitations and Future Research Directions. Despite its potential, the application of engineered biochar in saline soil reclamation involves several scientific and practical uncertainties. First, biochar variability remains a major challenge. Different feedstocks and production conditions produce materials with different carbon stability, alkalinity, salinity, and contaminant profiles. Standardized characterization is necessary to enable meaningful comparisons. Second, the durability of soil improvement must be established. Short-term increases in plant growth or water retention do not necessarily demonstrate successful long-term reclamation. Research should assess soil salinity, sodicity, infiltration, crop productivity, and carbon stocks over multiple seasons. Third, greenhouse gas responses are site-specific. A reduction in N_2O may coincide with increased CO_2 or CH_4 emissions under certain conditions. Comprehensive measurements and consistent accounting boundaries are required to determine net climate effects. Fourth, economic and environmental feasibility must be evaluated. Biomass collection, pyrolysis equipment, transportation, biochar application, and post-production treatment can influence costs and the overall environmental footprint. Life-cycle assessment should include realistic alternatives for the biomass feedstock and the energy generated during production. Fifth, saline soil reclamation requires water and salt management. Biochar cannot replace adequate drainage, appropriate leaching, or necessary amendments for sodic soils. Research should evaluate biochar as part of an integrated reclamation system rather than as a stand-alone

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solution. Future investigations should prioritize replicated field trials, standardized carbon-stability measurements, continuous or high-frequency greenhouse gas monitoring, and long-term assessment of soil and crop responses. Combining these measurements with life-cycle assessment would improve the reliability of estimates of net carbon sequestration and greenhouse gas mitigation.

Conclusion. Engineered biochar represents a promising complementary material for the reclamation of saline soils and the mitigation of climate change. Its potential value arises from the combination of relatively persistent carbon storage, modification of soil physical and chemical properties, and possible changes in greenhouse gas emissions. However, these benefits depend on the properties of the biochar, the characteristics of the affected soil, and the management practices used during reclamation.

The literature reviewed in this article supports five principal conclusions. First, engineered biochar can contribute to the improvement of selected soil properties, including water retention, porosity, nutrient availability, and soil structure. Nevertheless, its effectiveness in reducing salinity and sodicity must be assessed directly. Biochar cannot substitute for adequate drainage, salt leaching, or the calcium amendments required for certain sodic soils. Second, biochar can increase soil carbon storage by introducing carbon in forms that may be more resistant to decomposition than fresh biomass. The climate benefit must be calculated from the fraction of carbon expected to persist, rather than from total biochar carbon input alone. Third, the effect of biochar on greenhouse gas emissions is variable. Published meta-analyses generally indicate a potential for reducing N_2O emissions, but responses of CO_2 and CH_4 depend on soil properties, climatic conditions, biochar characteristics, and agricultural management. Fourth, life-cycle assessment is essential for establishing the net climate benefit. Production energy, feedstock availability, transportation, processing, application, carbon persistence, and changes in non-CO_2 emissions must be considered within a consistent accounting framework. In conclusion, engineered biochar should be regarded as a site-specific component of integrated saline soil reclamation and climate mitigation, rather than a universal solution. Its practical value will depend on the demonstration of sustained soil improvement, durable carbon storage, and a positive net greenhouse gas balance under real field conditions.

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