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Advances and Challenges in Biochar Application for Soil Amendment and Water Retention: A Global Synthesis

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التطورات والتحديات في استخدام الفحم الحيوي لتحسين التربة واحتباس الماء: دراسة شاملة

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Abstract:
Biochar, a carbon-rich product derived from the thermochemical conversion of biomass under oxygen-limited conditions (pyrolysis), has garnered significant attention as a sustainable soil amendment. This review synthesizes global research on biochar's efficacy in enhancing soil properties and improving water retention, critically evaluating its role within sustainable land management frameworks. Evidence consistently demonstrates that biochar application can improve soil physical structure (reducing bulk density, enhancing aggregation), increase cation exchange capacity (CEC), and significantly boost soil water holding capacity (WHC), particularly in coarse-textured or degraded soils. These improvements translate to enhanced crop resilience under drought stress and reduced irrigation demands. Furthermore, biochar contributes to long-term carbon sequestration, potentially mitigating climate change. However, the effectiveness is highly contingent on biochar properties (feedstock, pyrolysis temperature), soil type, climatic conditions, and application rates. Significant challenges persist, including variability in biochar performance, potential negative effects on certain soil biota or nutrient availability at high application rates, economic viability constraints, potential contaminants (e.g., PAHs, heavy metals), and the need for standardized sustainability assessment protocols integrating life cycle analysis (LCA) and long-term field trials. This synthesis underscores biochar's considerable potential as a sustainable amendment for soil health and water security but emphasizes that realizing this potential requires context-specific application strategies, rigorous quality control, economic optimization, and policies supporting its integration into circular bioeconomy models. Future research must prioritize long-term field studies, mechanistic understanding of biochar-soil-water-microbe interactions, and holistic sustainability assessments.

Keywords: Biochar, Soil conditioner, Water retention, Climate change, Biochar-soil interactions.

الملخص
اكتسب الفحم الحيوي، وهو منتج غني بالكربون مشتق من التحويل الكيميائي الحراري للكتلة الحيوية في ظل ظروف محدودة الأكسجين (التحلل الحراري)، اهتمامًا كبيرًا كمُحسِّن مستدام للتربة. تُلخص هذه المراجعة أبحاثًا عالمية حول فعالية الفحم الحيوي في تحسين خصائص التربة واحتباس الماء، مع تقييم نقدي لدوره في أطر الإدارة المستدامة للأراضي. تُثبت الأدلة باستمرار أن استخدام الفحم الحيوي يُمكن أن يُحسّن البنية الفيزيائية للتربة (من خلال تقليل الكثافة الظاهرية، وتعزيز التكتل)، وزيادة سعة تبادل الكاتيونات*(CEC)* ، وتعزيز قدرة التربة على الاحتفاظ بالماء *(WHC)* بشكل كبير، لا سيما في الترب ذات القوام الخشن أو المتدهورة. تُترجم هذه التحسينات إلى تعزيز قدرة المحاصيل على التكيف مع الجفاف وانخفاض متطلبات الري. علاوة على ذلك، يُساهم الفحم الحيوي في عزل الكربون على المدى الطويل، مما قد يُخفف من آثار تغير المناخ. ومع ذلك، تعتمد فعالية الفحم الحيوي بشكل كبير على خصائصه (المادة الخام، ودرجة حرارة التحلل الحراري)، ونوع التربة، والظروف المناخية، ومعدلات الاستخدام. ولا تزال هناك تحديات كبيرة قائمة، بما في ذلك تباين أداء الفحم الحيوي، والآثار السلبية المحتملة على بعض الكائنات الحية في التربة أو توافر المغذيات عند معدلات الاستخدام العالية، وقيود الجدوى الاقتصادية، والملوثات المحتملة (مثل الهيدروكربونات العطرية متعددة الحلقات والمعادن الثقيلة)، والحاجة إلى بروتوكولات تقييم استدامة موحدة تدمج تحليل دورة الحياة *(LCA)* والتجارب الميدانية طويلة الأمد. يؤكد هذا التحليل على الإمكانات الكبيرة للفحم الحيوي كمُحسّن مستدام لصحة التربة وأمن المياه، ولكنه يؤكد على أن تحقيق هذه الإمكانات يتطلب استراتيجيات تطبيق خاصة بكل سياق، ومراقبة جودة دقيقة، وتحسينًا اقتصاديًا، وسياسات تدعم دمجه في نماذج الاقتصاد الحيوي الدائري. يجب أن تُعطي الأبحاث المستقبلية الأولوية للدراسات الميدانية طويلة الأمد، والفهم الآلي لتفاعلات الفحم الحيوي مع التربة والماء والميكروبات، وتقييمات الاستدامة الشاملة.

الكلمات المفتاحية: الفحم الحيوي، محسنات التربة، احتباس الماء، تغير المناخ، تفاعلات الفحم الحيوي مع التربة.

Introduction

Global challenges of soil degradation, water scarcity, and climate change threaten agricultural productivity, ecosystem stability, and food security [1], [2], [3], [4]. Degraded soils often exhibit poor structure, low organic matter content, diminished nutrient retention, and critically, reduced water holding capacity, exacerbating vulnerability to drought [5], [6]. Sustainable soil management practices are urgently needed to enhance resilience and resource use efficiency.

Biochar, produced primarily through pyrolysis of organic feedstocks (e.g., agricultural residues, forestry waste, manure), has emerged as a promising multi-functional soil amendment [7] . Its highly porous structure and stable aromatic carbon matrix offer unique properties relevant to soil improvement and water management. The concept aligns strongly with sustainability principles: it utilizes waste biomass, sequesters carbon for centuries to millennia, potentially reduces dependence on synthetic fertilizers and irrigation, and can improve soil health [8], [9], [10], [11].

While numerous studies highlight biochar's benefits, a comprehensive global synthesis focusing specifically on its role in *sustainable* soil amendment for water retention, acknowledging both advances and persistent challenges, is needed.

This paper aims to: 1) Review the mechanisms by which biochar influences soil physical properties and water retention; 2) Synthesize global evidence of its effectiveness across diverse pedo-climatic conditions; 3) Evaluate biochar's contribution to sustainability goals (carbon sequestration, waste valorization, reduced resource inputs); 4) Critically analyze the major challenges hindering its widespread sustainable implementation; and 5) Provide recommendations for research, policy, and practice to optimize biochar's role in sustainable land and water management.

Mechanisms of Biochar Impact on Soil Properties and Water Relations

Biochar influences soil water dynamics and overall quality through several interconnected physical and chemical mechanisms:

- Physical Structure Enhancement: Biochar particles, particularly those with high porosity and surface area, act as scaffolds within the soil matrix. They reduce bulk density, increase total porosity, and promote the formation and stability of soil aggregates [12], [13]. Improved aggregation creates a network of pores of various sizes. Larger pores facilitate drainage and aeration, while smaller pores within and between aggregates are crucial for retaining plant-available water.
- Increased Surface Area and Porosity: Biochar itself possesses a vast internal surface area and intricate pore network (micro-, meso-, and macropores) [14]. These pores directly absorb and retain water molecules, acting as internal reservoirs. The specific surface area and pore size distribution are heavily influenced by feedstock and pyrolysis temperature (typically higher surface area with higher temperature for many feedstocks).
- Modification of Soil Hydraulic Properties: Biochar addition often decreases soil hydrophobicity (depending on feedstock and pyrolysis conditions) and alters the soil water retention curve

(SWRC). It typically increases water content at field capacity (the water held after free drainage) and, importantly, at the permanent wilting point, thereby increasing plant-available water capacity (PAW) [15], [16] . It can also enhance water infiltration rates, reducing runoff and erosion.

- Enhanced Cation Exchange Capacity (CEC): While variable, many biochars, especially those produced at lower temperatures or from certain feedstocks, develop significant surface charge (oxygen-containing functional groups) over time through oxidation ("aging") in soil [17] . Increased CEC improves the soil's ability to retain positively charged nutrients (e.g., NH_4^+, K^+, Ca^{2+}, Mg^{2+}), reducing leaching losses and improving nutrient availability to plants, indirectly supporting plant water uptake efficiency.
- Organic Matter Addition and Microbial Habitat: Biochar contributes stable organic carbon to the soil. While recalcitrant itself, it can stimulate microbial activity in the surrounding soil and provide habitat for beneficial microbes [18], [19], [20]. Some microbes contribute to soil aggregation (via polysaccharide production) and can influence soil water repellency.

Global Evidence for Soil Amendment and Water Retention Benefits

Research across diverse global contexts demonstrates biochar's potential:

- Arid and Semi-Arid Regions: Studies in water-stressed regions like Australia, Mediterranean climates, Sub-Saharan Africa, and parts of Asia consistently report significant increases in soil WHC (often 10-50%) and PAW following biochar application, leading to improved crop yields and survival rates under drought [11], [21], [22] .Benefits are often most pronounced in sandy soils with inherently low WHC.
- Temperate Regions: Benefits in temperate zones, while sometimes less dramatic than in arid areas, include improved water retention, reduced bulk density, and enhanced aggregate stability, particularly on marginal or degraded lands [23]. Reduced nutrient leaching (e.g., nitrate) is also a significant finding, protecting water quality.
- Tropical Regions: In highly weathered tropical soils (e.g., Oxisols, Ultisols) characterized by low CEC, acidity, and susceptibility to degradation, biochar improves pH (if alkaline), boosts CEC, enhances P availability, and increases water retention [24], [25], [26]. This can significantly improve productivity on deforested or intensively farmed land.
- Degraded and Contaminated Soils: Biochar shows promise in remediating degraded lands (mining sites, eroded areas) by improving physical structure and water holding capacity, facilitating vegetation establishment [27], [28] . Its sorption capacity also aids in immobilizing certain organic and inorganic contaminants, reducing their bioavailability and leaching potential [29], [30].

Biochar and Sustainable Amendment: Synergies and Contributions

Biochar's appeal lies in its alignment with multiple sustainability pillars:

- Carbon Sequestration: Biochar's inherent stability means a significant portion (estimated 50-90+%) of the biomass carbon is converted into a recalcitrant form resistant to microbial decomposition, effectively removing CO_2 from the atmosphere for centuries [8]. This contributes directly to climate change mitigation.
- Waste Valorization and Circular Economy: Biochar production utilizes diverse biomass residues (crop residues, forestry slash, manure, food processing waste, sewage sludge - with caution regarding contaminants) that might otherwise be burned (causing pollution) or left to decompose (releasing methane, a potent GHG). This transforms waste into a valuable resource, closing nutrient and carbon loops [14].
- Reduced Resource Inputs: By improving soil WHC, biochar can reduce irrigation frequency and volume. Enhanced nutrient retention reduces fertilizer requirements and associated energy costs for production and transportation, and mitigates nutrient pollution of waterways [31].
- Improved Soil Health and Resilience: Enhanced soil structure, water retention, nutrient availability, and microbial activity foster greater soil health and resilience to stresses like drought and extreme rainfall events, promoting long-term agricultural sustainability [13].

Persistent Challenges for Sustainable Implementation

Despite its promise, significant challenges hinder the widespread, sustainable deployment of biochar:

- Context-Dependent Performance: Biochar effects are not universal. Efficacy varies dramatically based on: 1) *Biochar properties:* Feedstock source, pyrolysis temperature, and duration drastically alter physical and chemical characteristics. 2) *Soil type:* Benefits are often greatest in sandy, degraded, or low-OM soils; effects can be minimal or even negative (e.g., temporary N immobilization, reduced pesticide efficacy) in fertile soils. 3) *Climate:* Impacts on water dynamics differ under varying rainfall patterns and evaporative demands. 4) *Application* *rate and method:* Optimal rates are context-specific; high rates can be economically prohibitive or cause unintended consequences.

- Economic Viability: Production costs (feedstock collection, transportation, pyrolysis technology, energy), application costs, and often delayed agronomic benefits challenge the economic competitiveness of biochar compared to conventional amendments or fertilizers, especially for smallholder farmers [32]. Carbon credit markets offer potential but remain complex and underdeveloped for biochar.
- Potential Environmental Risks: 1) *Contaminants:* Biochar can contain potentially harmful substances like polycyclic aromatic hydrocarbons (PAHs), dioxins (from incomplete pyrolysis), or heavy metals (if derived from contaminated feedstocks like some sewage sludges or treated wood) [33]. Rigorous feedstock selection and quality control (e.g., adhering to standards like EBC or IBI) are essential. 2) *Negative Soil Impacts:* High application rates can sometimes increase soil pH excessively, induce salinity, cause temporary nutrient lock-up (especially nitrogen), or negatively impact specific soil fauna.
- Knowledge Gaps and Long-Term Uncertainty: 1) *Long-Term Field Data:* Most studies span less than 5 years. Long-term effects on soil carbon dynamics, nutrient cycling, microbial communities, and contaminant stability remain inadequately documented. 2) *Mechanistic Understanding:* Complex interactions between biochar, soil minerals, organic matter, water, and the soil microbiome are not fully understood. 3) *Standardized Assessment:* Lack of universally accepted protocols for holistic sustainability assessment integrating LCA (including carbon footprint, energy balance), economic analysis, and long-term environmental/agronomic impacts.
- Scale-up and Infrastructure: Scaling production and application to have meaningful regional or global impact requires significant investment in decentralized or centralized pyrolysis facilities, logistics for bulky material, and farmer awareness/training.

Conclusion

Biochar presents a compelling, multifaceted strategy for sustainable soil amendment, demonstrably enhancing soil water retention and overall quality across diverse global environments. Its ability to sequester carbon, utilize waste streams, reduce irrigation and fertilizer needs, and rehabilitate degraded lands aligns powerfully with sustainability goals. The evidence for improved soil physical structure, increased WHC and PAW, particularly in vulnerable soils, is robust.

However, realizing biochar's full potential as a *sustainable* solution requires acknowledging and addressing significant challenges. Its performance is inherently context-specific, demanding tailored approaches rather than one-size-fits-all solutions. Economic barriers, potential environmental risks (especially from contaminants), and critical knowledge gaps regarding long-term impacts and complex soil interactions necessitate careful management and continued research.

Recommendations

Recommendations are pointed as following:

- Prioritize Context-Specific Design: Develop decision-support tools that match biochar properties (feedstock, pyrolysis conditions) to specific soil limitations (e.g., low WHC, low CEC, acidity) and climatic conditions. Optimize application rates and methods (e.g., banding vs. broadcasting) for targeted benefits.
- Enhance Economic Viability: Foster development of cost-effective, small-scale pyrolysis technologies suitable for on-farm or community use. Explore and develop robust carbon credit mechanisms and other economic incentives (e.g., payments for ecosystem services) that recognize biochar's carbon sequestration and environmental benefits. Integrate biochar production into waste management valorization schemes.
- Ensure Environmental Safety: Implement and enforce stringent biochar quality standards (e.g., EBC, IBI) based on rigorous contaminant testing. Promote best practices for feedstock selection (avoiding contaminated sources) and pyrolysis optimization to minimize PAH formation. Mandate comprehensive contaminant screening, especially for non-traditional feedstocks.
- Bridge Critical Knowledge Gaps: Intensify long-term (decadal) field trials across diverse agroecosystems to monitor persistence of benefits, carbon stability, and potential unforeseen consequences. Deepen research into the fundamental mechanisms of biochar-soil-water-microbe-mineral interactions using advanced analytical techniques. Develop standardized methodologies for holistic sustainability assessments integrating LCA, techno-economic analysis (TEA), and environmental risk assessment (ERA).
- Develop Supportive Policy and Infrastructure: Governments and international bodies should create supportive policy frameworks incentivizing sustainable biochar production and use,

including carbon farming initiatives. Invest in research, development, and deployment of production and application infrastructure. Support farmer education and extension services to build capacity and trust.

- Promote Circular Bioeconomy Integration: Position biochar as a key component within circular bioeconomy models, linking sustainable biomass sourcing, waste management, energy co-production (from pyrolysis gases), carbon sequestration, and regenerative agriculture.

By addressing these challenges through targeted research, responsible innovation, supportive policies, and context-specific implementation, biochar can transition from a promising concept to a cornerstone of truly sustainable soil and water management globally.

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