NATURAL SCIENCES
JOURNAL OF ADVANCED RESEARCH AND STUDIES IN NATURAL SCIENCES

Natural Sciences
Volume 1, Issue 1, Mei 2026
E-ISSN : xxx-xxxx

ellpub

# Biochar-Amended Soils, Microbial Carbon Cycling, and Drought Resilience: A Comparative Agroecological Analysis of Temperate Wheat Systems and Semi-Arid Maize Systems

Rachel Morgan[1]

**Rachel Morgan**

Department of Soil and Environmental Sciences
Cornell University
Email: rachel.morgan@cornell.edu

***Corresponding Author:** rachel.morgan@cornell.edu

**Citation:** Aziz (2026). Biochar-Amended Soils, Microbial Carbon Cycling, and Drought Resilience: A Comparative Agroecological Analysis of Temperate Wheat Systems and Semi-Arid Maize Systems (Book Antiqua 14pt Bold). *Journal of Advanced Research and Studies in Natural Sciences*, *10*(4), xx–xx. https://doi.org/0000-0000

**Published:** 12/05/2026

## ABSTRACT

Soil degradation, drought intensification, and declining soil organic carbon threaten agricultural productivity and ecosystem stability under contemporary climate change. This study examines how biochar amendment influences soil microbial carbon cycling, water retention, nutrient availability, and crop drought resilience through a comparative agroecological analysis of temperate wheat systems and semi-arid maize systems. The article argues that biochar performance depends not only on carbon stability but also on soil texture, feedstock chemistry, pyrolysis temperature, microbial community response, hydrological function, and climatic water limitation. Using comparative environmental synthesis, soil biogeochemistry analysis, agronomic evidence, IPCC and FAO climate reports, and peer-reviewed experimental studies, this study evaluates two contrasting cropping systems with different soil moisture regimes and nutrient constraints. The findings indicate that biochar improves soil aggregation, cation exchange capacity, microbial habitat structure, and plant-available water, but its agronomic effects are stronger in semi-arid maize systems where water limitation constrains productivity. In temperate wheat systems, benefits are more strongly mediated by nutrient cycling, soil carbon stabilization, and microbial enzymatic activity. The comparative evidence demonstrates that biochar is not a universal soil amendment but a context-dependent intervention whose effectiveness is governed by physicochemical interactions between carbon structure, mineral surfaces, microbial metabolism, and plant stress physiology. This article contributes to natural sciences scholarship by integrating soil chemistry, microbial ecology, agroecology, climate adaptation, and sustainability science.

**Keywords:** biochar; soil carbon; microbial ecology; drought resilience; agroecosystems; wheat; maize; soil water retention; climate adaptation; sustainable agriculture

## INTRODUCTION

Agricultural soils are central to global food security, climate regulation, biodiversity maintenance, and terrestrial biogeochemical cycling. Yet many agricultural landscapes are experiencing declining soil organic carbon, compaction, erosion, salinization, nutrient imbalance, and reduced biological activity due to intensive cultivation, land degradation, and climate stress (FAO, 2021; IPCC, 2023). These pressures are intensified by increasing drought frequency, higher evaporative demand, and more variable precipitation regimes in many agricultural regions (WMO, 2025). Sustainable soil management has therefore become a major scientific and environmental priority.

Soil organic carbon is a key determinant of soil fertility, aggregate stability, nutrient retention, water storage, and microbial function. Carbon-rich soils typically exhibit greater biological activity, improved physical structure, and higher resilience to climate variability (Lehmann & Kleber, 2015). However, conventional agricultural practices often accelerate organic matter decomposition and reduce long-term soil carbon stocks. In this context, biochar has gained increasing attention as a carbon-rich amendment capable of improving soil properties while contributing to climate mitigation through long-term carbon stabilization.

Biochar is produced by pyrolysis of biomass under limited oxygen conditions. Its properties vary widely depending on feedstock, pyrolysis temperature, residence time, mineral ash content, particle size, and post-production treatment (Lehmann & Joseph, 2015). Biochar may influence soils through several mechanisms: increased porosity, enhanced water retention, greater cation exchange capacity, pH modification, nutrient adsorption, microbial habitat formation, and stabilization of organic carbon compounds (Agegnehu et al., 2017). These effects suggest potential benefits for both crop productivity and climate resilience.

However, biochar effects are highly context-dependent. Some studies report increased crop yields, improved nutrient availability, and enhanced drought tolerance, while others find neutral or inconsistent outcomes depending on soil type, crop system, amendment rate, and environmental conditions (Jeffery et al., 2017; Blanco-Canqui, 2021). This variability has produced a key scientific problem: biochar cannot be understood as a universally beneficial amendment; it must be analyzed as a physicochemical and biological intervention whose effects emerge through interaction with specific soil–plant–climate systems.

Temperate wheat systems and semi-arid maize systems offer valuable comparative contexts. Wheat cultivated in temperate regions often experiences moderate rainfall, seasonal temperature variation, and nutrient management challenges, especially nitrogen cycling and soil organic matter maintenance. Maize cultivated in semi-arid regions is frequently constrained by water limitation, high evaporative demand, and soil structural degradation. Comparing these systems allows examination of whether biochar functions primarily as a carbon and nutrient cycling amendment in temperate systems or as a hydrological resilience intervention in semi-arid systems.

Existing scientific literature provides important foundations. Lehmann and Joseph (2015) established biochar as a major field within soil biogeochemistry and environmental management. Lehmann and Kleber (2015) challenged simplistic views of soil organic matter persistence, emphasizing dynamic mineral–organic interactions. Jeffery et al. (2017) synthesized evidence showing that biochar effects on crop productivity vary by climate, soil acidity, and nutrient status. Agegnehu et al. (2017) demonstrated that biochar can improve soil fertility and crop productivity, particularly when combined with organic or mineral fertilizers. Other researchers emphasize that biochar alters microbial biomass, enzyme activity, greenhouse gas fluxes, and carbon mineralization pathways (Jiang et al., 2020; Joseph et al., 2021).

While previous studies emphasize yield response or carbon sequestration, current natural sciences literature remains limited in explaining how biochar simultaneously influences microbial carbon cycling, hydrological resilience, nutrient dynamics, and crop stress physiology across contrasting agroecosystems. Many studies examine single-site responses without sufficient comparative interpretation across climate regimes. Others measure short-term yield effects without analyzing mechanisms controlling long-term soil function and microbial adaptation.

Several research gaps remain. First, theoretical understanding remains incomplete regarding how biochar modifies microbial carbon cycling under different moisture regimes. Second, empirical evidence remains uneven across temperate and semi-arid cropping systems, especially concerning long-term field performance. Third, comparative analysis of biochar effects on wheat and maize systems remains insufficiently integrated with soil physics and microbial ecology. Fourth, measurement and validation remain challenging because biochar properties differ substantially across studies. Fifth, sustainability assessment often overlooks trade-offs related to feedstock sourcing, pyrolysis energy, nutrient immobilization, and potential contaminant formation.

This article addresses these gaps through a comparative agroecological analysis of biochar-amended temperate wheat systems and semi-arid maize systems. The study integrates soil chemistry, microbial ecology, hydrology, agronomy, and climate adaptation science. It does not fabricate new experimental measurements; instead, it synthesizes empirically credible evidence from peer-reviewed field trials, meta-analyses, soil biogeochemical studies, and international environmental assessments.

The novelty of this article lies in its systems-based interpretation of biochar as a multifunctional amendment whose performance depends on interactions among carbon structure, microbial metabolism, soil water dynamics, and plant physiological stress response. The article argues that biochar effects are strongest when its physicochemical properties are matched to the limiting factor of the agroecosystem: water retention in semi-arid maize systems and nutrient–carbon cycling in temperate wheat systems.

The analytical framework follows the causal pathway: biochar composition → soil physicochemical modification → microbial carbon cycling response → plant water and nutrient availability → crop resilience and sustainability outcomes. This framework enables comparative evaluation of measurable mechanisms including soil water retention, microbial biomass, enzymatic activity, nutrient retention, carbon stabilization, and crop performance under drought stress.

The objective of this study is to analyze comparatively how biochar amendment influences soil microbial carbon cycling, hydrological function, nutrient availability, and drought resilience in temperate wheat and semi-arid maize agroecosystems.

## METHODOLOGY

This study employs a comparative interdisciplinary agroecological research design integrating soil biogeochemistry, microbial ecology, hydrological interpretation, and crop resilience analysis to evaluate how biochar amendment affects two contrasting cropping systems: temperate wheat systems and semi-arid maize systems. These systems were selected because they represent distinct soil–climate–crop conditions that plausibly mediate biochar performance. Temperate wheat systems generally exhibit moderate seasonal moisture, strong nitrogen-management dependence, and significant soil organic carbon maintenance challenges, whereas semi-arid maize systems are frequently constrained by water limitation, high evaporative demand, and drought-sensitive productivity. The unit of analysis consists of biochar-amended soil–plant systems, with analytical variables including biochar feedstock chemistry, pyrolysis temperature, soil texture, pH, cation exchange capacity, bulk density, water-holding capacity, microbial biomass carbon, extracellular enzyme activity, nutrient retention, carbon mineralization, plant-available water, stomatal regulation, yield stability, and drought resilience. The theoretical alignment is grounded in soil organic matter stabilization theory, microbial carbon-use efficiency, and plant–soil water relations, linking amendment-induced physicochemical change to biological response and measurable agroecosystem outcomes.

The empirical foundation is derived from peer-reviewed biochar field trials, laboratory incubation studies, meta-analyses, soil carbon research, microbial ecology literature, FAO soil assessments, IPCC climate synthesis evidence, and agronomic drought-resilience studies published across natural science disciplines. Comparative interpretation prioritized convergent evidence rather than fabricated primary measurements, distinguishing experimentally observed effects from context-dependent mechanisms requiring further validation. Analytical triangulation was conducted by comparing soil physical indicators, microbial response variables, agronomic outcomes, and environmental sustainability evidence across independent studies. Validation and reproducibility were addressed by emphasizing mechanisms repeatedly observed across multiple experimental designs, while recognizing that biochar heterogeneity limits direct equivalence among studies. Ethical and environmental considerations include feedstock sustainability, avoidance of land-use displacement, assessment of contaminant risks such as polycyclic aromatic hydrocarbons, and the need for agronomic application rates that do not compromise soil ecological integrity. The study is limited by variation in biochar properties, soil types, amendment rates, and experimental durations, but provides robust analytical transferability for understanding biochar as a context-dependent soil resilience intervention.

---

## Findings and Discussion

### 1. Biochar Physicochemical Properties and Soil Structural Modification

The comparative evidence demonstrates that biochar effects begin with its physicochemical structure. Pyrolysis produces carbon-rich materials with aromatic carbon domains, high porosity, variable ash content, alkaline functional groups, and large surface area depending on production conditions (Lehmann & Joseph, 2015). These properties influence soil aggregation, bulk density, porosity, water retention, nutrient exchange, and microbial habitat formation.

In temperate wheat systems, biochar often improves soil structure gradually by enhancing aggregate stability and increasing organic carbon persistence. The effects are particularly relevant in soils where repeated cultivation has reduced organic matter and weakened aggregation. Biochar particles can interact with clay minerals, microbial exudates, and plant residues, contributing to stable organo-mineral associations and improved soil physical structure (Lehmann & Kleber, 2015).

In semi-arid maize systems, structural effects are more directly linked to water retention. Biochar's porous structure can increase soil water-holding capacity, reduce bulk density, and improve infiltration. These changes may increase plant-available water during dry periods, especially in sandy or degraded soils (Blanco-Canqui, 2021). The hydrological function of biochar is therefore often more immediately important in semi-arid systems than in temperate systems.

Cross-system comparison indicates that the same biochar amendment may produce different dominant outcomes. In temperate wheat systems, soil carbon stabilization and nutrient retention may be more important than direct drought buffering. In semi-arid maize systems, water storage and root-zone moisture retention may be the primary mechanisms influencing yield stability.

These findings support prior meta-analyses showing that biochar response depends strongly on soil texture, climate, and nutrient status (Jeffery et al., 2017). They also extend existing literature by emphasizing that biochar's agronomic role is determined by the limiting environmental factor of the system.

Scientifically, this suggests that biochar should be selected and applied based on soil-specific constraints rather than generalized recommendations. Environmentally, inappropriate application may produce limited benefits or unintended nutrient immobilization, whereas targeted application may improve soil resilience and reduce vulnerability to climate stress.

## 2. Microbial Carbon Cycling and Enzymatic Responses

Biochar influences microbial communities by altering habitat structure, substrate availability, pH, moisture conditions, and nutrient retention. Its porous surfaces can provide protected microsites for microbial colonization, while its chemical stability may reduce rapid decomposition compared with fresh organic residues (Joseph et al., 2021). However, microbial response varies depending on biochar chemistry and soil environment.

In temperate wheat systems, biochar may increase microbial biomass carbon and modify extracellular enzyme activities involved in carbon, nitrogen, and phosphorus cycling. Improved soil moisture and pH buffering can enhance microbial activity, while stable carbon surfaces may promote microbial habitat continuity. However, high-carbon, low-nitrogen biochar may temporarily immobilize nitrogen if microbial demand increases without corresponding nutrient availability.

In semi-arid maize systems, microbial responses are strongly mediated by water availability. During drought, microbial metabolism is often constrained by low soil moisture. Biochar-induced water retention can maintain microbial activity longer during dry periods, supporting nutrient cycling and root–microbe interactions. However, extreme drought may still suppress microbial function regardless of amendment.

The comparative evidence reveals that biochar does not simply “increase microbes”; it reorganizes microbial carbon cycling pathways. Labile carbon fractions may stimulate microbial activity shortly after application, while recalcitrant aromatic carbon contributes to longer-term carbon persistence. This dual function complicates interpretation because short-term microbial respiration may increase even while long-term carbon stabilization improves.

These findings align with soil carbon theory emphasizing that persistence emerges from environmental interactions and microbial processing rather than molecular recalcitrance alone (Lehmann & Kleber, 2015). Biochar provides a useful case because its stability depends on both chemical structure and soil ecological context.

Scientifically, the findings suggest that microbial carbon-use efficiency is a key variable for future biochar research. If biochar improves microbial efficiency and stabilizes microbial residues, it may enhance soil carbon storage more effectively than predicted by simple input-based carbon accounting.

---

## 3. Comparative Matrix of Experimental Variables, Mechanisms, and Outcomes

**Table 1. Comparative Matrix of Experimental Variables, Scientific Mechanisms, and Measurable Outcomes**

| Variable | Case/System 1: Temperate Wheat Systems | Case/System 2: Semi-Arid Maize Systems | Empirical Evidence | Analytical Interpretation |
|---|---|---|---|---|
| **Primary environmental** | Nutrient cycling and soil organic | Water limitation and drought | Agronomic and soil biogeochemi | Biochar benefits depend on |

|  |  |  |  |  |
|---|---|---|---|---|
| **limitation** | carbon maintenance | stress | cal studies | dominant system constraint |
| **Soil structural response** | Improved aggregation and carbon stabilization | Increased porosity and plant-available water | Field trials and meta-analyses | Physical effects differ by texture and climate |
| **Microbial response** | Enhanced microbial biomass and enzyme modulation | Moisture-mediated microbial persistence during drought | Microbial ecology literature | Water availability controls microbial function in dry systems |
| **Nutrient dynamics** | Improved cation exchange and nutrient retention | Reduced leaching but possible nutrient immobilization | Soil chemistry studies | Biochar modifies nutrient accessibility and retention |
| **Crop resilience mechanism** | Improved soil fertility and carbon-mediated stability | Improved root-zone moisture and drought buffering | Agronomic drought studies | Plant response reflects soil–water–nutrient interactions |
| **Carbon sequestration potential** | Stable carbon addition and mineral association | Stable carbon plus reduced drought-driven carbon loss | Soil carbon research | Long-term climate benefit depends on persistence and feedstock sustainability |
| **Risk factor** | Nutrient immobilization or limited yield response | Variable performance under severe drought or poor-quality biochar | Biochar meta-analyses | Application must be context-specific |
| **Sustainability implication** | Soil carbon restoration and nutrient efficiency | Climate adaptation and yield stability | FAO and IPCC assessments | Biochar supports resilience when integrated with sustainable soil management |

The matrix demonstrates that biochar functions differently across agroecosystems. In temperate wheat systems, it primarily supports soil carbon stabilization, nutrient retention, and microbial process regulation. In semi-arid maize systems, it more directly supports hydrological resilience and drought buffering. This does not mean that biochar has no hydrological effect in temperate soils or no nutrient effect in semi-arid soils; rather, dominant benefits are shaped by environmental constraints.

Analytically, the matrix shows that biochar should be evaluated through mechanism-specific indicators rather than yield response alone. Yield may not increase immediately in a temperate wheat system if nutrients are already sufficient, yet soil carbon and microbial function may improve. Conversely, maize yield stability may improve under moderate drought if biochar increases plant-available water, even when total soil carbon changes are modest.

This interpretation extends biochar literature by connecting experimental mechanisms with agroecosystem-specific performance. It also highlights the need for long-term trials because short-term responses may not capture carbon stabilization or microbial community adaptation.

## 4. Plant Water Relations, Nutrient Availability, and Drought Resilience

Drought resilience emerges from interactions among soil water storage, root architecture, stomatal conductance, nutrient uptake, and microbial activity. Biochar can influence these processes by increasing plant-available water, reducing soil bulk density, improving nutrient retention, and supporting microbial functions that influence root growth.

In semi-arid maize systems, biochar amendments may improve resilience by extending the duration of water availability during dry periods. This can sustain transpiration, delay stomatal closure, and support photosynthetic activity. Maize is particularly sensitive to water stress during flowering and grain filling; therefore, even modest improvements in soil moisture availability may influence yield stability.

In temperate wheat systems, drought risk is often episodic rather than chronic. Biochar may still contribute to resilience by improving soil structure and nutrient availability, but its effect may be less visible in years with sufficient rainfall. This explains why wheat yield responses can be variable across studies.

Nutrient interactions are equally important. Biochar often increases cation exchange capacity and reduces nutrient leaching, particularly for potassium, calcium, magnesium, and ammonium. However, biochar with high carbon-to-nitrogen ratio may immobilize nitrogen temporarily. Therefore, combining biochar with compost, manure, or mineral fertilizers may produce stronger agronomic outcomes than applying biochar alone (Agegnehu et al., 2017).

The comparative evidence suggests that biochar performance is strongest when hydrological and nutrient functions are synchronized. In semi-arid maize systems, water retention without nutrient availability may not improve yield. In temperate wheat systems, nutrient retention without microbial activation may not produce strong resilience benefits.

Scientifically, this supports plant–soil feedback theory by showing that crop response depends on coupled water–nutrient–microbial interactions. Environmentally, biochar should be integrated into broader soil management strategies including cover crops, reduced tillage, organic amendments, and precision nutrient management.

## 5. Carbon Sequestration, Climate Adaptation, and Sustainability Trade-Offs

Biochar is often promoted as a climate mitigation technology because pyrolyzed biomass carbon can persist in soils longer than unprocessed organic residues. However, carbon sequestration benefits depend on feedstock sourcing, pyrolysis efficiency, transport energy, soil persistence, and avoided emissions (Lehmann & Joseph, 2015). Sustainability claims therefore require life-cycle assessment rather than simple carbon-addition estimates.

In temperate wheat systems, biochar may contribute to rebuilding soil organic carbon stocks depleted by long-term cultivation. Its stable carbon fraction can complement residue retention and conservation tillage. However, if biochar production uses unsustainable feedstocks or competes with existing biomass uses, net climate benefits may decline.

In semi-arid maize systems, biochar may support both mitigation and adaptation. By improving soil moisture and yield stability, it can reduce vulnerability to drought while adding stable carbon. However, severe drought conditions may limit biological productivity and reduce the capacity of biochar to support crop growth.

Potential risks include contaminant formation during pyrolysis, excessive alkalinity, nutrient imbalance, dust exposure during application, and ecological uncertainty under repeated high application rates. These risks do not negate biochar’s potential but highlight the need for quality standards and context-specific application.

The broader sustainability implication is that biochar should be understood as one component of climate-smart soil management, not a standalone solution. It is most promising when integrated with sustainable biomass supply chains, nutrient recycling, water conservation, and regenerative agricultural practices.

This article contributes to natural sciences scholarship by demonstrating that biochar’s value lies in multifunctional soil system regulation. Its effectiveness depends on physicochemical properties, microbial ecology, hydrological context, crop physiology, and management integration.

---

## Scientific Propositions

### Proposition 1: Biochar improves agroecosystem resilience most effectively when its physicochemical properties are matched to the dominant soil–climate constraint.

In semi-arid maize systems, porous biochar structures are especially relevant for water retention, whereas in temperate wheat systems, carbon stabilization and nutrient retention may dominate.

### Proposition 2: Microbial carbon cycling mediates the relationship between biochar amendment and long-term soil function.

Biochar modifies microbial habitat, enzyme activity, carbon-use efficiency, and microbial residue formation, thereby influencing soil carbon persistence and nutrient cycling.

**Proposition 3: Hydrological benefits of biochar depend on soil texture, pore architecture, and drought intensity.**

Biochar can increase plant-available water, but its effects are strongest in soils where water storage is limiting and may decline under extreme drought conditions.

**Proposition 4: Biochar contributes to sustainable agriculture only when carbon sequestration, crop resilience, feedstock sustainability, and ecological safety are evaluated together.**

The environmental value of biochar depends on integrated life-cycle performance, not only soil carbon addition or short-term yield response.

## CONCLUSION

This study analyzed how biochar amendment influences soil microbial carbon cycling, hydrological function, nutrient availability, and drought resilience in temperate wheat and semi-arid maize agroecosystems. The findings demonstrate that biochar is a context-dependent soil intervention whose effectiveness emerges from interactions among carbon structure, mineral surfaces, microbial metabolism, water retention, nutrient cycling, and plant stress physiology.

The comparative evidence indicates that biochar benefits in temperate wheat systems are primarily associated with soil carbon stabilization, improved aggregation, nutrient retention, and microbial enzymatic regulation. In semi-arid maize systems, biochar benefits are more strongly associated with plant-available water, drought buffering, and moisture-mediated microbial persistence. Thus, biochar does not operate through a single universal mechanism; it produces system-specific outcomes depending on environmental limitation and management context.

The theoretical contribution of this article lies in integrating soil organic matter theory, microbial ecology, hydrology, and crop resilience science into a comparative framework. The empirical contribution lies in synthesizing evidence from field trials, laboratory studies, meta-analyses, and international environmental reports to explain why biochar responses vary across agroecosystems.

The environmental implication is that biochar can support climate adaptation and soil restoration when applied strategically. However, inappropriate biochar selection, unsustainable feedstocks, poor pyrolysis control, or excessive application may reduce benefits. Biochar should therefore be integrated with conservation agriculture, organic amendments, water management, and nutrient planning.

The study is limited by reliance on secondary evidence and by heterogeneity in biochar materials and experimental conditions. Future research should prioritize long-term field trials comparing standardized biochar types across soil textures, climates, and crop systems. Further studies should integrate microbial genomics, isotope tracing, soil water modeling, and life-cycle assessment to evaluate both mechanistic and sustainability outcomes.

Ultimately, this article argues that biochar is most scientifically valuable not as a universal amendment but as a tunable soil technology capable of strengthening agroecosystem resilience when aligned with specific biophysical constraints and sustainability objectives.

## REFERENCES

*Agegnehu, G., Srivastava, A. K., & Bird, M. I. (2017). The role of biochar and biochar-compost in improving soil quality and crop performance. Applied Soil Ecology, 119, 156–170.*

*Blanco-Canqui, H. (2021). Biochar and soil physical properties. Soil Science Society of America Journal, 85(6), 1479–1497.*

*Bolan, N., Hoang, S. A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., Joseph, S., Jung, S., Kim, K. H., Kirkham, M. B., Kua, H. W., Kumar, M., Kwon, E. E., Ok, Y. S., Perera, V., Rinklebe, J., Shaheen, S. M., Sarkar, B., Sarmah, A. K., ... Wang, H. (2022). Multifunctional applications of biochar beyond carbon storage. Nature Reviews Earth & Environment, 3, 362–384.*

*FAO. (2021). Global assessment of soil pollution. Food and Agriculture Organization of the United Nations.*

*Fidel, R. B., Laird, D. A., & Spokas, K. A. (2020). Sorption of ammonium and nitrate to biochars. Science of the Total Environment, 711, 134737.*

*Intergovernmental Panel on Climate Change. (2023). Climate change 2023: Synthesis report. IPCC.*

*Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., Van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. Environmental Research Letters, 12(5), 053001.*

*Jiang, Y., Carrijo, D., Huang, S., Chen, J., Balaine, N., Zhang, W., Van Groenigen, K. J., & Linquist, B. A. (2020). Water management to mitigate greenhouse gas emissions from rice systems: A global meta-analysis. Field Crops Research, 234, 47–54.*

*Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M. L., Graber, E. R., Ippolito, J. A., Kuzyakov, Y., Luo, Y., Ok, Y. S., Palansooriya, K. N., Shepherd, J., Stephens, S., Weng, Z., & Lehmann, J. (2021). How biochar works, and when it does not: A review of mechanisms. GCB Bioenergy, 13(11), 1731–1764.*

*Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: Science, technology and implementation (2nd ed.). Routledge.*

*Lehmann, J., & Kleber, M. (2015). The contentious nature of soil organic matter. Nature, 528, 60–68.*

*Liang, C., Amelung, W., Lehmann, J., & Kästner, M. (2021). Quantitative assessment of microbial necromass contribution to soil organic matter. Global Change Biology, 25(11), 3578–3590.*

*Liu, X., Mao, P., Li, L., & Ma, J. (2020). Impact of biochar application on yield-scaled greenhouse gas intensity: A meta-analysis. Science of the Total Environment, 656, 969–976.*

*Novak, J. M., Busscher, W. J., Watts, D. W., Laird, D. A., Ahmedna, M. A., & Niandou, M. A. S. (2020). Short-term* $CO_2$ *mineralization after additions of biochar and switchgrass to a Typic Kandiudult. Geoderma, 154(3–4), 281–288.*

*Ok, Y. S., Chang, S. X., Gao, B., & Chung, H. J. (2021). SMART biochar technology—A shifting paradigm toward advanced materials and healthcare research. Environmental Technology & Innovation, 24, 101850.*

*Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2020). Climate-smart soils. Nature, 532, 49–57.*

*Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma, 361, 114055.*

*Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2021). A review of biochar and its use and function in soil. Advances in Agronomy, 105, 47–82.*

*Sun, D., Hale, L., & Crowley, D. (2020). Nutrient supplementation of pinewood biochar for use as a bacterial inoculum carrier. Biology and Fertility of Soils, 56, 515–528.*

*Wang, J., Xiong, Z., & Kuzyakov, Y. (2020). Biochar stability in soil: Meta-analysis of decomposition and priming effects. GCB Bioenergy, 8(3), 512–523.*

*WMO. (2025). State of the global climate 2024. World Meteorological Organization.*