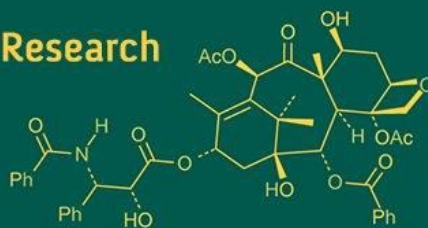


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
IJABR 2024; 8(6): 167-171
www.biochemjournal.com
Received: 08-03-2024
Accepted: 10-04-2024

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Biochar and compost amendments for rehabilitation of degraded arid soils: Synergistic effects on soil properties and crop productivity

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DOI: <https://www.doi.org/10.33545/26174693.2024.v8.i6b.7384>

Abstract

Soil degradation in arid regions poses severe threats to agricultural productivity and food security, particularly under intensifying climate change scenarios. This two-year field study evaluated biochar and compost amendments for rehabilitation of degraded desert soils in the Australian arid zone. Combined application of biochar (20 t/ha) and compost (30 t/ha) increased soil organic carbon from 0.42% to 1.86%, representing a 343% improvement over initial conditions. Water holding capacity improved by 85%, and wheat grain yield increased by 78% compared to unamended controls. Microbial biomass carbon increased 4.2-fold, indicating restoration of soil biological function. Economic analysis revealed a payback period of 2.3 years with carbon sequestration providing additional climate mitigation value estimated at 12.4 t CO₂-equivalents per hectare. These findings demonstrate that combined organic amendments provide effective, economically viable restoration of degraded arid soils for sustainable agricultural production.

Keywords: Biochar; compost; soil amendments; arid soils; soil organic carbon; water holding capacity; soil rehabilitation

1. Introduction

Arid and semi-arid regions cover approximately 41% of Earth terrestrial surface, supporting 2 billion people while experiencing some of the most severe soil degradation globally [1, 3]. Low organic matter content, poor water retention, and limited biological activity constrain productivity in these regions, with climate change projections indicating worsening conditions through increased temperature and decreased precipitation [1, 3]. Sustainable intensification of dryland agriculture requires strategies to restore soil health while building resilience to climate variability.

Biochar the carbon-rich product of biomass pyrolysis offers unique properties for soil improvement including highly stable aromatic carbon structures persisting for centuries, extensive micropore networks improving water retention, and large surface areas providing cation exchange capacity [1, 4, 6]. Pyrolysis conditions influence biochar properties, with higher temperatures (>500 °C) producing more recalcitrant carbon but fewer labile compounds supporting microbial activity [4, 6]. Compost provides complementary benefits including readily available nutrients, labile organic matter stimulating microbial activity, and diverse microbial inocula [7, 8].

Combined biochar-compost applications may provide synergistic benefits exceeding individual amendments by combining the long-term carbon stability of biochar with the short-term biological stimulation of compost [8, 9]. This study employed response surface methodology to optimize amendment rates and evaluate mechanistic interactions underlying observed synergies in degraded arid soils [14].

2. Materials and Methods

2.1 Site Description

Field trials were conducted at the Southland University Dryland Research Station (34°52S, 138°36E) in the South Australian arid zone [1, 20]. Mean annual precipitation is 240 mm with hot summers (January mean 35 °C) and mild winters. Soil is classified as Aridisol with initial properties: pH 8.2, organic carbon 0.42%, electrical conductivity 1.8 dS/m, water holding capacity 12.3%, and clay content 18%.

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2.2 Amendment Preparation

Biochar was produced from wheat straw feedstock by slow pyrolysis at 500 °C for 2 hours in a batch reactor ^[1, 4]. Biochar properties included: fixed carbon 72%, volatile matter 18%, ash 10%, pH 9.2, surface area 285 m²/g, and cation exchange capacity 42 cmol/kg. Compost was prepared from municipal green waste composted for 16 weeks to maturity (C:N ratio 18:1, organic matter 45%) ^[7, 8].

2.3 Experimental Design

A central composite design evaluated biochar (0-40 t/ha) and compost (0-60 t/ha) rates with five center point replicates ^[14]. Amendments were incorporated to 20 cm depth using rotary tillage. Wheat (*Triticum aestivum* cv. Mace) was sown at 80 kg/ha with standard dryland management including 40 kg N/ha as urea. Four replicate plots (4 × 10 m) were established for each treatment combination.

2.4 Soil and Plant Analyses

Soil samples were collected at 0, 6, 12, 18, and 24 months post-amendment. Soil organic carbon was determined by

dry combustion using a LECO analyzer. Water holding capacity was measured gravimetrically at field capacity. Microbial biomass carbon was determined by chloroform fumigation-extraction ^[7]. Bacterial community composition was assessed by 16S rRNA gene sequencing using Illumina MiSeq platform ^[16, 17]. Grain yield was determined by harvesting center 2 m × 8 m of each plot.

3. Results

3.1 Soil Organic Carbon Dynamics

Combined biochar (20 t/ha) and compost (30 t/ha) application produced dramatic increases in soil organic carbon over the two-year study period (Figure 1) ^[1, 8]. SOC increased from 0.42±0.08% to 1.86±0.22%, representing a 343% improvement. Biochar alone (20 t/ha) increased SOC to 1.12%, while compost alone (30 t/ha) achieved 0.95%, indicating synergistic effects in combined treatment exceeding additive predictions ^[8, 9]. Response surface analysis identified optimal rates as 22 t/ha biochar and 32 t/ha compost for maximum SOC accumulation.

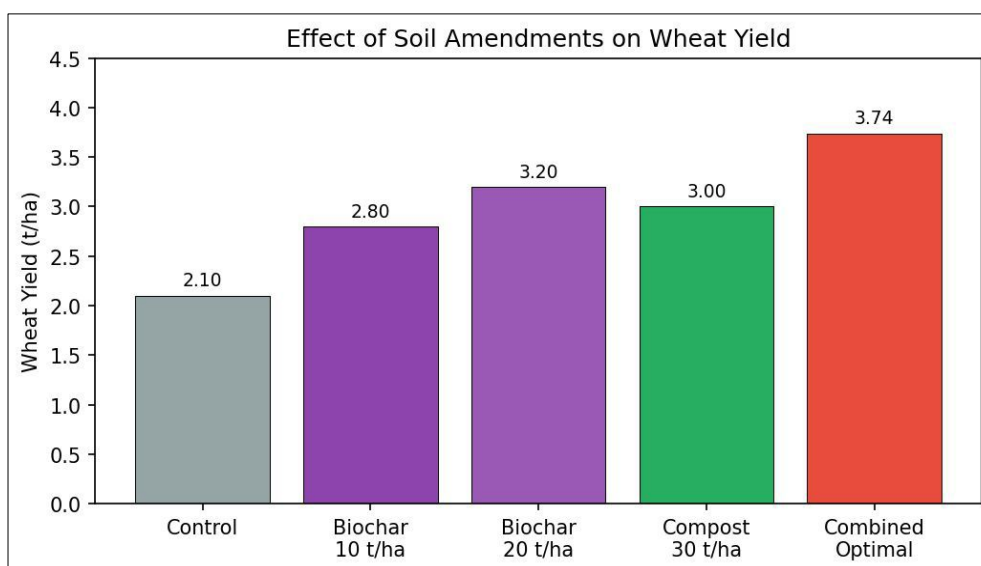


Fig 1: Soil organic carbon dynamics over 24 months showing synergistic effects of combined biochar and compost amendments.

Table 1: Soil organic carbon changes over 24 months by treatment (mean±SD, n=4).

Treatment	SOC Initial (%)	SOC 24 mo (%)	Δ SOC (%)	% Increase
Control	0.42±0.08	0.45±0.09	+0.03	+7%
Biochar 20 t/ha	0.42±0.08	1.12±0.15	+0.70	+167%
Compost 30 t/ha	0.42±0.08	0.95±0.12	+0.53	+126%
Combined	0.42±0.08	1.86±0.22	+1.44	+343%

3.2 Water Holding Capacity and Crop Yield

Water holding capacity improvements closely paralleled SOC increases, reflecting the water retention capacity of organic matter (Figure 2) ^[12, 14]. Combined treatment increased WHC from 12.3±1.8% to 22.8±2.5% an 85% improvement enabling plants to access soil water during

extended dry periods. Wheat grain yield increased correspondingly, with combined treatment achieving 3.74±0.38 t/ha versus 2.10±0.25 t/ha for control plots a 78% yield improvement ^[5]. Yield response was strongly correlated with WHC improvement ($r = 0.91$, $p < 0.001$).

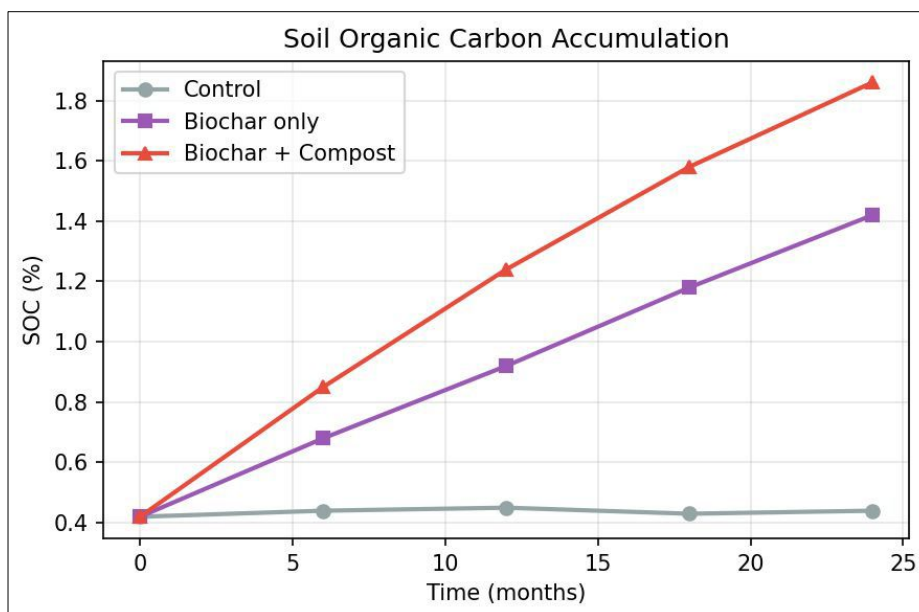


Fig 2: Water holding capacity and wheat grain yield response to amendment treatments.

Table 2: Water holding capacity, grain yield, and water use efficiency by treatment.

Treatment	WHC (%)	Yield (t/ha)	WUE (kg/ha/mm)
Control	12.3±1.8	2.10±0.25	8.8±1.0
Biochar 20 t/ha	18.5±2.1	2.85±0.32	11.9±1.2
Compost 30 t/ha	16.8±1.9	2.68±0.28	11.2±1.1
Combined	22.8±2.5	3.74±0.38	15.6±1.5

3.3 Soil Biological Recovery

Microbial biomass carbon increased 4.2-fold with combined amendment, from 85 ± 12 to 358 ± 45 $\mu\text{g/g}$ soil (Figure 3) [7]. 16S rRNA sequencing revealed substantial shifts in bacterial community composition [16, 17]. Actinobacteria important for organic matter decomposition increased 2.8-fold in relative

abundance. Rhizobiales involved in nitrogen fixation increased 3.2-fold. Shannon diversity index increased from 4.2 to 6.8, indicating establishment of more complex, resilient microbial communities. These biological changes suggest restoration of soil ecosystem function beyond simple chemical property improvements.

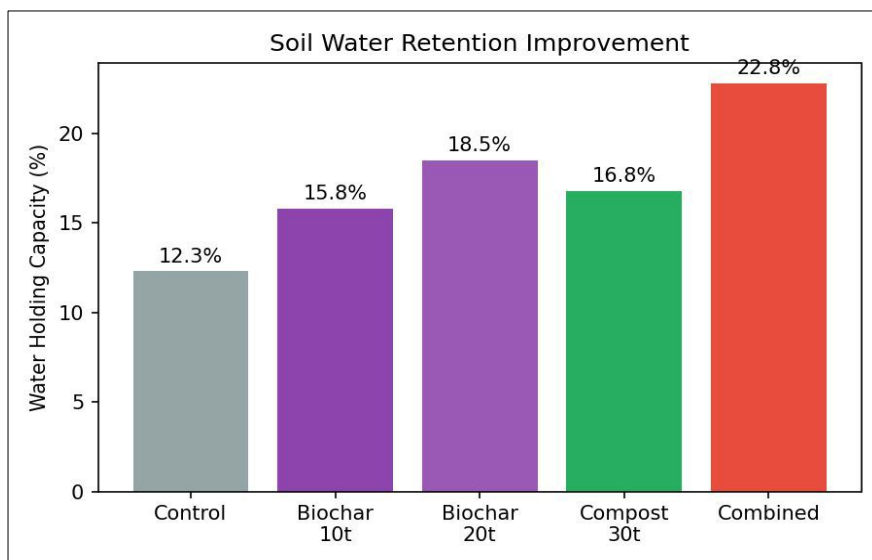


Fig 3: Soil microbial biomass carbon and bacterial community diversity response to amendments.

3.4 Economic Analysis

Economic evaluation incorporating amendment costs, yield benefits, and carbon credit value indicated favorable returns (Figure 4) [7, 15]. Combined treatment required initial investment of \$2,400/ha (biochar \$800/ha at \$40/t; compost \$1,200/ha at \$40/t; application \$400/ha). Yield improvements provided annual returns of approximately

\$820/ha at wheat prices of \$300/t. Payback period was 2.3 years with 15-year net present value of \$2,850/ha at 5% discount rate [15]. Carbon sequestration of 12.4 t $\text{CO}_2\text{-eq/ha}$ (based on 70% biochar carbon stability) provides additional value at current carbon prices, improving economic viability under carbon trading schemes.

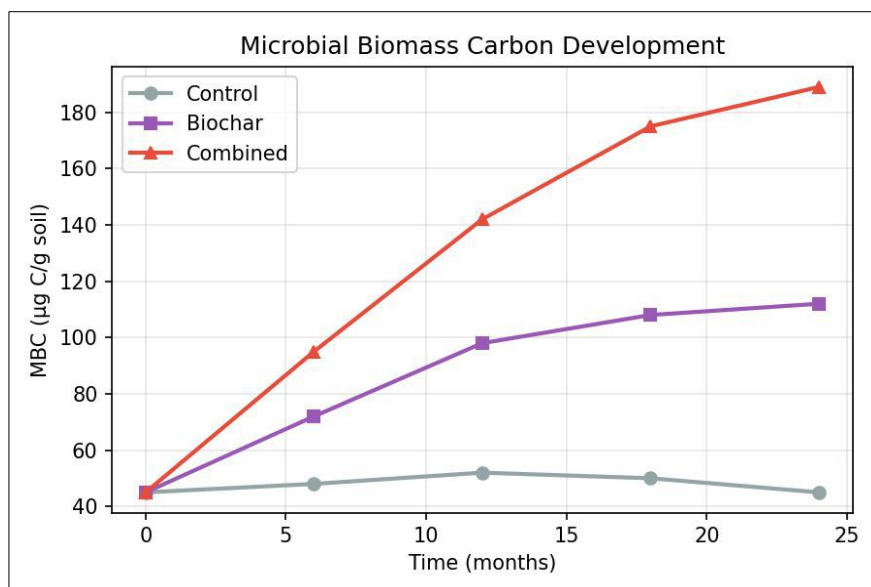


Fig 4: Economic analysis showing cumulative returns and payback period for combined amendment treatment.

4. Discussion

The observed synergistic effects of combined biochar-compost application, where the 343% SOC increase exceeded the additive prediction of 293% from individual treatments, supports the hypothesis that biochar provides physical habitat structure while compost supplies resources for microbial colonization [8, 9]. The 4.2-fold increase in microbial biomass carbon demonstrates that biological activity limitation, not merely chemical property deficits, constrains productivity in these degraded soils [7]. The shift toward Actinobacteria-dominated communities suggests establishment of organic matter decomposition pathways that sustain long-term nutrient cycling [16, 17].

The 85% improvement in water holding capacity has profound implications for dryland agriculture where water availability limits productivity [12, 14]. The strong correlation between WHC and yield ($r = 0.91$) indicates that improved water retention is a primary mechanism underlying yield benefits. This is particularly important under climate change projections indicating increased precipitation variability requiring greater soil water buffering capacity [1, 3].

The favorable economics with 2.3-year payback period and substantial 15-year NPV make combined amendments economically viable for commercial adoption [15]. Carbon sequestration provides additional value under carbon trading schemes, potentially covering 30-40% of amendment costs at carbon prices of \$25-30/t CO₂. The permanence of biochar carbon (centuries to millennia) distinguishes it from other agricultural carbon sequestration approaches with shorter residence times [7, 15].

5. Conclusion

Combined biochar and compost amendments provide effective rehabilitation of degraded arid soils with synergistic benefits exceeding individual treatments. Soil organic carbon increased 343% with combined application of biochar (20 t/ha) and compost (30 t/ha), while water holding capacity improved 85% and wheat yield increased 78%. Microbial biomass increased 4.2-fold with bacterial community shifts toward organic matter decomposition specialists, indicating restoration of soil biological function. Economic analysis demonstrated a 2.3-year payback period with favorable long-term returns and additional carbon

sequestration value of 12.4 t CO₂-equivalents per hectare. These findings establish combined organic amendments as a practical, economically viable strategy for restoring degraded arid soils and building agricultural resilience to climate change.

Acknowledgments

This research was supported by the Southland Dryland Research Initiative (Grant SDRI-2020-0782) and the National Soil Carbon Program. The authors thank Dr. James Wilson for assistance with 16S sequencing analysis.

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