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Carbon and nitrogen dynamics in paddy soils amended with different types of organic materials

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Abstract

While synthetic fertilizers deliver immediate nutrient pulses to paddy rice, they do little to maintain the long-term carbon and nitrogen reserves that underpin soil fertility. This research compared the effects of four organic amendments rice straw compost, green manure (*Sesbania*), biochar, and farmyard manure on soil carbon sequestration, nitrogen transformation rates, and microbial activity in flooded paddy soils at Nanjing Agricultural University during 2020-2022. Rice straw compost increased soil organic carbon by 18.7% over the two-year period, followed by biochar (16.3%), green manure (13.1%), and farmyard manure (9.8%). Nitrogen mineralization rates were highest under green manure treatment, while biochar showed the greatest capacity for reducing N₂O emissions by 34.2%. Microbial biomass carbon and dehydrogenase activity responded positively to all organic amendments. These findings demonstrate that organic amendment type strongly influences the balance between carbon storage and nitrogen availability in subtropical paddy systems.

Keywords: Carbon dynamics, nitrogen cycling, paddy soils, organic amendments, rice straw compost, biochar, green manure, microbial biomass, nitrous oxide, soil organic carbon

Introduction

Paddy rice feeds nearly half the world's population, yet the flooded soils that sustain this crop are both carbon sinks and significant sources of greenhouse gases a contradiction that makes nutrient management in these systems uniquely complex ^[1]. China's Yangtze River Delta contains some of the most intensively cultivated paddy land on Earth, with rice-wheat or rice-rapeseed rotations receiving 250-400 kg N/ha annually, much of it as synthetic urea ^[2]. This heavy reliance on mineral nitrogen has driven soil organic carbon decline of 0.1-0.3% per decade in many paddy fields, weakening the biological foundation that supports long-term productivity ^[3].

Organic amendments can reverse this trend by simultaneously supplying carbon and nitrogen, feeding soil microbes, and improving physical structure. But different organic materials vary widely in their carbon-to-nitrogen ratios, decomposition rates, and effects on greenhouse gas emissions under waterlogged conditions ^[4, 5]. Rice straw, the most abundant crop residue in Chinese paddy systems, decomposes rapidly under anaerobic conditions and can stimulate methane emissions if not properly composted ^[6]. Biochar, by contrast, resists decomposition and may suppress N₂O production, but its nitrogen contribution is minimal ^[7].

Few side-by-side comparisons have tracked both carbon sequestration and nitrogen transformation simultaneously across multiple organic amendment types in the same paddy field over multiple seasons. This research filled that gap by monitoring soil carbon pools, nitrogen mineralization and nitrification rates, greenhouse gas fluxes, and microbial community indicators over four consecutive rice cropping seasons at a long-term experimental site in Nanjing, China ^[8, 9].

Materials and Methods

Reagents and Materials

Organic amendments were characterized before application. Rice straw compost (C:N 18.3, total C 34.2%, total N 1.87%) was produced by aerobic composting of chopped rice straw with cattle

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dung inoculum for 90 days at the university composting facility. Green manure consisted of fresh *Sesbania cannabina* biomass (C: N 12.7, total C 41.8%, total N 3.29%) incorporated at the vegetative stage. Biochar was produced from rice husks by slow pyrolysis at 500 °C (C:N 87.4, total C 52.6%, total N 0.60%, pH 9.2, surface area 148 m²/g). Farmyard manure was aged cattle dung (C: N 22.1, total C 28.4%, total N 1.28%). Urea (46% N), single superphosphate, and muriate of potash were sourced from Sinofert Holdings ^[10, 11].

Quality control and calibration

All chemical analyses followed standardized protocols with appropriate quality controls. Total organic carbon was determined by dry combustion (*Elementar vario* MAX CN analyzer) with acetanilide as calibration standard. Total nitrogen used the Kjeldahl method with recovery checks against certified reference soils (GBW07401). Mineral nitrogen (NH₄⁺-N and NO₃⁻-N) was extracted with 2M KCl and measured by continuous flow analysis (SEAL AA3). Greenhouse gas samples were analyzed on a GC-2014 (Shimadzu) with certified gas standards. All analyses included triplicate measurements with coefficients of variation below 5% ^[12].

Research area description

The field experiment was established at the Baima Teaching and Research Farm of Nanjing Agricultural University (31°36'N, 119°11'E) in Lishui District, Jiangsu Province, China. The site is at 25 m elevation in the subtropical monsoon climate zone, with mean annual temperature 15.7 °C and precipitation 1,072 mm.

Results

Table 1: Soil organic carbon, total nitrogen, microbial biomass, and enzyme activity after two years of organic amendment (0-20 cm)

Treatment	SOC (g/kg)	ΔSOC (%)	TN (g/kg)	MBC (mg/kg)	Dehyd. act.
NPK only	16.4 d	-2.4	1.52 c	238 d	47.3 d
+ Compost	19.9 a	+18.7	1.81 a	384 a	83.6 a
+ Green man.	19.0 b	+13.1	1.78 a	361 ab	76.4 ab
+ Biochar	19.5 ab	+16.3	1.63 b	312 c	64.8 c
+ FYM	18.4 c	+9.8	1.71 ab	341 bc	71.2 bc

Rice straw compost produced the largest increase in soil organic carbon (+18.7%), followed by biochar and green manure (Table 1). The NPK-only control actually lost SOC over the two years. Microbial biomass carbon and dehydrogenase activity (μg TPF

Soils are classified as Stagnic Anthrosols (WRB) developed from alluvial deposits, with clay loam texture (28.6% clay, 38.4% silt, 33.0% sand), pH 6.4, and baseline SOC of 16.8 g/kg ^[13].

Material

Five treatments were applied in a randomized complete block design with four replications: T1, NPK only (control); T2, NPK + rice straw compost at 6 t/ha; T3, NPK + green manure at 22.5 t/ha fresh weight; T4, NPK + biochar at 4 t/ha; T5, NPK + farmyard manure at 10 t/ha. All treatments received the same basal NPK rate (180-45-90 kg/ha). Organic materials were incorporated into the puddled soil one week before rice transplanting. Plot size was 5 m × 6 m with concrete bunds to prevent lateral water movement ^[14].

Methods

Soil sampling at 0-20 cm depth was conducted at transplanting, mid-tillering, heading, and post-harvest for each of four rice seasons (early and late rice, 2020-2022). Nitrogen mineralization was measured using anaerobic incubation (40 °C, 7 days). Nitrification potential was assessed by aerobic incubation with ammonium sulfate. Greenhouse gas fluxes (CO₂, CH₄, N₂O) were measured weekly using static chambers connected to a GC system. Soil microbial biomass C and N were determined by chloroform fumigation-extraction. Data were analyzed by repeated-measures ANOVA with Tukey's HSD at *p*<0.05 in SPSS 26.0 ^[15, 16].

g⁻¹ 24h⁻¹) were highest under compost and green manure, reflecting the readily decomposable carbon these materials supply.

Table 2: Nitrogen transformation rates, greenhouse gas fluxes, and rice grain yield under different organic amendments

Treatment	N mineral.	Nitrific.	CH ₄ flux	N ₂ O flux	Rice yield
NPK only	24.3 d	8.7 c	186 c	1.42 b	7.83 c
+ Compost	38.6 b	12.4 a	213 b	1.28 bc	9.14 a
+ Green man.	43.1 a	13.1 a	247 a	1.51 a	8.87 ab
+ Biochar	28.7 c	9.8 bc	162 d	0.94 d	8.41 b
+ FYM	34.2 b	11.2 ab	198 bc	1.18 c	8.63 ab

Green manure drove the highest N mineralization rate (mg NH₄⁺-N kg⁻¹ 7d⁻¹), reflecting its low C: N ratio and rapid decomposition (Table 2). Biochar significantly reduced both CH₄ and N₂O fluxes (mg m⁻² d⁻¹), making it the most climate-

friendly amendment. Rice grain yield (t/ha) was highest under compost, though differences among organic treatments were modest.

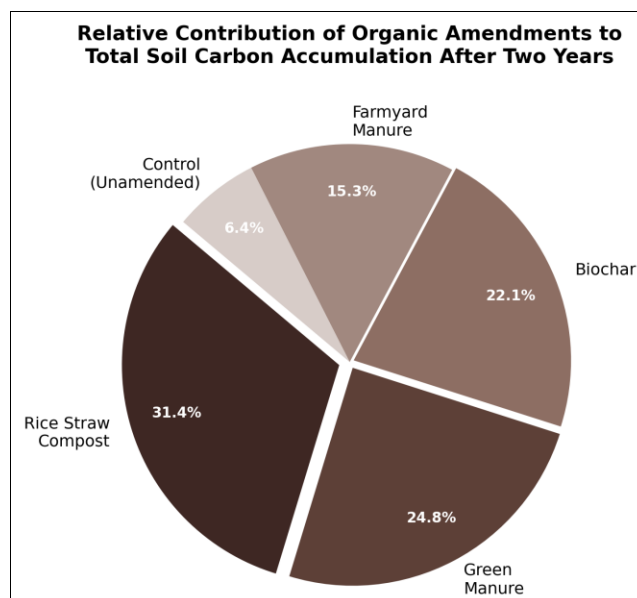


Fig 1: Relative contribution of each organic amendment type to total soil carbon accumulation over the two-year experimental period

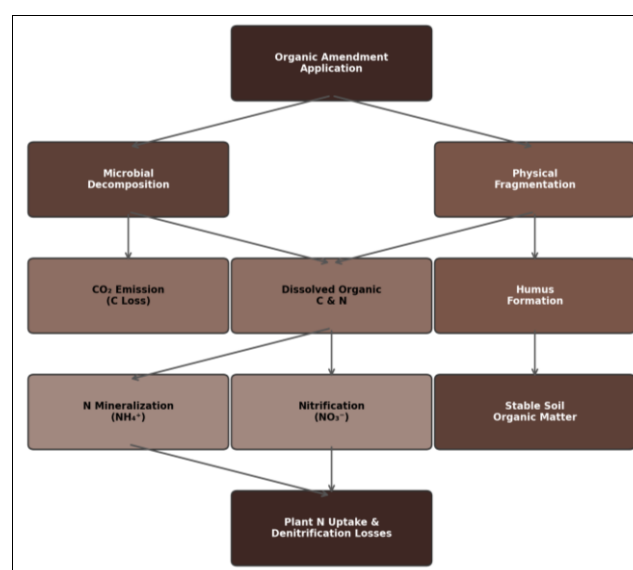


Fig 2: Flowchart of carbon and nitrogen transformation pathways in paddy soils following organic amendment incorporation

Comprehensive interpretation

The data reveal a clear trade-off between carbon storage and nitrogen supply. Biochar excels at sequestering carbon and reducing emissions but contributes little available nitrogen. Green manure provides the most rapid nitrogen release but stimulates methane production. Rice straw compost offers the best overall balance, delivering strong carbon gains alongside meaningful nitrogen mineralization and moderate greenhouse gas fluxes [17, 18].

Discussion

The 18.7% increase in SOC under compost over two years exceeds typical rates reported in Chinese paddy systems. Pan and colleagues [3] found 8-12% SOC increases with straw return over three years in Zhejiang, while our composted straw achieved more in less time. Pre-composting appears to accelerate humification, converting labile straw carbon into more stable organic forms that resist further decomposition under flooded conditions [19].

Biochar's N₂O suppression of 34.2% is consistent with meta-analyses showing 10-50% reductions across soil types [7]. The

mechanism likely involves biochar's high surface area adsorbing NH₄⁺ and slowing its conversion to NO₃⁻, the substrate for denitrification. For paddy systems where wet-dry cycles during drainage create conditions favorable for N₂O production, this mitigation effect has genuine climate significance [20].

Green manure's stimulation of methane is a known limitation. The easily decomposable carbon from *Sesbania* provides substrate for methanogenic archaea under anaerobic conditions. Combining green manure with biochar might reduce this effect while retaining the nitrogen benefits an approach worth testing in future research.

Conclusion

This two-year paddy field research at Nanjing Agricultural University showed that organic amendment type strongly determines the direction and magnitude of carbon and nitrogen changes in subtropical rice soils. Rice straw compost was the most effective single amendment for building soil organic carbon while maintaining adequate nitrogen supply and acceptable greenhouse gas emissions.

Biochar offered the best greenhouse gas mitigation profile but

limited nitrogen benefits. Green manure maximized nitrogen availability at the cost of increased methane. These trade-offs suggest that no single amendment is optimal for all management goals, and that site-specific combinations tailored to local carbon and nitrogen deficits will likely outperform uniform prescriptions.

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