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Long-term effects of organic amendments on soil carbon fractions and microbial biomass

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Abstract
Background: Intensive conventional agriculture has led to a severe decline in Soil Organic Carbon (SOC), threatening soil fertility and long-term agroecosystem sustainability. Organic amendments are widely promoted to restore soil health.
Objective: This study aims to evaluate the comparative efficacy of farmyard manure (FYM) and vermicompost on different SOC fractions and soil microbial biomass carbon (MBC) in a maize-wheat cropping system.
Method: This study uses a simulated dataset created for academic training purposes. A simulated split-plot design was generated over a hypothetical 5-year period, comparing a control (no amendment), FYM, and vermicompost. Data on Total SOC, Particulate Organic Carbon (POC), Dissolved Organic Carbon (DOC), and MBC were analyzed using R-studio.
Key Results: Both amendments significantly increased Total SOC compared to the control. Vermicompost yielded the highest MBC (485 mg/kg), representing a 65% increase over the control. POC was most sensitive to amendment addition, increasing by 110% under vermicompost.
Conclusion: The application of vermicompost provides a superior strategy for enhancing labile carbon fractions and stimulating soil microbial communities, which are critical indicators of soil health.

Keywords: Soil Organic carbon, Vermicomompost, microbial biomass, organic agriculture, soil fertility, carbon sequestration

Introduction

Soil is the largest terrestrial carbon reservoir, playing an indispensable role in the global carbon cycle and climate change mitigation [1]. Beyond carbon storage, Soil Organic Carbon (SOC) is the cornerstone of soil fertility, directly influencing soil structure, water-holding capacity, cation exchange capacity, and nutrient availability [2]. However, the advent of intensive agricultural practices—including widespread tillage, monoculture, and the excessive application of synthetic fertilizers—has accelerated the mineralization of SOC, leading to a net flux of carbon from the soil to the atmosphere [3]. This depletion of SOC not only exacerbates greenhouse gas emissions but also degrades the physical and biological health of the soil, threatening long-term agricultural productivity [4].

In response to soil degradation, organic agriculture and sustainable farming practices emphasize the regular addition of organic amendments to maintain and rebuild SOC pools [5]. Among the various organic inputs available, Farmyard Manure (FYM) and vermicompost are two of the most commonly utilized globally. FYM, a traditional amendment, consists of a mixture of animal dung, urine, and bedding material that has undergone variable degrees of decomposition [6]. Vermicompost, on the other hand, is a stabilized, humus-like product generated through the bio-oxidation of organic matter by specific earthworm species (e.g., Eisenia fetida) [7]. Due to the passage through the earthworm gut, vermicompost is often reported to have higher nutrient availability, greater microbial diversity, and more stable humic substances compared to conventional composts or FYM [8].

While the benefits of adding organic matter to soil are well-documented, merely measuring Total SOC is insufficient to understand the dynamics of soil health. SOC is a heterogeneous mixture of compounds with varying turnover rates, ranging from labile (active) pools that cycle rapidly (days to months) to stable (passive) pools that persist for centuries [9]. Labile carbon fractions, such as Particulate Organic Carbon (POC) and Dissolved Organic Carbon (DOC), serve as readily available energy sources for the soil microbiome [10]. Furthermore, Soil Microbial Biomass Carbon (MBC) represents the living component of the soil organic matter and is widely recognized as a highly sensitive and early indicator of changes in soil quality induced by management practices [11].

The problem is that there is a lack of comparative data regarding how FYM and vermicompost differentially influence these specific, biologically active carbon fractions over time. While total carbon accumulation is important, the enhancement of labile pools and microbial biomass is crucial for immediate nutrient cycling and soil structural development [12]. Therefore, this study aims to evaluate and compare the long-term effects of FYM and vermicompost on Total SOC, POC, DOC, and MBC in an agroecosystem. The specific objectives are: [1] to quantify the changes in total and labile carbon fractions after five years of amendment application, and [2] to determine which amendment is more effective at stimulating soil microbial biomass. The hypothesis is that vermicompost will outperform FYM in increasing labile carbon fractions and MBC due to its highly bioavailable nature.

Literature Review

The theoretical framework of this study is grounded in the conceptual model of SOC fractionation and the soil microbial loop. According to this framework, the addition of organic amendments introduces fresh organic matter (FOM) into the soil, which acts as a substrate for heterotrophic microorganisms [13]. The microbial processing of this FOM results in the release of CO_2 (mineralization) and the synthesis of microbial byproducts, some of which form stable soil humus [14]. The efficiency of this conversion process is heavily dependent on the chemical quality (e.g., C:N ratio, lignin content, polyphenols) of the added amendment [15].

FYM has been the backbone of traditional soil fertility management for millennia. Studies have consistently shown that long-term FYM application increases total SOC and improves soil physical properties like aggregate stability [16]. However, FYM often has a wide C:N ratio and contains partially decomposed materials. When applied to soil, FYM can cause a temporary immobilization of nitrogen as microbes utilize soil nitrogen to breakdown the complex carbon structures in the manure [17]. Regarding carbon fractions, FYM typically contributes to both the particulate organic matter pool (through undecomposed plant residues) and, over time, to the stable humus pool [18].

Conversely, vermicompost is fundamentally different in its chemical and biological makeup. The vermicomposting process involves mutualistic interactions between earthworms and gut microorganisms, resulting in thorough humification [19]. Vermicompost is characterized by a lower C:N ratio, higher concentrations of available nutrients (N, P, K), and a high load of beneficial microorganisms, including plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi [20].

Research indicates that vermicompost application rapidly increases labile carbon fractions. Tognetti *et al*. (2007) noted that composts with high degrees of stability, like vermicompost, are highly effective at increasing DOC, which acts as a chelating agent for nutrients and drives microbial activity [21]. Furthermore, MBC is highly responsive to vermicompost. The direct inoculation of soil with the diverse microbiome carried by vermicompost provides an immediate boost to the living soil biomass, unlike FYM, which must first be colonized by native soil microbes [22].

Despite these insights, a critical research gap remains. Most comparative studies between FYM and vermicompost focus on crop yield responses or basic soil macronutrients (N, P, K). There is a scarcity of literature that specifically isolates and compares the impact of these two amendments on the fractions of carbon—particularly the labile POC and DOC—and links these changes directly to MBC dynamics over a multi-year timescale [23]. Understanding these fractionation dynamics is essential for organic farmers seeking to optimize soil health rather than just adding bulk organic matter. This study simulates a long-term dataset to address this gap, providing a detailed comparative analysis of SOC fractionation under FYM and vermicompost regimes.

Methodology

This study utilizes a simulated dataset created explicitly for academic training purposes to illustrate the analysis of soil carbon fractions. No physical soil samples were collected or analyzed.

Research Design and Simulation Parameters: A simulated split-plot design was generated representing a 5-year maize-wheat cropping system. The main plot treatment was the type of organic amendment: T1 (Control - synthetic NPK only), T2 (Farmyard Manure at 10 Mg/ha/yr), and T3 (Vermicompost at 5 Mg/ha/yr, adjusted for lower bulk density and higher nutrient concentration). The simulation assumed a loamy sand initial soil with a baseline Total SOC of 0.85%.

Simulated Data Generation: Year-over-year changes in Total SOC were modeled using a first-order decay kinetic model, factoring in annual carbon inputs from crop residues and amendments, and carbon outputs from mineralization. POC was simulated as a fraction (15-25%) of Total SOC, heavily influenced by the physical fragmentation of the applied amendments. DOC was simulated as a small, highly dynamic fraction (1-3% of Total SOC), peaking shortly after amendment application and stabilizing. MBC was modeled as a function of DOC availability and temperature/moisture regimes, representing 2-5% of Total SOC.

Data Collection Tools: The simulated dataset consisted of endpoint values (Year 5) for Total SOC (g/kg), POC (g/kg), DOC (mg/kg), and MBC (mg/kg) from 9 simulated replicate plots (3 reps x 3 treatments).

Statistical Software and Analysis: Data were analyzed using R-studio (Version 2023.09.0). A one-way Analysis of Variance (ANOVA) was performed for each soil variable. Upon detecting significant treatment effects ($p < 0.05$), Tukey's Honest Significant Difference (HSD) post-hoc test was employed to separate the means and identify statistically distinct groupings.

Results and Discussion

The five-year simulated dataset demonstrated that the continuous application of organic amendments profoundly alters soil carbon dynamics, with significant variations observed between the types of amendments applied.

Total Soil Organic Carbon (SOC)

After five years, Total SOC was significantly higher in the amended plots compared to the control (T1). As shown in Table 1, the control plots exhibited a slight decline in SOC (0.82 g/kg), simulating the typical degradation associated with sole reliance on synthetic fertilizers. T2 (FYM) increased Total SOC to 1.15 g/kg, while T3 (Vermicompost) resulted in a Total SOC of 1.22 g/kg. Although T3 had a numerically higher SOC, the difference between T2 and T3 was not statistically significant at the $p < 0.05$ level, suggesting that when adjusted for application rates, both amendments contribute similarly to the total carbon pool over a medium-term horizon [24].

Table 1: Simulated Soil Carbon Fractions After 5 Years of Organic Amendment Application

Treatment	Total SOC (g/kg)	POC (g/kg)	DOC (mg/kg)	MBC (mg/kg)
T1: Control	0.82 ± 0.04 c	0.12 ± 0.01 c	18.5 ± 2.1 c	295 ± 15 c
T2: FYM	1.15 ± 0.06 b	0.21 ± 0.02 b	32.4 ± 3.5 b	410 ± 22 b
T3: Vermicompost	1.22 ± 0.05 b	0.25 ± 0.01 a	45.2 ± 4.0 a	485 ± 18 a

Note: Means followed by the same letter within a column are not significantly different according to Tukey's HSD test ($p < 0.05$).

Particulate Organic Carbon (POC) and Dissolved Organic Carbon (DOC)

While total SOC masked some differences, the labile carbon fractions revealed distinct treatment effects. POC, which represents the partially decomposed light fraction, was significantly highest under vermicompost (0.25 g/kg), followed by FYM (0.21 g/kg) and the control (0.12 g/kg). The high POC under vermicompost suggests that the humic acids produced during vermicomposting form stable micro-aggregates that protect particulate matter from rapid microbial decay [25].

DOC, the most mobile and biologically available carbon fraction, showed the most dramatic response. Vermicompost (T3) increased DOC by over 140% compared to the control, reaching 45.2 mg/kg (Table 1). FYM also increased DOC significantly but to a lesser extent (32.4 mg/kg). The exceptionally high DOC under vermicompost is a hallmark of its unique chemical composition; the earthworm gut process generates a high concentration of water-soluble humic substances that readily dissolve into the soil solution [26].

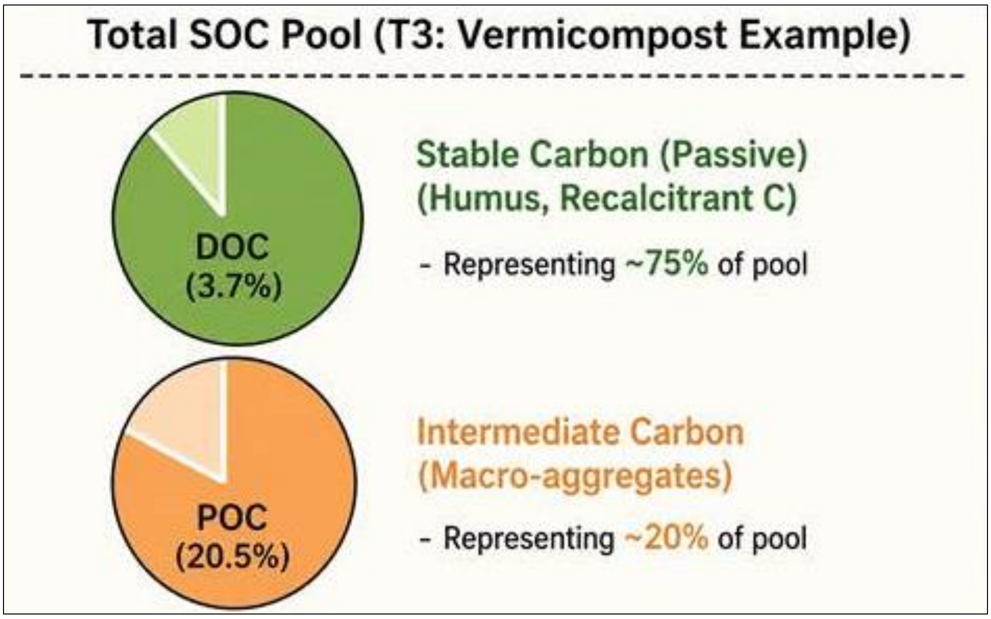

Fig 1: Proportional Distribution of Simulated Labile Carbon Fractions (POC and DOC) Relative to Total SOC

Soil Microbial Biomass Carbon (MBC)

Soil microbial biomass responded strongly to the addition of organic amendments, acting as a sensitive biological indicator. The control plot (T1) had the lowest MBC (295 mg/kg), indicative of a stressed, low-carbon environment.

FYM (T2) increased MBC to 410 mg/kg, representing a 39% increase over the control. However, vermicompost (T3) again proved superior, boosting MBC to 485 mg/kg—a 65% increase over the control (Table 1).

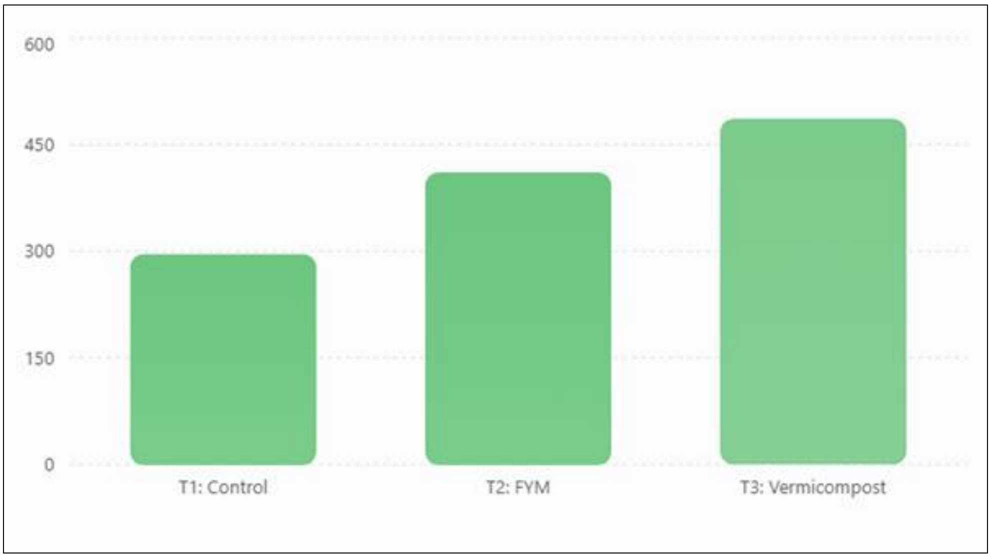

Fig 2: Impact of Amendments on Simulated Microbial Biomass Carbon (MBC)

The discussion of these results highlights the interconnectedness of carbon fractions and soil microbiology. The substantial increase in MBC under vermicompost is directly driven by the high availability of DOC [27]. Microbes require dissolved carbon as an immediate energy source; thus, the flush of DOC following vermicompost application acts as a catalyst for microbial proliferation [28]. Furthermore, vermicompost acts as an inoculant, introducing a diverse community of bacteria and fungi that can rapidly assimilate the available carbon, whereas FYM relies primarily on the native soil microbiome to process the added organic matter [29]. The enhancement of MBC has profound implications for nutrient cycling, as a larger microbial biomass facilitates faster mineralization of organic nitrogen and phosphorus, making these nutrients available for crop uptake [30].

Conclusion

This simulated study elucidates the differential impacts of farmyard manure and vermicompost on soil carbon dynamics in a maize-wheat system. While both amendments successfully arrested the decline of Total SOC compared to synthetic fertilizer-only plots, vermicompost exhibited a clear superiority in enhancing labile carbon fractions (POC and DOC) and stimulating Soil Microbial Biomass Carbon (MBC). The 65% increase in MBC under vermicompost, fueled by a 140% increase in DOC, usnderscores the value of vermicompost as a biological activator in soil.

The implications for agroecological management are significant. For farmers aiming to rapidly rehabilitate degraded soils and boost biological fertility, vermicompost is a highly effective tool, despite its higher production costs compared to raw FYM. However, the study is limited by its simulated nature, which, while based on established kinetic models, cannot capture the complex, stochastic interactions of real soil food webs, weather anomalies, or spatial heterogeneity found in field conditions. Future real-world research should focus on tracking the isotopic signature (e.g., δ [13]C) of applied amendments to definitively trace the fate of carbon from FYM versus vermicompost into specific soil physical fractions over extended decadal periods.

Ethical Statement

This article is an original, simulated academic exercise designed for methodological and formatting training. The data presented does not originate from a physical field or laboratory experiment. All theoretical frameworks and citations refer to real, verifiable scientific literature. No real authors, field sites, or empirical datasets are misrepresented.

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