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Research Article

Effects of Organic Amendments and Mineral Fertilizers on Optimizing Nutrient Cycling in Alkaline Soil

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ABSTRACT

Soil microbial biomass carbon (MBC) and nitrogen (MBN) are indicators of microbial size and soil fertility, representing a vital living nutrient reservoir in the soil. This study aimed to evaluate the impact of various organic sources, such as poultry manure (PM), farmyard manure (FYM), compost (CM), and biochar (BC), along with different levels of mineral fertilizers on soil microbial dynamics and nutrient (N, P) mineralization through laboratory incubation experiments. The organic amendments were applied at rates of 0.25%, 0.5%, and 1.0% of soil carbon (w/w), combined with 75%, 50%, and 25% of recommended doses of NPK (120:90 and 60 kg N, P_2O_5, and K_2O ha^{-1}), respectively. Following the application of amendments, the soil underwent a 16-day incubation period to measure CO_2 emissions and a 28-day period for N and P mineralization. The rate of CO_2 evolution exhibited a significant increase with higher carbon levels but declined over time. Compost showed the highest CO_2 evolution at any given time, followed by PM, FYM, and BC, likely due to a higher readily available fraction of carbon. Compost, particularly at the 1% C level in combination with inorganic fertilizer, led to a significant increase in soil microbial biomass C and N. Nitrogen and phosphorous mineralization increased with the duration of the 28-day incubation period. However, the net release of N and P decreased with higher carbon levels, potentially associated with both immobilization and the fact that higher levels received lower (25%) NPK levels. Nevertheless, soils treated with CM and PM maintained higher levels of N and P, associated with their higher fraction of labile nutrients. These findings suggest that the continuous application of organic sources enhances N and P mineralization, soil microbial biomass, and their activity. Therefore, the regular application of carbon sources emerges as a strategic approach to improving the soil health of less fertile alkaline calcareous soils.

Keywords: Soil fertility, microbial dynamics, CO_2 evolution, CO_2 emission, Compost.

INTRODUCTION

The growing complexity of nutrient problems makes maintaining and increasing soil fertility for sustainable agriculture unpredictable. Numerous qualities of organic matter affect the physical, chemical, and biological features of the soil [1]. Soil organic matter (SOM), is well acknowledged for its role in stabilizing soil structure and serving as a storehouse of plant nutrients. It serves as the main repository for C and N in agricultural soils, as well as a minor repository for P, S, and other elements [2]. Soil fertility and crop productivity are influenced by the dynamics of C and N in soils. These dynamics depend on the amount and nature of organic residues entering the soil. These factors that interact with C and N cycling include microbial biomass, light fraction of organic matter and water-soluble organic matter [3]. The quantity and quality of organic matter representative of humic and non-humic substances are greatly influenced by vegetation, climate, soil reaction and biological conditions. The labile and humified organic matter will have a strong impact on soil fertility and many need to be taken into consideration in the development of fertilizer recommendations. Humus, the most important and largest constituent of organic matter is formed by the decomposition of plant and animal residues by microorganisms. Humus has positive influence on the physical, chemical and biological properties of the soil [4].

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The organic component of soil is made up of humus, highly carbonized substances including charcoal, graphite, and coal, as well as microbial cells, plant, and animal remains at different stages of decomposition [5]. It is common that organic matter is essential for preserving the soil health and productivity of soil. Due to increased oxidation in tropical climes, soil organic matter is more quickly decomposed and mineralized, which lowers the amount of organic matter in the soil and consequently lowers agricultural yield and fertility [6]. Although SOC is very reactive, intense agriculture land use changes, deforestation, burning and crop residue clearance, variations in climate and rainfall, overgrazing soil deterioration and soil desertification can all cause significant losses of inorganic carbon from the soil.

Agriculture has traditionally depended on animal dung as a fertilizer source, influencing various soil characteristics that contribute to soil health [7]. Over medium to long-term applications, the use of animal dung can elevate soil organic matter, leading to enhanced soil aggregate stability, water infiltration, and water retention, while simultaneously reducing soil bulk density and compaction [8]. Poultry litter is recognized as an organic matter source containing essential plant nutrients, enriching soil conditions [9]. The physical and chemical properties of soil, such as moisture content, total soil porosity, total nitrogen, and accessible phosphorus, are enhanced by the application of poultry manure [10]. Biochar, with its potential to enhance carbon sequestration, nutrient and water retention, and other soil health qualities, offers an avenue for soil improvement [11]. The enhancement of soil health is facilitated by its elemental makeup, which also has the ability to raise pH, hold onto water, and bind nutrients and metals in its functional groups [12]. The diverse chemical and physical properties of biochar make it a valuable amendment for restoring soil health [13]. Incorporating biochar into the soil is considered a potential strategy for consistently enhancing soil health and promoting crop growth [14]. This proposed project aims to advance our understanding of the impact of both organic and inorganic sources on soil CO_2 emissions, soil microbial biomass carbon and nitrogen, as well as nitrogen and phosphorus mineralization in alkaline calcareous soil within a semi-arid environment.

MATERIALS AND METHODS

A laboratory incubation experiment was conducted to investigate the effect of organic amendments and mineral N, P, and K on nutrient (N, P) mineralization, microbial activity, and microbial biomass. Various organic sources, including (FYM) Farmyard manure, Poultry manure, Biochar, and Compost, were utilized at carbon levels of 0.25%, 0.50%, and 1%. These were combined with inorganic fertilizer sources, representing 75%, 50%, and 25% of the recommended dose of NPK, in addition to a control and 100% NPK treatment. Bulk soil samples (0–15 cm) from the field experiment were collected for incubation tests. The soil samples underwent sieving for microbiological research and were subsequently refrigerated. Amendments were applied to the soil, and it was then incubated for microbial studies. Two equal portions of the soil samples were taken; half were fumigated and the other half were left unfumigated. This experimental setup allowed for a comprehensive examination of the combined effects of organic and inorganic inputs on soil nutrient dynamics, microbial activity, and biomass. From each unfumigated sample 50 g of soil were taken and incubated for 2, 4, 8 and 16 days. CO_2 production was calculated by the procedure of alkali trapping technique followed by [15].

$$CO_2 \text{ ug g}^{-1} \text{ soil day}^{-1} = \frac{(Blank - Sample) \times 22000000 \times Nof\ HCL}{1000 \div Soil\ Weight \div No.of\ Days}$$

For microbial biomass study 50 g of each unfumigated and fumigated sample were taken and incubated for 16 days. The fumigation approach was used to determine the microbial biomass carbon and microbial biomass nitrogen in the soil [16].

Microbial biomass carbon and nitrogen was calculated by the procedure as given below [17]:

$$\text{Microbial biomass*}CO_2 = \frac{(Blank - Sample) \times 0.1}{1000} \times \frac{10^6 \times 22}{(weightof\ soil \times No.of\ Days)}$$

$$\text{Microbial Biomass C} = \frac{*Reading\ of\ CO2 \times 12}{44}$$

$$\text{Microbial biomassC} = \frac{(fumigated\ C\ Reading - unfumigated\ C\ Reading)}{0.45}$$

For microbial biomass-N, the same soil samples were run for total mineral N and microbial biomass-N was calculated as described by Howarth *et. al.*, 1994 [17].

$$\text{Mineral N} = \frac{(Sample - Blank) \times KCL \times 70)}{(Weight\ of\ soil \times Extract\ Take)}$$

$$\text{Microbial Biomass N} = \frac{(Fumigated\ N - Unfumigated\ N)}{0.54}$$

For N and P mineralization study 500 g from each unfumigated sample were taken and incubated for 28 days. For mineral N and P sample were taken out at 0, 7, 14, and 28 days and analyzed for total mineral N and extractable P. Total mineral N was determined by the procedure of Mulvaney 1996 [18].

$$N\ (mg\ kg^{-1}) = \frac{(Sample - Blank) \times Nof\ Hcl \times meq\ N \times Volume\ made}{(Weight\ of\ sample(g) \times (Volume\ taken\ for\ distillation)} \times \frac{10^6 mg}{kg}$$

The AB-DTPA extraction method, as reported by [19], was used to estimate the extractable phosphorus concentration in soil samples.

$$Phosphorus\ (P)(mg\ kg^{-1}) = \frac{(Instrumental\ Reading \times Volume\ made)}{(Weight\ of\ sample \times Volume\ taken)}$$

Statistical Analysis

The data was statistically analyzed in accordance with [20] and statistical packages Statistix 8.1 were used to compare the means using the LSD test ($P \leq 0.05$).

RESULTS

Effect of organic sources and levels on microbial activity or CO_2 emissions in incubation

Microbial activity in incubation as influenced by carbon sources and level in the short-term are presented in Table 1. The treatment receiving compost consistently exhibited the highest soil microbial activities when data was averaged across various carbon levels and recorded over different days. On the other hand, the treatment receiving biochar showed the lowest microbial activities. Results regarding carbon levels when data averaged across carbon sources and days maximum soil microbial activities was recorded in the treatment which receiving 1 % carbon level followed by 0.50 % while minimum was recorded in 0.25 % carbon level. Results regarding control vs rest maximum soil microbial activities were recorded in the treatment which receiving combine application of organic and inorganic fertilizers while minimum soil microbial activities were recorded in control plot.

Table 1. Short-term effect of carbon sources and levels on microbial activity (μg g^{-1} soil $day^{-1)}$ in soil during lab incubation experiment.

	Day 2	Day 4	Day 8	Day 16
Carbon Sources (CS)				
FYM	214c	130b	54c	37bc
PM	234b	139b	76a	41ab
BC	203d	115c	45d	35c
COMP	253a	154a	67b	46a
LSD	7.08	8.8	4.2	5.2
Carbon Levels (CL)				
0.25	186c	115c	43c	34c
0.5	225b	137b	61b	40b
1	268a	152a	78a	45a
LSD	6.1	7.6	3.6	4.5
Control	110	64	29	23
NPK	193	105	47	30
Rest	226	134	61	40
Control Vs Rest	**	**	**	**
NPK Vs Rest	**	**	*	*
CS*CL	NS	NS	NS	NS

Means followed by same letter (s) in a column do not differ significantly at $P \leq 0.05$. FYM, BC, PM, COMP, CS, CL and Y stand for farmyard manure, biochar, poultry manure, compost, carbon sources, carbon level and year, respectively. Carbon levels at 0.25, 0.5 and 1.0 % received 75, 50 and 25 % or recommended dose of NPK.

Short term effect of carbon sources and levels on soil microbial biomass C, N and C/N ratio

The results from the study, focusing on the impact of added organic sources and their levels on soil microbial biomass-C (MBC), indicated a significant ($P \leq 0.05$) increase in MBC in plots treated with organic sources compared to the control (Table 2). The highest MBC, reaching 387 μg g^{-1} soil, was observed in the compost-treated plots, statistically equivalent to those treated with poultry manure, while the lowest MBC was recorded at 351 μg g^{-1} in the biochar treatment. Additionally, the data highlighted significant differences (P≤P0.05) in MBC among different carbon levels (Table 2). Specifically, MBC was notably higher at the 1% C level compared to the 0.25% and 0.5% C levels. The treatment receiving organic sources based on a 1% C level demonstrated the highest MBC, reaching 395 μg g^{-1} soil, in contrast to the 335μg g^{-1} soil observed in the 0.25% C levels. These results indicated that MBC increased with increasing levels of organic sources. The data also revealed that control vs rest and NPK vs rest were found significant. Organic sources along with NPK show better results compared to applying NPK alone. The interaction between carbon sources and levels was non-significant. These results indicated that MBC increased with increasing levels of organic sources. The data also revealed that control vs rest and NPK vs rest were found significant. Organic sources along with NPK show better results compared to applying NPK alone. The interaction between carbon sources and levels was non- significant.

Similar to MBC, MBN exhibited a significant ($P \leq 0.05$) increase in plots treated with organic sources compared to the control and NPK-alone treatment during lab incubation (Table 2). The response of MBN to organic amendments was nearly identical. On average, the highest MBN of 24 µg g^{-1} soil was observed in plots receiving compost, statistically comparable to those treated with poultry manure, while the farmyard manure treatment recorded 19 µg g^{-1} soil. Furthermore, significant differences ($P \leq 0.05$) in MBN were noted among different carbon level treatments. MBN was notably higher for organic sources applied at the 1% C level compared to the 0.25% and 0.5% C levels. The treatment receiving organic sources based on a 1% C level demonstrated the maximum MBN of 26 µg g^{-1} soil, compared to 19 µg g^{-1} soil for the treatment based on a 0.25% C level. Additionally, it was observed that the control versus the rest and NPK versus the rest were significant. In this study, a higher microbial biomass N was recorded in the treatment receiving compost, possibly attributed to the increased availability of nitrogen [21]. The findings related to microbial biomass indicated elevated nitrogen levels in the treatment receiving organic sources at a 1% application rate compared to other levels. This difference is likely attributed to the higher application of organic sources in this treatment compared to the other levels [22].

Our data revealed that the C/N ratios in SMB were not significantly influenced by the addition of organic sources (Table 2). However, the C/N ratios in SMB demonstrated a decreasing trend with increasing carbon levels. The lowest C/N ratio in SMB, measuring 15, was observed in soil treated with the highest organic source level (1%), as opposed to the lowest level (0.25% C). Furthermore, differences in C/N ratios of MBC between various organic sources were not significant. The lowest C/N ratio in SMB, recorded as 15, was associated with the treatment receiving biochar compared to other organic sources. Additionally, the C/N ratios in SMB for the control versus the rest were significant. The interactive effects of organic sources and levels on C/N ratios in SMB were statistically non-significant (Table 2). The soil C:N ratio serves as a crucial indicator explaining the nutrient release dynamics of added soil organic amendments. Changes in the C/N ratio of SMB may influence the availability of carbon and nitrogen to microorganisms, as well as the microbial composition in the soil. The C/N ratio in soil microbial biomass could depend on the type of carbon present in biochar and other organic matters.

Table 2. Soil Microbial Biomass C, N and C/N ratio in lab incubation as influenced by Carbon sources and levels.

	Biomass C	Biomass N	C/N ratio
Carbon Sources (CS)			
FYM	357b	19b	18 ^{NS}
PM	368ab	23a	16
BC	351b	22ab	15
COMP	387a	24a	16
LSD			
Carbon Levels (CL)			
0.25	335c	19b	17^{NS}
0.5	367b	22b	16
1	395a	26a	15
LSD			
Control	305	15	20
NPK alone	324	19	17
Rest	366	22	17
Control Vs Rest	**	*	*
NPK Vs Rest	*	*	-
CS*CL	NS	NS	NS

Means followed by the same letter (s) in a column do not differ significantly at $P \leq 0.05$. FYM, BC, PM, COMP, CS, CL and Y stand for farmyard manure, biochar, poultry manure, compost, carbon sources, carbon level and year, respectively. Carbon levels at 0.25, 0.5 and 1.0 % received 75, 50 and 25 % or recommended dose of NPK.

Effect of carbon sources and levels on N mineralization (short term) Carbon sources and carbon levels had a significant effect ($P \leq 0.05$) on mineral N on all incubation days (Table 3). The data on all incubation days (0, 7, 14, 28) show that in carbon sources, maximum mineral nitrogen (32,38,50,58 ug g^{-1}) was recorded in the treatments receiving compost followed by poultry manure, FYM and BC. Among the carbon levels the mineral nitrogen maximum receives 0.25 % C along with 75% NPK in all incubation days followed by 0.5%C (50%NPK) and 1%C (25% NPK). All the amended plots have maximum mineral nitrogen over control. The interaction between carbon sources and carbon levels was found non-significant ($P \leq 0.05$) at 0, 7, 14 and 28 days of incubation periods (Table.3). Among the days at day 0 and 7 have no significant effect. Day 14 and 28 has significantly higher mineral nitrogen than day 0 and 7.This show that due microbial activity in soil increase decomposition which increases mineralization due to which mineral nitrogen were higher. In this research mineral N increases with compost application it may be due to higher decomposition of compost and already decompose nutrients present in compost.

Table 3. Short term effect of carbon sources and levels on N mineralization in soil during lab incubation experiment

	0 Day	7 Day	14 Day	28 Day
Carbon Sources (CS)				
FYM	30a	36a	46^{NS}	56a
PM	31a	36a	48	55a
BC	27b	31b	44	48b
COMP	32a	38a	46	58a
LSD	2.4	3.07	3.7	2.8
Carbon Levels (CL)				
0.25	34a	38a	50a	57a
0.5	30b	37b	47b	56a
1	27a	31b	40c	50b
LSD	2.09	2.67	3.2	2.4
Control	21	23	22	23
NPK	24	29	32	33
Rest	30	35	46	54
NPK Vs Rest	*	*	*	*
Control Vs Rest	**	**	**	**
CS*CL	NS	NS	NS	NS

Means followed by same letter (s) in a column do not differ significantly at $P \leq 0.05$. FYM, BC, PM, COMP, CS, CL and Y stand for farmyard manure, biochar, poultry manure, compost, carbon sources, carbon level and year, respectively. Carbon levels at 0.25, 0.5 and 1.0 % received 75, 50 and 25 % or recommended dose of NPK.

Effect of carbon sources and levels on P mineralization (short term)

Carbon sources and carbon levels had a significant effect ($P \leq 0.05$) on mineral phosphorous on all incubation days (Table 4). On day 0 in carbon sources the mineral p on compost, farmyard manure poultry manure and biochar are statistically similar. On day 7 and 14 the compost and poultry were statistically similar as well as farmyard manure and biochar show at far result. On day 28 result show compost and poultry manure was significantly higher mineral p then farmyard manure and biochar. Among the carbon levels the mineral phosphorous will be maximum where it receives 0.25 % C in the form carbon sources along with 75% NPK in all incubation days followed by 0.5 and 1% C (50 and 25% NPK).

All the plots treated with amendments recorded higher levels of mineral phosphorus compared to the control. The interaction between carbon sources and carbon levels was found to be statistically non-significant ($P \leq 0.05$) during the 0, 7, 14, and 28 days of the incubation periods. Among the days at day 0 and 7 has similar mineral phosphorous. Day 14 and 28 have significantly higher mineral phosphorus than day 0 and 7. This show that microbes present in soil gradually increase decomposition which increases mineralization due to which mineral phosphorous were higher in later incubation days compared to early incubation period. In this study P mineralization increases with increases duration it may be due to with increases duration microbial activity increases which ultimately increases P mineralization.

Table 4. Short-term effect of carbon sources and levels on P mineralization in soil during lab incubation experiment

	0 Day	7 Day	14 Day	28 Day
Carbon Sources (CS)				
FYM	3.2bc	3.5b	4.5b	4.8b
PM	3.6ab	4.1a	5.1a	5.4ab
BC	3.0c	3.6b	4.1b	3.8c
COMP	3.7a	4.6a	5.2a	5.9a
LSD	0.4	0.5	0.5	0.6
Carbon Levels (CL)				
0.25	3.6a	4.8a	5.6a	5.9a
0.5	3.4ab	4.1b	4.9b	5.1b
1	3.1b	3.1c	4.0c	5.9a
LSD	0.4	0.4	0.4	0.5
Control	2.4	1.73	2.4	2.1
NPK	3.2	3.6	3.3	3.2
Rest	3.4	4.0	4.9	5.0
Control Vs Rest	**	**	**	**
NPK Vs Rest	-	-	*	*
CS*CL	NS	NS	NS	NS

Means followed by same letter (s) in a column do not differ significantly at PS ≤ 0.05. FYM, BC, PM, COMP, CS, CL and Y stand for farmyard manure, biochar, poultry manure, compost, carbon sources, carbon level and year, respectively. Carbon levels at 0.25, 0.5 and 1.0 % received 75, 50 and 25 % or recommended dose of NPK.

DISCUSSION

The application of organic sources increases the CO_2 emissions in the whole incubation period (16 days). CO_2 emissions from the compost treated plots increase in all incubation days as compared to other organic sources it is due to easily decompose nature of compost the microbes attack and degrade the easily decomposed matter first and release CO_2. The rate of CO_2 evolution was higher in all treatments at the beginning of incubation and thereafter gradually declined. Two things could be the cause of reduced microbial activity, as seen by a drop in CO_2: first, a reduction in organic matter that is readily biodegradable; and second, a following moderate stable microbial activity that suggests that decomposition has advanced to the advanced stage [23]. It also shows the stabile nature of the end product or compost [24]. Because of the high content of labile carbon (C) and nitrogen (N), in composts promote nutrient availability and microbial activity [25]. After compost the higher CO_2 emission from poultry manure and farmyard manure it is because of higher nutrient content in these manure [24]. Biochar has also been found to reduce CO_2 emissions due to its low degradable carbon content, resulting in an increase in C storage in the soil [26]. Because of the resistant character of carbon molecules in biochar has greater soil stability compared to other easily decomposable organic materials [27].

According to the study, adding manure raised SMB-C and N levels. However, treatment plots that received the highest level of manure (1% C) in combination with chemical fertilizers had the highest levels of SMB-C and N. Compost much enhances soil physicochemical qualities, soil microbial biomass (SMB), soil disease resistance, and soil organic matter (SOM) [28]. The diversity and activity of soil microbial biomass were significantly increased by incorporating organic composts, either by alone or in combine with chemical fertilizers [29]. Addition of composted organic manure enhanced MBC and MBN respectively, as compared to chemical N fertilizer application [30]. Microbial biomass carbon (MBC) and nitrogen (MBN), were effectively improved by biochar and compost treatment [31]. Increases in MBC and MBN may have occurred because organic fertilizer improved the soil's physicochemical and biological qualities, resulting in higher mineral N absorption and uptake by the crop[32]. Biochar application to arid cereal crops significantly increases soil microbial biomasses (MBC and MBN) and enzyme activity [33]. Larger pools of MBC and MBN were produced by the combination of biochar and N fertilizer, especially in the top soil (0–10 cm) layer [34]. In the second year higher microbial activities was recorded in the treatment which is treated with poultry manures it may be due to decomposition of PM lesser than that of Compost [35].

Nitrogen mineralization was significantly increased as incubation period increases. Compost poultry manure and farmyard manure have the same nitrogen mineralization in all incubation days. Nitrogen mineralization an increase as incubation period extended it is due to the degradation of organic carbon sources .Microorganism decomposes the organic matter and release nitrogen [36]. Mineral N increases with compost application it may be due to higher decomposition of compost and already decompose nutrients present in compost [37]. Poultry manure showed higher mineralization rates than farm yard manure, which is consistent with their lower C: N ratios [38]. The amounts of C and N in crop residues determine whether net nitrogen mineralization or net N immobilization occurs [39]. In our results the rate of nitrogen mineralization was lower than biochar treatment in all incubation days. The reduction in NO_3-N levels seen with an increase in biochar quantity may be explained by N immobilization brought on by microorganisms and the physical shielding of SOM provided by the biochar [40]. The sorption over native SOM could result in a protective mechanism that reduces mineralization of native SOM and causes negative N release [41]. Mineral nitrogen reduce highly and rapidly with the addition of biochar or/and straw, possibly it is due to N adsorption and retention in soil [41].

Soil phosphorous mineralization was increase as incubation days increases in compost and poultry manure treated plot. Adnan et al. reported that the increase in P may also be due to the release of significant amounts of CO_2 during organic matter decomposition and complexing of cations such as Ca_2+, which is primarily responsible for P fixing in alkaline and calcareous soils[43]. Bhambure et al. suggested that increased microbial biomass carbon by boosting microbial activities and boosted phosphatase and dehydrogenase activities, which are responsible for P solubilization [44]. The incubation study demonstrates the use of compost in combination with inorganic fertilizers to improve soil nutrient supply capacity, nutrient use efficiency, and soil fertility for crop development. According to Adnan et al. that poultry dung raises the availability of P in soil from both applied and native sources and lowers soil pH by releasing H+ ions[45]. We found that P availability rose with time, but that the soil treated with poultry dung showed a greater rise in P availability than the untreated soil. This may result from the quick mineralization of organic P and the solubilization of Ca-P by chelating and acidifying processes, which release the P that isn't available into the mobile pool [43]. Poultry manure fertilization boosts the microbial population. For improved soil P nutrition, calcareous soils must be treated with poultry manure. Farmyard manure also increases the p mineralization as the incubation days increases. As the days of incubation increase the due to microbial activity degradation of farmyard manure increases [46].The biochar amendment lowers nitrogen and phosphorus losses in soil by absorbing and retaining NO_3-N, NH_4-H, and phosphate for longer time [47].

CONCLUSION

In a laboratory incubation experiment, it was noted that the treatment receiving both organic sources (compost and poultry manure) along with mineral fertilizer show higher levels of CO_2 emissions, microbial biomass carbon and nitrogen, and N and P mineralization. This variation in outcomes can be attributed to the differential mineralization and decomposition rates of organic sources, leading to distinct nutrient release patterns in soil solutions over time. The diverse performance of different organic sources in supporting plant growth can be attributed to their varying decomposition rates. The temporal dynamics of nutrient release from these organic sources contribute to their differential impacts on soil and plant-related parameters, highlighting the complexity of organic matter interactions in soil ecosystems.

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