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Research Article

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The Effect of Different Organic and Inorganic Fertilizer Applications on Soil Carbon Budget of the Soybean Crop Under Long-Term Field Conditions

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ABSTRACT
The study aims to investigate the effects of different organic and inorganic fertilizer applications on SOC content. A long-term field experiment was conducted in 1996 at the Cukurova University field site (37° 0'55.53"N 35° 21'20.56"E), in the same experiment, inorganic fertilizer (NPK), animal manure (25 t ha^{-1}), compost (25 t ha^{-1}), and mycorrhizal compost (10 t ha^{-1}) were applied as a regular procedure. To verify the hypothesis, the same trial area (long-term organic and inorganic fertilizer applications) was repeated with different plants (soybean planted) in 2023 and after harvest, soil samples were taken (from 0-15 and 15-30 cm soil depth) and total and soil organic carbon analysis was performed. The results showed that SOC concentrations in soybean-planted plots were measured at depths of 0-15 cm and 15-30 cm % 1.18 and % 1.11 as in control plots, respectively, while carbon concentrations at the same depths in animal manure-applied plots were 1.71% and 1.48%, respectively. Overall, more SOC was retained in soybean plots treated with compost and compost+mycorrhiza. Statistical analysis, which also accounted for differences between experimental subjects, revealed significant differences in total C and SOC concentrations. At the 0-15 cm soil depth, compared to the control, the contributions were 23% for mineral fertilizer, 38% for animal manure, 36% for compost, and 43% for compost + mycorrhiza. Similar patterns were observed with lower percentages at 15-30 cm soil depth. Spore counts were significantly higher than those obtained with the control and mineral fertilizers. The animal manure application counted 44 spores/10g of soil at depths of 0–15 cm and 40 spores/10g of soil at depths of 15–30 cm, respectively, while the mycorrhiza+compost application counted 77 spores/10g of soil and 33 spores/10g of soil, respectively. P_2O_5 was highest in the mineral fertilizer application (189.73 kg ha^{-1}) at the surface and in the animal manure application (141.50 kg ha^{-1}) at the lower depth. There is a positive correlation between spore counts and organic carbon values. This indicates that organic practices increase microbial activity, especially spore numbers. Increased microbial activity, as is well known, improves soil health, which indirectly reduces the adverse effects of climate change. Evaluation of organic fertilizers, including compost, compost + mycorrhiza, and animal manure, reveals significant benefits for sustainable agriculture and climate change mitigation.
Keywords: Soybean, Organic Carbon, Organic and inorganic fertilizers, Long-term experiment, Total Carbon

INTRODUCTION

Human life is fundamentally dependent on agricultural production, and therefore, sustainable agricultural production (Aznar-Sanchez et al., 2019). To produce the food needed for human nutrition, intensive, inappropriate soil and crop management practices are adopted in agricultural areas. This intensive, inappropriate crop and soil management reduces soil organic matter content. In other words, mineral fertilizers applied to the soil negatively affect soil health, reducing microbial activity and organic carbon content. This reduced organic matter and organic carbon, in turn, creates infertile soils. In short, intensive agricultural practices and uncontrolled fertilizer application have negatively impacted soil microbial activity and soil fertility (Aksahin et al., 2021). Continuous production on infertile soils requires constant fertilizer application, which is unsustainable, uneconomical, and harmful to the environment. As a result of disruptions to nature's mechanisms, the soil cannot fully function or retain the carbon dioxide it should. It's clear that some of the gas released into the atmosphere is a result of agricultural processes, and we need to reintroduce it to agriculture and reduce its amount in the atmosphere. Increasing the amount of organic carbon in soils and ensuring sustainable plant, soil, and crop management are crucial for reducing atmospheric CO_2 concentrations. Increasing CO_2 emissions into the atmosphere contribute to climate change Managing agricultural systems is crucial for reducing CO_2 emissions, which are considered the primary cause of global warming (Ortas, 2022). For proper soil management, organic material removed from the soil must be returned to the soil. Materials removed from the soil naturally become organic materials. As is known, adding organic matter to the soil significantly impacts soil carbon dynamics (Ortas et al., 2013) We can only provide this organic material through natural mechanisms, namely sustainable soil and plant management. In doing so, we need to utilize microorganisms and organic fertilizers, which are among nature's existing mechanisms. Consequently, they have a positive impact on soil carbon sequestration and the enhancement of soil fertility (Aksahin et al., 2021). Thanks to the organic material and symbiotic (mutually beneficial) relationship between mycorrhizae and plants, plants produce more biomass while simultaneously transferring carbon dioxide from the atmosphere to the soil through photosynthesis (Figure 1).

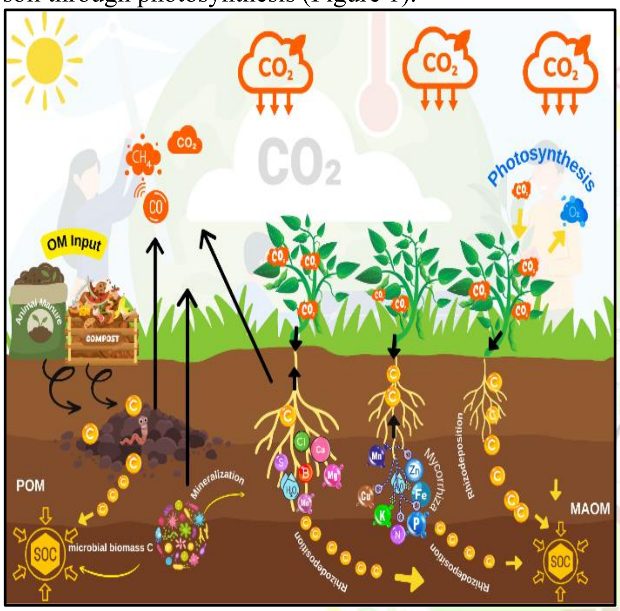

Figure 1. Effect of different organic fertilizers on SOC.
POM – Particulate Organic Matter (It is the "active, temporary organic matter" part.) MAOM – Mineral-Associated Organic Matter. (It is the "stable, long-lived organic matter" part.). Rhizodeposition is the release of organic compounds from plant roots into the surrounding soil. (This figure was created by the author using Canva)

Organic fertilizers applied to soil are crucial for enhancing the benefits of microorganisms and improving the soil's physical, chemical, and biological properties. Organic matter sources include compost, animal manure, stubble, biochar, leonardite, green manure, and humic acids (Gezgin, 2018).The most commonly used of these fertilizers, animal manure and compost, play a key role in the soil-plant-atmosphere relationship. In other words, the well-known organic fertilizers such as animal manure, compost and mycorrhizal fungi, make substantial contributions to the incorporation of organic materials into the soil (Aksahin et al., 2023).

The long-term application of organic fertilizers and the establishment of trials are crucial for sustainable agriculture. According to Mustafa et al. (2021), 28 years of organic and inorganic fertilization increased C-mineralization, corn biomass, and the physical preservation of SOC. They reported that this fertilizer application was the most effective strategy for improving crop biomass, C-mineralization, and soil fertility.

The study aims to predict that inorganic and organic fertilizers application (including mycorrhizal inoculation) will increase the soil total and organic carbon concentration and have a long-term impact on the soil carbon budget and mycorrhizae spore numbers. The tested hypothesis is that organic fertilizer sources applied to soil (including mycorrhizal inoculation) may increase soil organic Carbon and soil microbial activity, including mycorrhizal spores.

MATERIALS AND METHODS

The experiment was established at Typic Xerofluvents (Menzilat soil series) in 1996 and continues to this day. The experiment is located on the Research Farm of Cukurova University in the Eastern Mediterranean region of Turkiye. The experiment consisted of 15 plots with five different treatments and three replicates. An image of the experiment's plot and treatments is shown in Figure 2. And soil properties are shown in Table 1. Annually, organic fertilizers (animal manure, compost, and compost + mycorrhizae) were uniformly spread on the soil surface just before sowing and incorporated into the 0-15 cm surface layer with a disc harrow. Mixed mycorrhizae were used and applied at a rate equivalent to 100 mycorrhizal spores per plant. This calculation was made on a hectare basis. Similar tillage practices were followed for all the treated plots. Soybean seeds were planted at 2023 as a test plant.

The experiment was conducted using a randomized complete block design with five treatments and three replications. Each experimental plot measured 10m×20m, corresponding to an area of 200 m². The treatments included:

Control (no fertilizer application),

Mineral fertilizer, supplying 100 kg N ha^{-1} as $(NH_4)_2SO_4$, 26 kg P ha^{-1} as $Ca(H_2PO_4)_2 \cdot H_2O$ and 83 kg K ha^{-1} as K_2SO_4,

Animal manure applied at a rate of 25 t ha^{-1} (fresh weight basis),

Compost applied at 25 t ha^{-1} Compost,

Compost applied at 10 t ha^{-1} Compost in combination with mycorrhiza.

Soil samples were taken from 2 different depths (0-15 cm and 15-30 cm) for each plot.

Soil samples were air-dried, ground, and passed through a 2 mm sieve for soil analysis. Also, for determining total carbon (C) concentrations and nitrogen (N), the soil was further ground and sieved through a 0.25-mm sieve. Soil samples were analyzed by the dry combustion method at 900 °C using a C and N elemental analyzer (Fisher-2000). Inorganic C was determined by measuring the total $CaCO_3$ content using a calcimeter (schibler type) device. Soil phosphorus analysis was conducted using the Olsen (1954) method, and soil mycorrhizal spore counts were conducted using the (Gerdemann and Nicolson, 1963) method.

The SOC concentration was analyzed by subtracting soil inorganic C from total C (Ortas et al., 2013; Ortas and Bykova, 2020).

The obtained data were analyzed with JMP16 Pro statistical software to assess the effects of different treatments and soil depths on soil properties. Treatment means were compared using the least significant difference test (P <0.05). Furthermore, Principal Component Analysis PCA) was made by XLSTAT Statistical Software, and correlation analyses were made by Origin Pro.

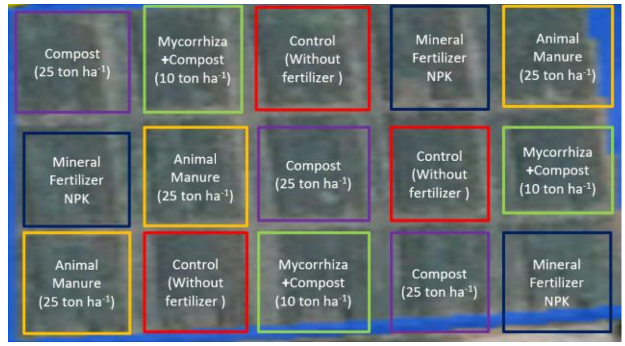

Figure 2. Experiment design, Amount and sequence of treatments used in the trial. (Mineral fertilizer, supplying 100 kg N ha⁻¹ as $(NH_4)_2SO_4$, 26 kg P ha⁻¹ as $Ca(H_2PO_4)_2 \cdot H_2O$ and 83 kg K ha⁻¹ as K_2SO_4,).

Table 1. Some pre-trial analyses of the soil and organic materials used.

Aplications	CaCO3		IC		TC		OC		OM		TN		P	
	%												kg da^{-1}	
Control	27,2	±0,10	3,26	±0,01	4,43	±0,04	1,17	±0,03	2,01	±0,04	0,16	±0,10	2,91	±0,49
Minral Fertilizer	27,5	±0,36	3,30	±0,04	4,83	±0,06	1,53	±0,03	2,63	±0,06	0,21	±0,00	10,19	±3,50
Animal Manure	27,1	±0,30	3,25	±0,04	5,69	±0,28	2,44	±0,25	4,20	±0,43	1,03	±1,32	28,66	±5,23
Compost	27,4	±0,46	3,29	±0,05	5,34	±0,33	2,05	±0,38	3,53	±0,66	0,24	±0,04	8,90	±2,81
Compost+ Myco.	27,4	±0,15	3,29	±0,02	5,15	±0,32	1,86	±0,34	3,21	±0,58	0,26	±0,04	4,20	±0,85

	C-WEOC (mg C/kg soil)		H-WEOC (mg C/kg soil)		SEOM (mg soil)	C/kg	MBC (mg C/kg soil)		pH		EC (µS/cm)		MWD (mm)		WSA (%)	
Control	35,2	±10,13	93,8	±30,07	47,7	±23,98	470,5	±78,78	8,18	±0,07	178,4	±55,51	1,77	±0,21	73,8	±10,29
Minral Fertilizer	47,1	±24,10	114,0	±24,61	45,2	±11,69	587,7	±57,77	8,11	±0,04	169,7	±17,42	1,78	±0,59	78,5	±14,05
Animal Manure	56,0	±37,14	134,3	±9,97	39,9	±19,87	526,4	±186,35	7,95	±0,15	176,5	±307,33	2,82	±0,46	81,0	±1,56
Compost	44,7	±8,47	130,1	±26,82	42,1	±15,66	439,2	±198,69	8,18	±0,09	156,3	±12,77	2,34	±0,05	88,2	±4,91
Compost+Myco.	46,0	±1,24	94,1	±29,51	52,6	±19,43	815,9	±22,43	8,20	±0,04	183,7	±60,92	2,27	±0,40	81,2	±6,51

Material	CaCO3	IC	TC	OC	TN	P2O5	pH	EC
	%							(MS/cm)
Animal Manure	6,26	0,75	20,60	19,85	1,96	0,15	7,56	10,59
Compost	7,51	0,90	21,35	20,45	0,98	0,25	7,51	4,18

Mean of three replicates ±SD. C-WEOC (mg C/kg soil): Cold water–extractable organic carbon, H-WEOC (mg C/kg soil): Hot water–extractable organic carbon, SEOM: Soluble/extractable organic matter, MBC: Microbial biomass carbon, MWD (mm): Mean weight diameter, WSA (%): Water stable aggregates

RESULTS AND DISCUSSION

Phosphorus and Soil Mycorrhizal Spore Count

Phosphorus and mycorrhizal spore counts are shown in Figure 3. When comparing mycorrhizal spore counts from long-term organic and inorganic fertilizer applications, a statistically significant difference ($p<0.011$) was found between the means at 0–15 cm depth at the 5% level.

The highest spore count was obtained in the Compost + AMF treatment at a depth of 0–15 cm, with 77 spores/10 g of soil. The highest value at a depth of 15–30 cm was determined in the Animal Manure treatment, with 40 spores/10 g of soil. Consequently, it was determined that organic animal manure significantly increased microbial biomass and activity (Nur et al., 2007).

When P_2O_5 values were examined, statistically significant differences were found between the treatments at both depths ($p<0.020$ at 0–15 cm, $p<0.007$ at 15–30 cm). At a depth of 0–15 cm, the highest P_2O_5 content was 189.73 kg P_2O_5 ha^{-1} in the mineral fertilizer application, followed by 175.92 kg P_2O_5 ha^{-1} in the animal manure application. At a depth of 15–30 cm, the highest P_2O_5 was 141.50 kg P_2O_5 ha^{-1} in the animal manure application. The reason for the difference in phosphorus at different depths is thought to be due to the higher P_2O_5 at 0–15 cm, which is due to the mineral fertilizer remaining soluble on the surface, while the higher P at 15–30 cm is due to the animal manure being in organic form and being transported to deeper depths over time. Mycorrhizae are also thought to be more abundant in the topsoil, at a depth of 0–15 cm, due to root density and probably oxygen abundance. When the mycorrhizae and phosphorus results are examined together, the negative relationship between phosphorus and mycorrhizae is explained by the fact that mycorrhizae are suppressed under high phosphorus conditions. Studies have shown that soil P supply exceeding the plant's P requirements can inhibit mycorrhizal development (Grant et al., 2005), but moderate soil P availability does not significantly inhibit root colonization (Cely et al., 2016).

In recent studies on maximizing the nutrient value of animal manure after mineral fertilizer, it is also reported that using organic matter sources, especially in areas with low organic matter content, can improve fertilizer efficiency by increasing available phosphorus (Ceylan et al., 2003). According to Aksahin et al. (2023) the highest soil total organic carbon, total nitrogen, and P_2O_5 concentrations were obtained in plots where animal manure was applied. Erdal and Aydemir (2003) reported that rose pomace applied at increasing doses resulted in significant increases in soil P content.

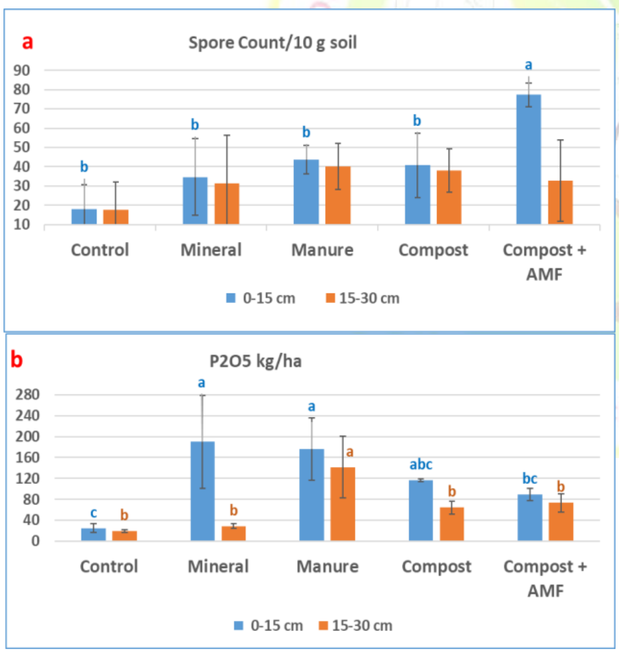

Figure 3. Effect of different organic and inorganic fertilizer applications on soil phosphorus and mycorrhizal spore count. a: Mycorrhiza spore count b:P_2O_5 of soil (Lines above the bars indicate ±SD.) (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha^{-1} as $(NH_4)_2SO_4$, 26 kg P ha^{-1} as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha^{-1} as K_2SO_4, animal manure: 25 t ha^{-1} (fresh weight basis); compost: 25 t ha^{-1} Compost, compost+mycorrhiza; 10 t ha^{-1} Compost in combination with mycorrhiza).

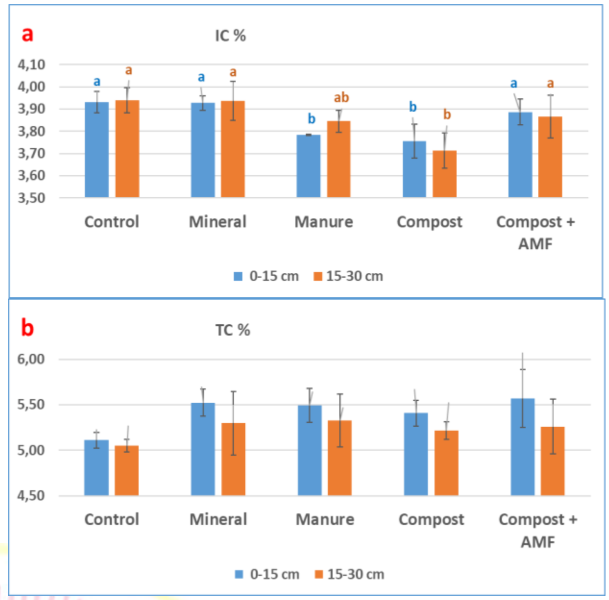

Figure 4. Effect of different organic and inorganic fertilizer applications on soil total carbon. a: Soil inorganic carbon b: Soil carbon (Lines above the bars indicate ±SD.) (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha^{-1} as $(NH_4)_2SO_4$, 26 kg P ha^{-1} as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha^{-1} as K_2SO_4, animal manure: 25 t ha^{-1} (fresh weight basis); compost: 25 t ha^{-1} Compost, compost+mycorrhiza; 10 t ha^{-1} Compost in combination with mycorrhiza).

Soil Carbon Concentration

When inorganic carbon (IC) ratios were examined (Figure 4), statistically significant differences at the 5% level were found between the treatments at depths of 0–15 cm and 15–30 cm. The highest IC values at both depths were observed in the control and mineral fertilizer treatments, ranging from 3.93 to 3.94%. No statistically significant difference was found in total carbon (TC) values at either depth. However, when average values were examined, the highest TC content was found at the 0–15 cm depth in the compost + AMF treatment at 5.57%, and at the 15–30 cm depth in the animal manure treatment at 5.33%. Generally, inorganic carbon was higher in the mineral fertilizer and control treatments, while total carbon was relatively higher in treatments supplemented with organic fertilizers and the mycorrhizae treatment. A study showed that the addition of fresh organic matter resulted in a rapid increase in the soil organic carbon fraction, while inorganic carbon remained unchanged (Ahmed et al., 2024). These results indicate that organic material and mycorrhizae support a greater fraction of organic carbon in the soil carbon cycle, while mineral fertilizers maintain the inorganic carbon ratio. According to Aksahin et al. (2023) the highest soil total organic carbon was obtained in plots where animal manure was applied. In studies conducted by Ortas et al. (2013), it was reported that animal manure, compost, and compost+mycorrhiza applications applied to soil increased OC values compared to controls, and that adding organic matter to soil significantly affected soil carbon dynamics, such as the soil carbon pool. Furthermore, long-term organic fertilizer application has been reported to increase soil TC and TOC concentrations and the total carbon pool more than the control application. Increasing the amount of organic carbon in the soil has a positive effect on plant growth, and, consequently, reducing atmospheric CO_2 concentration is extremely important (Aksahin et al., 2021).

Total Soil Organic Carbon

When examining organic carbon (OC) levels, a statistically significant difference of 5% was found between treatments at 0–15 cm (p=0.041), whereas the difference at 15–30 cm was not significant (p=0.279). The highest OC value was found in the animal manure treatment at a depth of 0–15 cm, at 1.71%, followed by compost and compost + AMF treatments. The highest value was measured in the compost treatment at 15–30 cm depth, at 1.50%.

When evaluating total organic carbon (TOC) levels, a significant difference of 5% was observed between treatments at 0–15 cm (p=0.022), whereas the difference was insignificant at 15–30 cm (p=0.487). The highest TOC value was obtained in the compost + AMF application at 0–15 cm depth (36.17 Mg/ha) and in the animal manure application at 15–30 cm depth (33.10 Mg/ha; Figure 5). In one study examining the relationship between mycorrhiza and organic carbon, (Aksahin and Ortas, 2024) reported that applications with Funneliformis mosseae followed by native mycorrhizal spores resulted in an increase in soil organic carbon (OC) concentration compared to control treatments. The addition of organic matter increased soil organic carbon, thereby positively affecting the soil organic carbon stock. In their studies, Ortas et al. (2013) reported that applications of animal manure, compost, and compost + mycorrhiza to soil increased OC values compared to the control. Additionally, animal manure application resulted in significant increases in total soil carbon (TC), organic carbon (OC), and particulate organic matter (POM) (Ahmed et al., 2024). Adding organic matter to soil significantly affected soil carbon dynamics, such as the soil carbon pool. Malhi et al. (2006) reported that TOC was lower in stubble-free areas compared to stubble-applied areas. Similarly, Bokhtiar and Sakurai (2005) reported that applying organic fertilizer to soil would increase soil organic carbon content. Batjes (1996) stated that projected global warming could significantly affect the size of the soil organic carbon pool and directly influence atmospheric greenhouse gas concentrations. Finally, in their study (Aksahin et al., 2023); Aksahin et al. (2021), it was reported that long-term organic fertilizer application increased the TC and TOC concentrations and the total carbon pool in the soil more than the control application and in addition, increasing the amount of organic carbon in the soil has a positive effect on plant growth and, as a result, reducing atmospheric CO_2 concentration is extremely important and organic fertilizers should be used in agriculture to increase the carbon budget of the soil and ensure adequate food security.

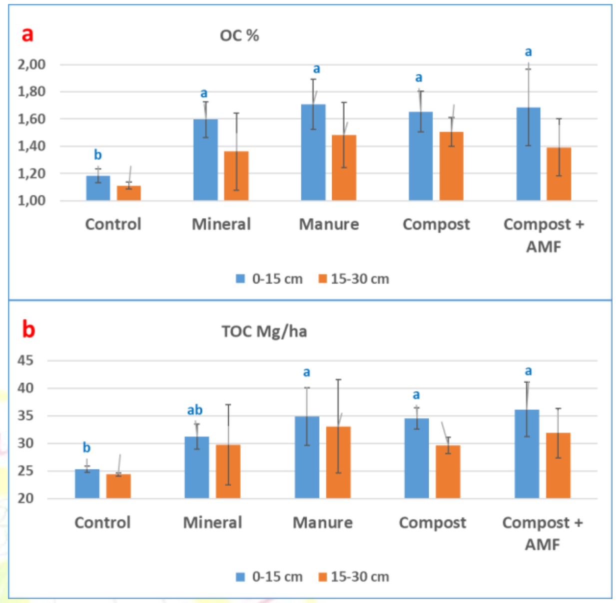

Figure 5. Effect of different organic and inorganic fertilizer applications on soil total organic carbon. a: Soil organic carbon b: Soil total organic carbon (Lines above the bars indicate ±SD.) (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha^{-1} as $(NH_4)_2SO_4$, 26 kg P ha^{-1} as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha^{-1} as K_2SO_4, animal manure: 25 t ha^{-1} (fresh weight basis); compost: 25 t ha^{-1} Compost, compost+mycorrhiza; 10 t ha^{-1} Compost in combination with mycorrhiza).

Correlation Between Soil Parameters

The correlation between the values obtained from post-harvest soil analyses in a soybean field following organic and inorganic fertilizer applications (Figure 6). When the correlation graph is examined, the relationships between carbon, mycorrhiza (spore count), and phosphorus are clearly evident. Strong and positive correlations were observed between organic carbon (OC), total carbon (TC), and total organic carbon (TOC) values. In contrast, a significant negative correlation was observed between mycorrhizal spore count and phosphorus (P_2O_5); This suggests that mycorrhizal colonization is suppressed in environments with increased phosphorus levels, while mycorrhizal activity increases under low phosphorus conditions (Figure 3). Furthermore, the weak but positive correlations between carbon fractions and mycorrhizae suggest that mycorrhizae indirectly support organic matter turnover and carbon accumulation in soil. Overall, the results indicate that mycorrhizal activity decreases under high phosphorus conditions, while organic matter and carbon accumulation are maintained more evenly by the presence of mycorrhizae.

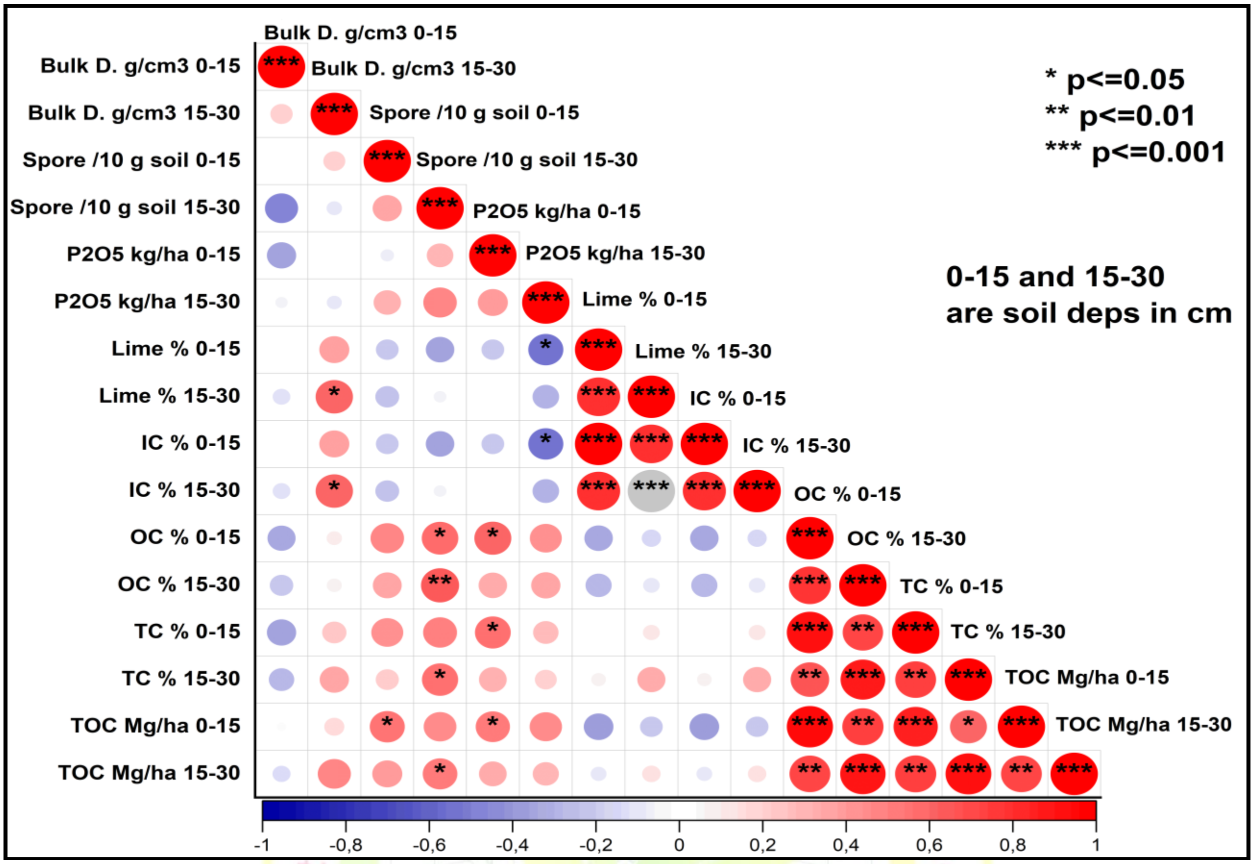

Figure 6. Correlation analysis of soil parameters obtained from the effects of different organic and inorganic fertilizer applications.

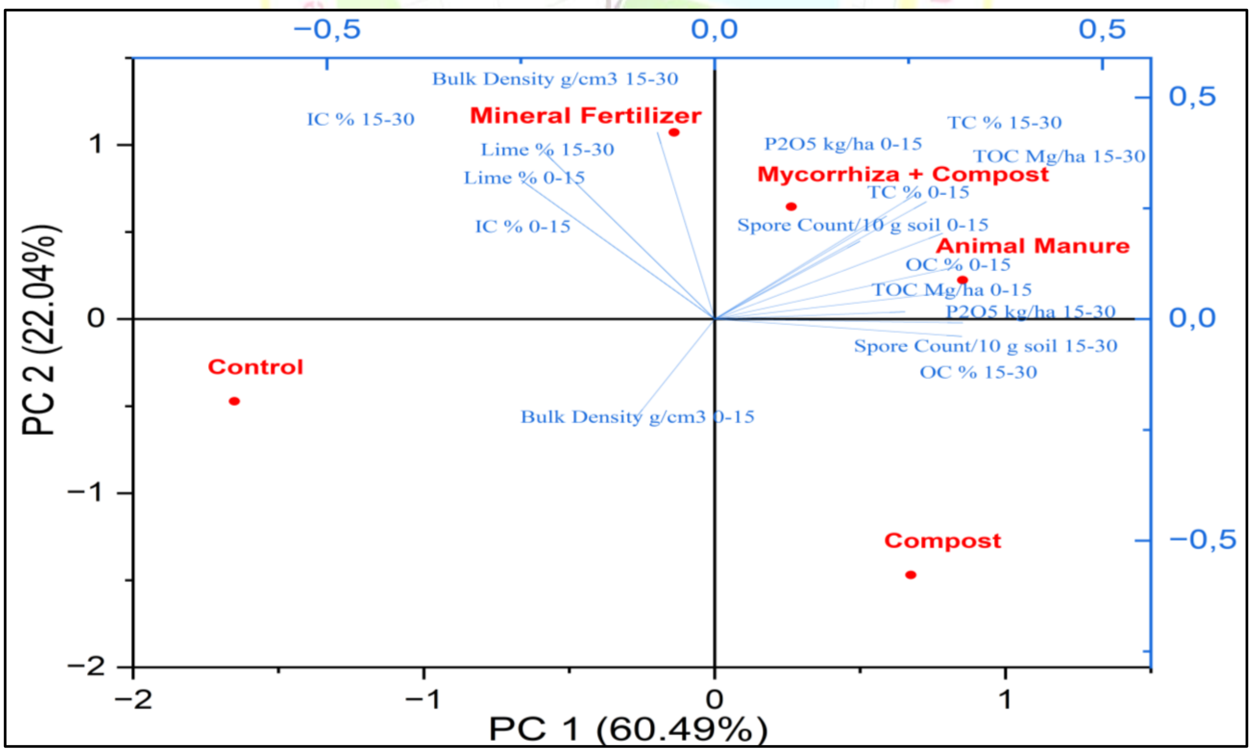

Figure 7. PCA analysis of soil parameters obtained from the effects of different organic and inorganic fertilizer applications. (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha^{-1} as $(NH_4)_2SO_4$, 26 kg P ha^{-1} as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha^{-1} as K_2SO_4, animal manure: 25 t ha^{-1} (fresh weight basis); compost: 25 t ha^{-1} Compost, compost+mycorrhiza; 10 t ha^{-1} Compost in combination with mycorrhiza).

PCA Analysis of Soil Parameters

The PCA analysis is presented in Figure 7. According to the PCA analysis, PC1 explains 60.49% of the total variance, and PC2 explains 22.04%, for a total of 82.53%. Mycorrhizae+Compost is linked to phosphorus (P_2O_5), total carbon, and spore count; animal manure is linked to increased organic carbon, total organic carbon, and phosphorus in the lower layers. Composting supports organic matter enrichment, but its effects are more pronounced in the superficial layer.

The Control group is most significantly different from the other treatments and is located furthest along the PC 1 axis. This indicates that the Control group has the lowest values for traits such as nutrients and organic matter content, which lie in the positive region. Mineral fertilizer application is positively associated with PC1 and PC2, particularly with soil density, lime, and inorganic carbon. Generally, organic practices (Compost, Animal Manure, Mycorrhizae+Compost) increase carbon, phosphorus, and microbial activity in the soil, while mineral fertilizers affect mineral fractions and do not contribute to organic recovery. Aksahin et al. (2021) reported that in a PCA analysis of the results of a previous study conducted in the same area, the control application was located on the negative side of the XY axis, far from all other applications. These results indicated that the control application had no effect on the trial results. However, organic fertilizer applications were associated with many measured parameters.

CONCLUSION

The effects of different organic and inorganic fertilizer applications on some post-harvest soil values in soybean-grown areas were examined, and the resulting values were presented in the form of items. The highest mycorrhizal spore counts were obtained at 0–15 cm depth (77 spores/10 g soil) in the Compost + AMF application and at 15–30 cm depth (40 spores/10 g soil) in the animal manure application. P_2O_5 was highest in the mineral fertilizer application (189.73 kg ha^{-1}) at the surface and in the animal manure application (141.50 kg ha^{-1}) at the lower depth. Total carbon and total organic carbon values were highest in the compost + mycorrhiza application at the surface and in the animal manure application at the lower depth. Organic carbon reached the highest values in the animal manure application (1.71%) at the surface and in the compost application (1.50%) at the lower depth.

A negative relationship was found between phosphorus and mycorrhizae, and mycorrhizal activity decreased at high phosphorus levels. PCA results indicated organic fertilizers are significantly different than mineral fertilizer. When the results are taken together, the continuous addition of organic matter to soils is extremely important for both plant and soil health. Organic matter not only serves as a direct source of organic carbon for the soil but also supports photosynthesis as it affects the development of plants, thus helping to store carbon dioxide gas in the atmosphere in the soil, which in turn helps to reduce the amount of carbon in the atmosphere and has a positive effect on global warming.

CONFLICT OF INTEREST

The author here declares there is no conflict of interest in the publication of this article.

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