International Journal of Agricultural and Applied Sciences, December 2025, 6(2): 68-77
https://www.agetds.com/ijaas
ISSN: 2582-8053
https://doi.org/10.52804/ijaas2025.6210

Research Article

OPEN ACCESS

The Effects of Long-Term Organic and Mineral Fertilizer Applications on the Mineral Nutrient Concentration and Carbon-Nitrogen Dynamics of Faba Beans

Veysi, Aksahin*, Mehmet Isık, Sadiye Kibritci and Ibrahim Ortas
Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Cukurova University, Adana-Türkiye
**Corresponding author e-mail: veysiaksahin@gmail.com*
(Received: 10/08/2025; Revised: 21/10/2025; Accepted: 30/10/2025; Published: 20/12/2025)

ABSTRACT
This study investigates the long-term effects of mineral and various organic fertilizer (animal manure, compost, and mycorrhizae) applications on yield, nutrient uptake, and soil properties of faba bean (*Vicia faba* L.). A long-term field experiment was established in 1996 at the Cukurova University Research Centre in Adana/Türkiye. Since then, for each cropping season: Control (no fertilizer), Mineral fertilizer (NPK), Animal Manure (25 t ha^{-1}), Compost (25 t ha^{-1}), and Compost (10 t ha^{-1}) + Arbuscular Mycorrhizal Fungi treatments were applied. In the present study, faba beans were grown in winter 2021 and harvested in spring 2022. At harvest, shoot and root dry weight, as well as seed yield, were measured. Plant tissue mineral nutrients were determined, and plant total nitrogen and carbon uptake were calculated. When dry weight data were examined, the highest values for shoot (11.35 t ha^{-1}), grain (9.77 t ha^{-1}), and total dry matter (22.23 t ha^{-1}) were obtained in the compost treatment, while the lowest values were 6.81, 5.32, and 13.09 t ha^{-1} in the control treatment, respectively. The highest nitrogen (N) concentration in plant tissues was 5.26% in compost+mycorrhiza treatment, while the highest grain nitrogen content was 0.37 t N ha^{-1} in compost application. In terms of carbon (C) accumulation, compost-treated plants stored 8.65 t C ha^{-1}, equivalent to 31.73 t CO_2 ha^{-1}. In comparison, control plots stored only 5.49 t C ha^{-1} (20.13 t CO_2 ha^{-1}). Fertilizer application significantly increases shoot K, P, and Zn concentrations, and root P and Zn concentrations. In conclusion, organic fertilizers, such as compost and animal manure, have a positive influence on both plant yield and nutrient quality. These results demonstrate that long-term organic fertilization significantly enhances biomass, seed yield, and mineral nutrient concentration, especially under compost and compost + mycorrhizae treatments. Organic fertilizers fixed significantly more CO2 than control treatments, which is important for combating climate change driven by greenhouse gases.
Keywords: Faba bean, root infection, organic and mineral fertilizer, carbon fixation, nitrogen, yield

INTRODUCTION
Mineral fertilizer applications to soil have negatively impacted soil health, leading to decreases in organic carbon and soil microbial carbon (SMC) due to reduced microbial activity. Excessive mineral nitrogen application has been reported to reduce soil microbial diversity, possibly by creating an acidic soil environment due to high ammonium concentrations (Zhang et al., 2015). The intensive exploitation of agricultural lands has negative impacts on sustainability, reducing soil organic matter and increasing CO2 and other greenhouse gas emissions into the atmosphere. Before the Industrial Revolution, atmospheric CO_2 concentration was 280 ppm (Ortas et al., 2017), reaching 420 ppm in 2022 (SOEST, 2022). This decreased organic matter and organic carbon creates infertile soils. As a result, intensive agricultural practices and uncontrolled fertilizer applications have negatively impacted soil microbial activity and soil fertility (Aksahin et al., 2021). As a result of disruptions to natural mechanisms, the soil cannot fully function or retain the carbon dioxide it should. It is clear that some of the gas released into the atmosphere results from agricultural processes, and we need to reduce its amount by returning it to agriculture. Increasing organic carbon reserves in soils and ensuring sustainable management of plants, soils, and crops are vital for reducing atmospheric CO_2 concentrations. For proper soil management, the organic matter removed from the soil must be returned to the soil. As is known, adding organic matter to the soil significantly impacts soil carbon dynamics (Ortas et al., 2013).

We can only provide this organic matter through natural mechanisms, namely sustainable soil and plant management. In doing so, we must utilize microorganisms and organic fertilizers, which are part of natural processes. This has positive effects on soil carbon sequestration and increased soil fertility (Aksahin et al., 2021), one of these natural mechanisms is mycorrhizae. Thanks to the symbiotic (mutually beneficial) relationship between plants and mycorrhizae, plants produce more biomass while simultaneously transferring carbon dioxide from the atmosphere to the soil through photosynthesis (Figure 1). In addition to mycorrhizae, we also need to recycle organic waste into soils. Long-term application of organic fertilizers rather than inorganic fertilizers will increase soil microbial activity and add organic carbon. Adding organic matter to soil significantly affects soil carbon dynamics, including the soil carbon pool (Ortas et al., 2013).

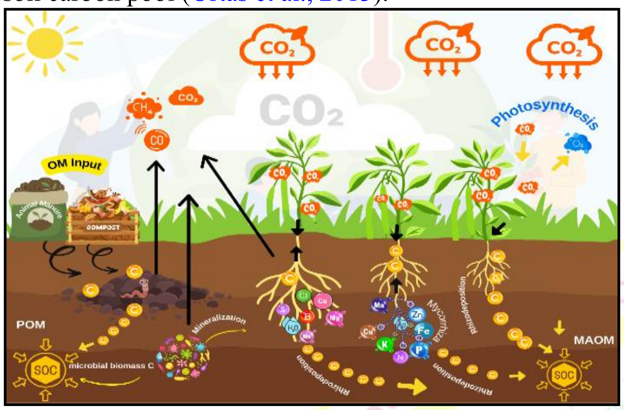

Figure 1. Effect of different organic fertilizers on SOC.
This figure was created by the author using Canva. MAOM – Mineral-Associated Organic Matter. (It is the "stable, long-lived organic matter" part). POM – Particulate Organic Matter (It is the "active, temporary organic matter" part). Rhizodeposition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

The study aims to increase the total biomass, carbon content, and nitrogen content of faba bean plants by applying inorganic and organic fertilizers (including mycorrhizal inoculation) to the legume before planting. This increase also aims to increase CO_2 fixation by the plant. The hypothesis tested was that organic fertilizer sources (including mycorrhizal inoculation) applied to soil can increase plant biomass, nutrient concentration, carbon-nitrogen content, and the amount of CO2 the plant can retain.

MATERIALS AND METHODS

The experiment was established in 1996 and continues to this day at Typic Xerofluvents (Menzilat soil series). The trial is conducted on the Research Farm of Cukurova University, located in the Eastern Mediterranean region of Turkey. 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 (compost, animal manure, and compost + mycorrhizae) were uniformly spread on the soil surface just before sowing and incorporated into the 0-15 cm surface layer using a disc harrow. Similar tillage practices were followed for all the treated plots. Faba Bean was planted as a crop.

The experiment was arranged in a randomized complete block design (RCBD) with five treatments and three replications. Each plot covered an area of 200 m² (10 m × 20 m). The treatments consisted of a control with no fertilizer application; a mineral fertilizer treatment 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; an animal manure treatment applied at 25 t ha^{-1} on a fresh weight basis; a compost treatment applied at 25 t ha^{-1}; and a combined treatment of compost at 10 t ha^{-1} together with mycorrhiza. Mixed mycorrhizae spors were used and applied at a rate equivalent to 100 mycorrhizal spores per plant. This calculation was made on a hectare basis. In the present study, faba beans were grown in winter 2021 and harvested in spring 2022.

At the end of the experiment, the shoots, roots, and grains were harvested together and dried in a 70° oven. The dry weights of the green parts, roots, and grains were then taken, and the green parts were ground and prepared for analysis. K, P, and Zn analyses were performed in homogenized samples using an inductively coupled plasma optical emission spectrometer (ICP-OES) on extracts obtained by dry digestion Kacar and Inal (2008). Carbon and nitrogen analyses were performed on the samples prepared for analysis at 900°C using a C-N elemental analyzer (Fisher-2000).

The obtained data were analysed using Tukey's test in JMP16 Pro to evaluate the effects of different treatments. Graphical plots, correlation, and principal component analysis (PCA) were created using Origin Pro and visual plots were created using Canva visualization software.

Figure 2. Experiment design, Amount and sequence of treatments used in the trial. (Mineral fertilizer, supplying

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 C/kg soil)		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

Dry Matter and Total Biomass

The effects of organic and inorganic fertilizer applications on dry matter yield of different faba bean parts are shown in Figure 3. When examining the root dry weight data, the differences between the averages were not statistically significant, while the dry weight data for green parts ($p<0.004$), grains ($p<0.004$), and total biomass ($p<0.0007$) were significant. The highest root dry weight value was 1.10 t ha^{-1} in the compost treatment, while the lowest value was 0.81 t ha^{-1} in the compost+mycorrhiza treatment. The highest dry weight value of the green parts was 11.35 t ha^{-1} in the compost treatment, while the lowest value was 6.81 t ha^{-1} in the control treatment. The highest grain dry weight value was 9.77 t ha^{-1} in the compost application, 8.14 t ha^{-1} in plots treated with animal manure, and 8.50 t ha^{-1} in plots treated with mineral fertilizer. The lowest value was 5.32 t ha^{-1} in the control application. The highest total biomass value was 22.23 t ha^{-1} in the compost application, while the lowest value was 13.09 t ha^{-1} in the control application. The current study was initiated in 1996 and continues under the fertilizer application guidelines specified in the method. Differences in nutrient and organic matter content occur periodically in compost and animal manure.

In the current study, compost application increased plant growth relatively more than animal manure. Because the nutrients provided by compost are not absorbed from plant tissues, as with animal manure, it appears to have played an active role in improving the physical, biological, and chemical properties of the soil through its effect on soil structure. Alzamel et al. (2022) conducted a study on the effects of organic and inorganic fertilizer applications on sunflower yield. They reported that organic fertilizers increased plant growth and soil physical fertility due to their high nutrient content and stimulation of microbial activity. Yoldas et al. (2011) conducted a 2-year study of organic and inorganic fertilizer applications and reported that they increased onion plant yield and nutrient uptake. In the study, as animal manure doses increased, plant yield increased compared to the control, but onion yield was even higher in the second year. Naturally, the role of organic fertilizers in accumulating over time can be emphasized. Therefore, monitoring the effects of long-term organic fertilizer applications is of great importance both ecologically and economically. Abedi et al. (2010) reported that compost application could be an alternative to mineral fertilizers in wheat cultivation. Ayoola and Makinde (2009) stated that animal manure, with its N and P content, could be an alternative to mineral fertilization in corn cultivation. In another study, Heeb et al. (2006) reported that organic fertilization was less effective than mineral fertilization in tomato plant development under greenhouse conditions. Concentrated, ready-mixed, water-soluble mineral fertilizers may have a greater, more rapid effect under greenhouse conditions.

Plant K, P, and Zn Concentration

Post-harvest plant tissue analysis revealed the highest potassium levels in the upper parts (Table 2) in plots treated with 4% animal manure. in comparison, the lowest was achieved in the control treatment at 3.17%. However, the highest relative potassium concentration was recorded in the roots at 4.61% with compost and

4.60% with animal manure. Similarly, Güzel et al. (2002) reported that the plant-sufficient K concentration ranged from 0.5% to 6.0% K in their study. The data obtained in our study are within this range, supporting our research findings.

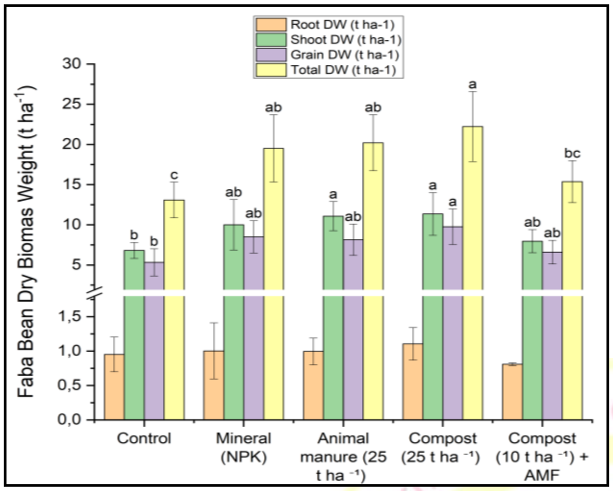

Figure 3. Effect of different organic and inorganic fertilizer applications on dry matter and biomass (Lines above the bars indicate ±SD.) (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha^{-1} as $(NH_4)_2SO_4$, 26 kg P ha^{-1} as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha^{-1} as K_2SO_4.

Table 2 examines the long-term effects of different organic and inorganic fertilizer applications on phosphorus concentration in various plant parts. The phosphorus concentration in the treatments is statistically significant, and organic fertilizers have higher %P concentrations than the control and inorganic fertilizer applications.

The highest %P values in postharvest green tissue were obtained in animal manure (0.261%), compost (0.20%), mineral fertilizer (0.19%), compost+mycorrhiza (0.17%), and control (0.14%) treatments. The highest phosphorus concentration in root tissues, similar to the top layer, was measured in the animal manure treatment (0.20%). The highest phosphorus concentration in grains was measured in the control plots (0.31%) and in plots with mineral fertilizer (0.42%). The required adequate P concentration in the plant is between 0.1% and 0.5% Güzel et al. (2002). In our study, P concentrations in different parts of the faba bean plant were within the determined optimum ranges.

In terms of zinc (Zn) concentrations in plant tissues, the application of organic fertilizers increased the root and grain concentrations of faba bean plants, and this increase was statistically significant (Table 2). Zn concentrations in the aerial tissues varied significantly, with the compost+mycorrhiza treatment showing the highest value at 13.92 mg Zn kg^{-1}, followed by the compost treatment at 12.35 mg Zn kg^{-1}. Zn concentrations in roots were generally below the critical value compared to root-surface and grain Zn concentrations. The highest concentration in root tissues was 6.43 mg Zn kg^{-1} in the animal manure treatment, and the lowest was 3.98 mg Zn kg^{-1} in the mineral fertilizer treatment. Zn concentrations in grains were similar to those in the root-surface tissues, ranging from 13.92 mg Zn kg^{-1} in the mineral fertilized plots to 11.10 mg Zn kg^{-1} in the control plots, with no statistically significant difference found between treatments According to some studies, the adequate Zn concentration in faba bean seeds ranges from 21.6 to 73.6 mg kg^{-1} (Nadgórska-Socha et al., 2013; Sileshi et al., 2022). The grain Zn concentrations obtained in our study are below this amount. It has previously been reported (Ortas, 2012a, 2019; Ortas et al., 2019) that nitrogen-fixing plants such as faba bean generally contain higher micronutrient concentrations than non-nitrogen-fixing plants. Therefore, organic fertilizers resulted in higher concentrations of P, K, and Zn in plant tissues than in the control and mineral fertilizers. This may also be due to the physical effects of long-term organic fertilizers on soil structure. Additionally, the beneficial nutrients contained in organic fertilizers may also have played a role (Li et al., 2007; Ortas and and Bykova, 2018). Kumar and Jat (2010) similarly stated that organic fertilizers improve plant nutrition due to their high nutrient concentrations.

Research results indicate that concentrations of macro- and micronutrients in plant tissues are generally higher under organic fertilizer applications, and these differences are statistically significant (Table 2). It has also been determined that compost and mycorrhiza applications increase the absorption of soil-limited nutrients such as P and Zn (Hayman, 1982; Ortas, 2012b). Incorporating plants such as faba beans into the system within the framework of sustainable agriculture can reduce fertilization requirements and enhance plant health, thereby creating both ecological and economic value.

Plant N Content and Total N

Post-harvest plant tissue N content (t N ha^{-1}) showed statistically significant differences between inorganic and organic fertilization treatments. When examining the N content data in grain, compost, animal manure, mineral fertilizer, compost + mycorrhiza, and control treatments, the following values were obtained: 0.37, 0.34, 0.33, 0.30, and 0.26 t ha^{-1}, respectively. Similar trends were observed in the upper part of the N content. The highest values were 0.42, 0.41, 0.39, and 0.30 t ha^{-1} in the compost, animal manure, mineral fertilizer, and compost+mycorrhiza treatments, respectively, providing higher results than the control. When examining root tissue N content, the lowest value was 0.01 t N ha^{-1} in the control, while the highest value was 0.03 t N ha^{-1} in the compost treatment, which was found to be statistically significant. Total N content in all plant tissues was 0.81, 0.75, 0.74, 0.61, and 0.53 t N ha^{-1} in the compost, mineral fertilizer, animal manure, compost + mycorrhiza, and control treatments, respectively (Figure 4).

Table 2. Effects of Inorganic and Organic Fertilizers on K, P, and Zn Concentrations in Plant Tissues

Applications	%K		
Control	Shoot	Root	Grain
Mineral Fertilizer (NPK)	3.23±0.35 c	3.40±1.63	3.05±1.24
Animal Manure (25 t/ha)	4.00±0.47 a	4.60±0.98	2.51±0.13
Compost (25 t/ha)	3.74±0.37 ab	4.61±0.61	2.49±0.27
Com. (10 t/ha) +Mycorrhiza	3.54±0.51 b	3.66±0.74	2.32±0.28
Significance Level	P<0.0008	ns	ns
%P			
Control	0.14±0.03 c	0.09±0.01 c	0.31±0.02
Mineral Fertilizer (NPK)	0.19±0.04 b	0.12±0.04 bc	0.42±0.13
Animal Manure (25 t/ha)	0.26±0.03 a	0.20±0.05 a	0.39±0.03
Compost (25 t/ha)	0.20±0.01 b	0.15±0.03 b	0.40±0.06
Com. (10 t/ha) +Mycorrhiza	0.17±0.01 bc	0.11±0.01 c	0.35±0.04
Significance Level	p<0.0001	p<0.0001	ns
Zn (mg kg^{-1})			
Control	9.80±1.42	3.83±0.89 cd	11.10±0.41
Mineral Fertilizer (NPK)	11.83±2.17	3.98±0.32 d	13.92±7.38
Animal Manure (25 t/ha)	11.08±1.99	6.43±1.30 a	11.32±1.48
Compost (25 t/ha)	12.35±2.81	5.12±0.84 bc	12.45±2.22
Com. (10 t/ha) +Mycorrhiza	13.92±1.84	5.78±0.87 ab	12.94±1.75
Significance Level	ns	P<0.0003	ns

Data represent the mean of three replicates. ± represents standard deviations. Letters indicate differences between means using the Tukey test. ns = not statistically significant. (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.

The significant increases observed in grain and aerial parts nitrogen under both mineral and organic fertilizer treatments confirm that externally supplied nutrients alleviate soil nitrogen limitations on vegetative and generative tissues. Although mineral fertilizer rapidly supplied N to aboveground tissues, compost application alone significantly increased root N content, suggesting that the gradual mineralisation under compost and the effect of organic matter on soil structure encouraged greater root proliferation and rhizosphere activity.

This is consistent with the findings of Balci et al. (2016), who reported that root N content in strawberry was higher with hazelnut shell-derived compost than with mineral fertilizer. The moderate nitrogen retention performance of the compost+mycorrhiza application may have limited short-term nutrient availability when the compost rate was reduced by 15 t per hectare. Although plant nitrogen content was similar with mineral fertilizer application, its potential to support belowground microbial communities or significantly contribute to soil organic matter was lower (Farooq et al., 2024). The concentration of N in plants was generally higher under organic fertilizer applications than under the control or mineral fertilizers. Previous studies have reported that organic fertilizer application resulted in higher nutrient concentrations in plant tissues compared to control and mineral fertilizer applications. In a study on this subject, Ozkan et al. (2013) reported that applying different types of organic and inorganic fertilizers in greenhouse pepper cultivation increased nitrogen content in pepper plants compared to the control. Ahmed et al. (2023) reported that under field conditions, the use of various organic and inorganic fertilizers, including compost + mycorrhizae and animal manure, increased nitrogen content in chickpea plants compared to the standard application. Specifically, samples treated with organic fertilizer were observed to have higher concentrations than the control. Furthermore, Akşahin et.al. (2021) reported that under the same field conditions, C and N concentrations were higher in plants fertilized with animal manure, compost, and compost + mycorrhizae than in the control application.

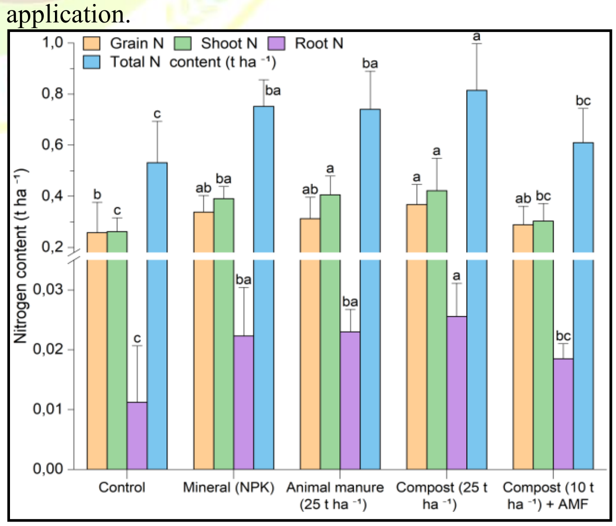

Figure 4. Effect of Different Organic and Inorganic Fertilizer Applications on Nitrogen (N) Content (Lines above the bars indicate ±SD.) (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha^{-1} as

$(NH_4)_2SO_4$, 26 kg P ha⁻¹ as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha⁻¹ as K_2SO_4.

Plant C Content and Total C

The carbon content in plant tissues (Figure 5) (t C ha⁻¹) and the corresponding CO_2-equivalent carbon sequestration (Figure 6) were calculated, and the differences between the averages obtained for all plant parameters as a result of the treatments were found to be statistically significant. The average carbon sequestration in the upper parts of plants treated only with mineral fertilizer (NPK), animal manure, or compost was 4.42 t C ha⁻¹, approximately 64% higher than the control group (2.69 t C ha⁻¹), and the compost+mycorrhiza treatment provided 3.33 t C ha⁻¹ of carbon sequestration.

Plant grain carbon also showed similar trends; Compost reached 3.88 t C ha⁻¹, mineral fertilizer, and animal manure reached approximately 3.48 and 3.32 t C ha⁻¹, respectively, all of which were significantly higher than the control group (2.49 t C ha⁻¹). Compost and mycorrhizae provided 3.70 t C ha⁻¹ of canopy carbon. Root carbon content increased the most with compost application (0.35 t C ha⁻¹), and was measured at 0.12 t C ha⁻¹ in the control application. Other fertilizer applications remained at approximately 0.30 t C ha⁻¹. As a result, total biomass carbon was obtained as 8.65, 8.07, 8.18, 6.44, and 5.49 t C ha⁻¹ for compost, animal manure, mineral, compost+mycorrhiza, and control treatments, respectively. C sequestration in CO_2-equivalent followed the same trend as total carbon (Figure 5), measuring 20.13 t CO_2 ha⁻¹ in the control group and 31.73 t CO_2 ha⁻¹ under the compost treatment. Compared to the control, compost, mineral fertilizer (NPK), animal manure, and compost+mycorrhiza treatments increased CO_2-equivalent sequestration in plant tissues by approximately 58%, 49%, 47%, and 17%, respectively (Figure 6). Fertilization treatments significantly increased carbon assimilation in the plant by providing the nutrients necessary to maintain photosynthetic rates. Organic fertilizers have shown that total carbon uptake is equal to or greater than that under mineral fertilization. At the same time, compost alone provided the highest increase in root carbon, which has been identified as a critical budget for soil organic matter formation and long-term soil fertility maintenance (Chirinda et al., 2012). The relatively low root carbon observed in compost + mycorrhiza application suggests that photosynthetic products are diverted to other sources such as mycorrhizal symbionts and aboveground structures rather than root biomass, which is consistent with studies by (Miller et al., 2002) and (Wang et al., 1989). In conclusion, the application of compost alone maximizes both C and N uptake and provides the highest CO_2 equivalent carbon sequestration. The research findings indicate a direct relationship between the higher biomass yield of faba bean under compost application and the C content retained in plant tissues. The long-term effects of organic fertilizers on both plant nutrition and soil physical fertility are valuable for climate-smart soil management. Organic fertilizers provide macro and micro nutrients that support long-term photosynthesis, whereas mineral fertilizer application has been interpreted as initially providing rapid but short-term benefits (Boutasknit et al., 2024). Furthermore, Chirinda et al. (2012) reported that C concentrations in root tissues were higher with organic fertilizers than with inorganic systems in spring barley and wheat cultivation. Furthermore, Akşahin et al. (2021) reported that C and N concentrations were higher in plants fertilized with animal manure, compost, and compost+mycorrhizae than in the control treatment under the same field trial conditions.

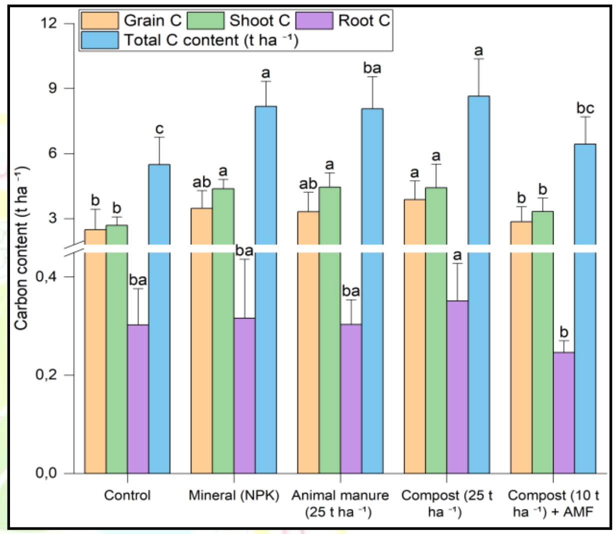

Figure 5. Effect of Different Organic and Inorganic Fertilizer Applications on Carbon (C) Content (Lines above the bars indicate ±SD.) (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha⁻¹ as $(NH_4)_2SO_4$, 26 kg P ha⁻¹ as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha⁻¹ as K_2SO_4.

Amount of Carbon Dioxide Captured by Plants

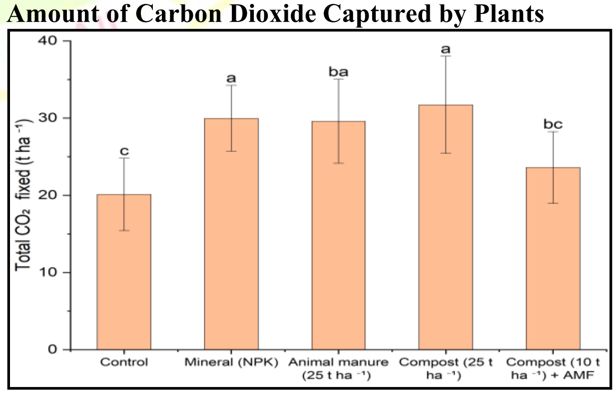

Figure 6. Effect of Different Organic and Inorganic Fertilizer Applications on Carbon Dioxide Capture (CO2) Content (Lines above the bars indicate ±SD.) (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha⁻¹ as $(NH_4)_2SO_4$, 26 kg P ha⁻¹ as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha⁻¹ as K_2SO_4.

Principal Component Analysis (PCA)
The principal component analysis (PCA) biplot illustrates (Figure 7), the relationships among treatments and measured variables based on the first two principal components, which together explain 84.79% of the total variance. The control is positioned on the negative side of PC1, indicating distinct characteristics compared to the other treatments, while the compost and animal manure treatments are located on the positive side, showing relatively similar response patterns. The substantial contribution of PC1 suggests that most of the variability among treatments is explained by the first component, with mineral fertilizer showing a clear separation toward the lower positive quadrant and animal manure toward the upper positive quadrant, implying different influences on the measured plant variables. The clustering of several variable vectors in the positive PC1 region suggests that compost, mineral fertilizer, and animal manure treatments enhanced multiple measured parameters relative to the control and compost + mycorrhiza treatments, which showed lower or distinct responses. A Principal Component Analysis (PCA) of the results from a previous study conducted in the same area reported by Aksahin et al. (2021) showed that 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 did not affect the trial outcomes. In contrast, organic fertilizer applications were associated with many of the measured parameters.

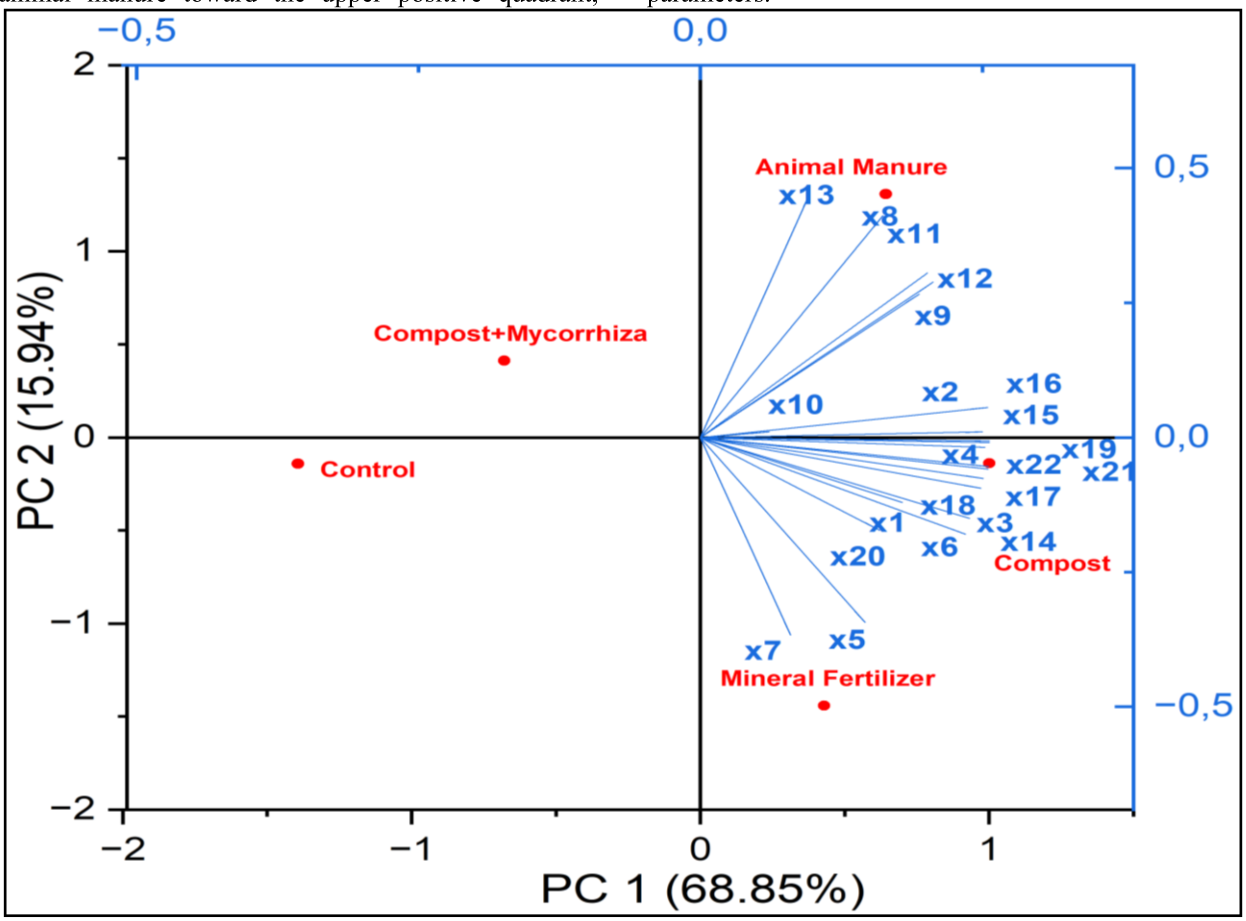

Figure 7. Effect of Different Organic and Inorganic Fertilizer Applications on PCA. (Control: (no fertilizer application), mineral fertilizer: 100 kg N ha⁻¹ as $(NH_4)_2SO_4$, 26 kg P ha⁻¹ as $Ca(H_2PO_4)_2 \cdot H_2O$, and 83 kg K ha⁻¹ as K_2SO_4, animal manure: 25 t ha⁻¹ (fresh weight basis); compost: 25 t ha⁻¹ Compost, compost+mycorrhiza; 10 t ha⁻¹ Compost in combination with mycorrhiza).x1: Root dry weight (ton ha⁻¹), x2: Shoot dry weight (t ha⁻¹), x3: Grain dry weight (t ha⁻¹), x4: Total dry weight (t ha⁻¹), x5: Grain K (%), x6: Grain P (%), x7: Grain Zn (mg kg⁻¹), x8: Shoot K (%), x9: Shoot P (%), x10: Shoot Zn (mg kg⁻¹), x11: Root K (%), x12: Root P (%), x13: Root Zn (mg kg⁻¹), x14: Grain N (t ha⁻¹), x15: Shoot N (t ha⁻¹), x16: Root N (t ha⁻¹), x17: Total N (t ha⁻¹), x18: Grain C (t ha⁻¹), x19: Shoot C (t ha⁻¹), x20: Root C (t ha⁻¹), x21: Total C (t ha⁻¹), x22: Total CO_2 (t ha⁻¹)

Correlation of Plant Parameter

An examination of the correlation results for all plant parameters below (Figure 8) shows that the plant's N and C values are highly and positively correlated. This strong relationship demonstrates that as N accumulation increases within the plant, C accumulation also increases in parallel, suggesting that structural and metabolic accumulation processes proceed in tandem. In particular, the parallelism between total C and CO_2 equivalents, as well as between total N, reflects the plant's C-conversion capacity due to increased biomass. Yield variables (x2 shoot, x3 grain, x4 total yield) also exhibit a significant positive correlation with both nitrogen and carbon parameters. As shoot and grain yields increase, both N contents and C fractions increase significantly. This suggests that increased plant growth rate and tissue formation simultaneously stimulate nutrient uptake (especially N) and C storage. Overall, the graph's correlation structure reveals that the nitrogen-carbon-yield triad exhibits a close, convergent, and strongly positive relationship. This pattern suggests that increased yield not only increases biological growth but also the plant's N accumulation and C storage capacity. That is, all key functional indicators in the system—yield, N accumulation, C accumulation, and CO_2 equivalent—form a network of interactions that increase together and consistently.

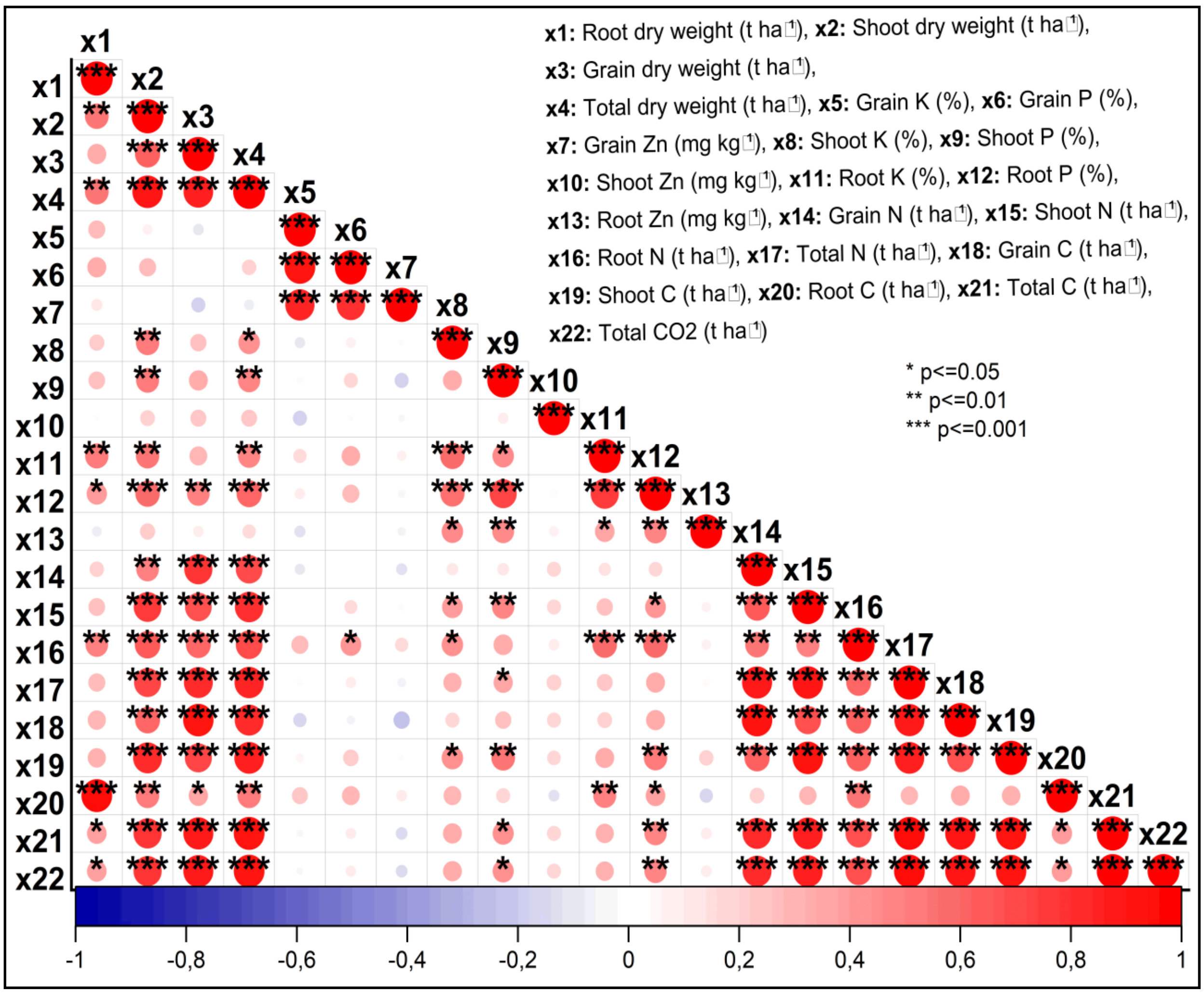

Figure 8. Correlation graph between all parameters of the faba bean plant following different organic and inorganic fertilizer applications. x1: Root dry weight (ton ha^{-1}), x2: Shoot dry weight (t ha^{-1}), x3: Grain dry weight (t ha^{-1}), x4: Total dry weight (t ha^{-1}), x5: Grain K (%), x6: Grain P (%), x7: Grain Zn (mg kg^{-1}), x8: Shoot K (%), x9: Shoot P (%), x10: Shoot Zn (mg kg^{-1}), x11: Root K (%), x12: Root P (%), x13: Root Zn (mg kg^{-1}), x14: Grain N (t ha^{-1}), x15: Shoot N (t ha^{-1}), x16: Root N (t ha^{-1}), x17: Total N (t ha^{-1}), x18: Grain C (t ha^{-1}), x19: Shoot C (t ha^{-1}), x20: Root C (t ha^{-1}), x21: Total C (t ha^{-1}), x22: Total CO_2 (t ha^{-1})

CONCLUSION

Long-term application of organic (compost and animal manure) and inorganic (mineral) fertilizers to the soil resulted in significant increases in biomass yield, macro- and micronutrient concentrations, nitrogen (N), and carbon (C) retention in faba bean plants. Compost application, in particular, stood out as the practice that maximized biological growth, increased nutrient uptake and retention the most, and thus improved both plant health and soil quality. Organic fertilizers applications significantly increased overall biomass and grain yield. Compost and animal manure provided the most significant nutrient and yield increases, and N, P, and K concentrations were higher in plant tissues than in the control group.

The control group performed least well in all parameters, including C concentration. Plant yield variables (grain and shoot) were highly and positively correlated with nitrogen (N) and carbon (C) content. This finding confirms that increased biological growth simultaneously directly increases nutrient uptake (N) and carbon storage capacity (C). Compost and animal manure applications showed relatively similar and enhancing response patterns on the measured parameters, clustering on the positive side of PC1, while mineral fertilizer was in a different positive sub-quadrant.

Organic fertilizers have a long-term effect by improving soil structure. Organic fertilizers such as compost and animal manure provide organic structure and, consequently, increased soil organic carbon, thereby protecting against climate change and the greenhouse effect. They have also become a strong alternative to mineral fertilization.

CONFLICT OF INTEREST

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

ACKNOWLEDGEMENT

This work was supported by PRIMA SHARING-MED-2211. Research also supported by Cukurova University Scientific Research Unit, Project no: FYL-2023-15931.

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Citation: Aksahin, Veysi; Isık, Mehmet; Kibritci, Sadiye and Ortas Ibrahim 2025. The Effects of Long-Term Organic and M ineral Fertilizer Applications on the Mineral Nutrient Concentration and Carbon-Nitrogen Dynamics of Fava Beans. *International Journal of Agricultural and Applied Sciences,* 6(2): 68-77. https://doi.org/10.52804/ijaas2025.6210