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Effect of Adopting the Integrated Soil Fertility Management (ISFM) Concept on Some Fertility Properties of Calcareous Soil and Broccoli Yield

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ABSTRACT: A Field Experiment was conducted to study the effect of adopting the Integrated Soil Fertility Management (ISFM) concept on some fertility properties of soil. The field trial for the 2023-2024 agricultural season was carried out in an agricultural field located in Al-Suwaira District, Wasit Governorate. The experiment used a Randomized Complete Block Design (RCBD) with three replications, based on a Split Plot Design system. The first factor included two types of soil amendments: Gypsum (G) and Sulfur (S). The second factor consisted of three levels of fertilization recommendations: 0% (F0), 100% (F1), and 125% (F2). The fertilization recommendation was as follows: 100 kg ha^{-1} of N, 100 kg ha^{-1} of P_2O_5, and 100 kg ha^{-1} of K_2O. The third factor included three types of organic amendments: Green Manure (GM), Earthworm Castings (VC), and Organic Solution (JM).

The results indicated an increase in the total yield of broccoli plants, with an overall average of 22.63 tons ha^{-1}. It was also observed that the levels of nitrogen, phosphorus, and potassium in the soil increased after harvest, with an average of 52.63, 29.02, and 119.09 mg kg $soil^{-1}$, respectively. The increase in fertilization levels resulted in a significant improvement in the studied traits. The highest average was recorded for the F2 treatment, with a total yield of 27.38 tons ha^{-1} and nutrient concentrations of 58.63, 31.63, and 128.08 mg kg $soil^{-1}$ for N, P, and K, respectively. Additionally, the gypsum (G) amendment showed a significant superiority over sulfur (S) in all the studied traits. Regarding the type of organic material, the results indicated that the organic solution (JM) outperformed both earthworm castings (VC) and green manure (GM), showing the highest increase in the total yield, which reached 24 tons ha^{-1}. Furthermore, it gave the highest average values for N, P, and K, which were 54.25, 29.43, and 121.08 mg kg $soil^{-1}$, respectively.

KEYWORDS: Soil Fertility, Manure, Amend.

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INTRODUCTION

Iraqi soils are characterized by a low organic matter content due to the absence of crop residues and the limited use of various organic fertilizers. In addition, the hot and dry climate conditions lead to the oxidation and mineralization of organic matter, preventing its retention in the soil. The excessive use of chemical fertilizers also disrupts the nutrient balance in the soil and contributes to environmental pollution. Moreover, the unbalanced use of nutrients and poor soil management, along with harsh climatic conditions and other factors, have contributed to soil degradation, including the depletion of soil fertility in developing countries (Mugwe et al., 2019).

Over the past decades, numerous concepts and perspectives related to soil fertility, sustainable agriculture, and natural resource management have been proposed, such as Integrated Natural Resource Management (INRM), Integrated Nutrient Management (INM), Rice Intensification Systems, Conservation Agriculture, Organic Farming, Integrated Pest Management (IPM), Agroforestry, Precision Agriculture, and Integrated Soil Fertility Management (ISFM), among others (Rosegrant et al., 2014).

Integrated Soil Fertility Management (ISFM) is defined as a set of good soil management technologies that can be applied in an integrated manner. Each component of ISFM contributes positively to soil fertility and crop productivity. The goal is to integrate multiple technologies to exploit synergies between different practices while addressing the barriers that hinder the expected efficiencies in nutrient use (Vanlauwe et al., 2010). ISFM has also been defined as a set of soil fertility management practices that include the use of mineral fertilizers, organic inputs, soil amendments, and genetic improvements, coupled with knowledge of how to adapt these practices to local conditions, aiming to maximize the agricultural use efficiency of applied nutrients and improve crop productivity (Lambrecht et al., 2016).

Integrated Soil Fertility Management (ISFM) has also been defined as a set of locally adapted soil fertility technologies and improved agricultural practices promoted to enhance soil fertility and crop productivity (Hörner & Wollni, 2021).

ISFM is a set of practices tailored to local conditions to maximize nutrient use efficiency, water utilization, and agricultural productivity (Qaswar et al., 2020). The strategies of ISFM focus on the use of mineral fertilizers and the integrated use of locally available soil amendments (such as gypsum, sulfur, and rock phosphate), as well as organic matter (crop residues, green manure) to replenish and address nutrient deficiencies in agricultural soils (Han et al., 2021).

This approach improves both soil quality and fertilizer efficiency (Lian et al., 2022), as well as the efficiency of other agricultural inputs. Furthermore, ISFM encourages the use of genetically improved crop varieties, agroforestry, and promotes the practice of crop rotation and/or intercropping with legumes (Mugwe et al., 2019). ISFM practices should be coupled with knowledge of how to adapt these practices to local conditions, thereby supporting crop intensification and the conservation of natural resources (IAEA & FAO, 2022).

Integrated Soil Fertility Management (ISFM) aims to achieve the highest efficiency in nutrient use and to improve crop productivity through sustainable management strategies for intensifying agricultural production. Sustainable intensification increases output from the same land area while simultaneously reducing its negative environmental impacts (Hörner & Wollni, 2021). The integration of nutrients from organic materials with mineral fertilizers enhances soil productivity by improving structure, biological activity, cation exchange capacity, and the soil's ability to retain water (Fang et al., 2023). The concept strongly emphasizes the synergies and complementarities that can arise from the joint application of several technologies (Rosegrant et al., 2014). Furthermore, the concept strikes a balance between productivity and environmental quality, both of which are significantly influenced by human management decisions and land use (Kremer, 2017).

Integrated Soil Fertility Management (ISFM) has the potential for agricultural sustainability, as the efficiency of applied chemical fertilizers and amendments also increases when used in combination with organic manure. Therefore, this study aimed to highlight this concept and its application in calcareous soil to assess its importance in increasing broccoli yield and in the content of major nutrients in the soil after harvest, as well as its significance for subsequent crops.

MATERIALS AND METHODS

A field experiment was conducted to study the effect of adopting the Integrated Soil Fertility Management (ISFM) concept on soil fertility properties and broccoli yield in calcareous soil. The field trial was carried out in an agricultural field located in Al-Zubaydia sub-district, Al-Suwaira district, Wasit Governorate, during the 2022-2023 agricultural season, using calcareous soil for broccoli cultivation. The experiment included three replications for each treatment, with a total of 54 experimental units (323*3) per site. The experiments were designed using a Split Plot Design based on a Randomized Complete Block Design (RCBD). A total of 18 treatments were applied, representing combinations of the study factors. After data collection, the experimental data were analyzed statistically using Analysis of Variance (ANOVA), and means were compared using the Duncan's Multiple Range Test at a 0.05 significance level, using the Genstat Diction program (Alraawy et al., 2000).

Random soil samples were collected from the surface layer (0-30 cm) at the experimental site. The samples were mixed to form a composite sample representative of the study site, air-dried, ground, and then passed through a sieve with a 2 mm mesh size to determine some of the soil's physical and chemical properties (Table 1).

- **Factor 1:** Type of soil amendments (Gypsum, Sulfur), denoted by (G, S).
- **Factor 2:** Fertilization recommendation for NPK fertilizer at three levels (0%, 100%, 125%) for broccoli cultivation, denoted by (F0, F1, F2), respectively.
- **Factor 3:** Type of organic fertilizer (Green Manure, Earthworm Castings, Organic Solution), denoted by (GM, VC, JM), respectively.

Soil amendments were applied to the main plots at a rate of 3 tons ha^{-1} for both gypsum and sulfur. Urea (46% N) was added as a nitrogen source in three split doses: the first at transplanting, the second 30 days after planting, and the third 50 days after planting, using a side-dressing method at a rate of 100 kg N ha^{-1}. Triple superphosphate was applied at a rate of 43 kg P ha^{-1} for all treatments in a single application before planting, and it was thoroughly mixed with the soil.

Table (1): Some physical and chemical properties of the study site before planting.

No	parameter	value	unit
1	Sand	460	g kg^{-1} soil
2	Silt	200	
3	Clay	340	
4	Texture	S.C.L	
5	pH	7.24	--
6	EC	3.56	dsm m^{-1}
7	$CaCO_3$	277.5	g kg^{-1} soil
8	$CaSO_4.2H_2O$	10.01	
9	O.M	8.89	
10	N	26.24	mg kg^{-1} soil
11	P	13.50	
12	K	91.50	

Potassium sulfate was applied as a source of potassium in three split doses, similar to nitrogen, using a side-dressing method for each plant at a rate of 83 kg K ha^{-1}. These quantities of N, P, and K represent 100% of the fertilization recommendation from the Ministry of Agriculture. Green manure, using forage (Jat) plants collected from outside the field, was applied to the plots after being chopped and mixed with the soil at a rate of 23.11 tons ha^{-1}. An organic solution, locally prepared as Jeevamrutha, was also used as an organic fertilizer. This fertilizer was prepared from fresh cow dung and fermented cow urine, and was applied through irrigation in three doses: the first at planting, the second 30 days after planting, and the third 50 days after planting, at a rate of 800 liters ha^{-1}. Furthermore, locally prepared earthworm castings from Balad District were used as organic fertilizer at a rate of 5 tons ha^{-1}, as per the study by Mjbil (2022).

Agricultural operations: Tillage, leveling, and smoothing were carried out using disc harrows. The field was then divided into three blocks according to the Randomized Complete Block Design (RCBD), with a distance of 1 meter between each block in the form of raised beds. After applying the study factors, broccoli seedlings of the MAX F1 variety were planted at a spacing of 55 cm between plants on October 15, 2023. Harvesting began on January 10, 2024.

Study Indicators:

- Ready nitrogen in the soil after harvest
- Ready phosphorus in the soil after harvest
- Ready potassium in the soil after harvest
- Total yield of flower heads (tons ha^{-1}): This was calculated by multiplying the individual plant yield by the plant density.

RESULTS

-Ready nitrogen in the soil (mg kg soil^{-1}).

The results presented in Table 2 show that the level of NPK fertilizer application significantly affected the ready nitrogen concentration in the soil after harvest. The F2 nitrogen fertilizer treatment gave the highest concentration of ready nitrogen in the calcareous soil, reaching (58.63) mg kg^{-1}, with a (21.85%) increase compared to the F0 non-fertilized treatment, which recorded (45.82) mg kg^{-1}. The latter concentration was higher than the ready nitrogen in the soil before planting, which was (26.24) mg kg^{-1} (Table 1). This effect is attributed to the role of the applied NPK fertilizer at varying levels and stages throughout the growing period. An increase in fertilization recommendation leads to higher levels of mineral nutrients in the soil, thereby enhancing nutrient storage after fulfilling the plant's needs, especially nitrogen. This also reduces losses through leaching or volatilization, which results in an increase in ready nitrogen in the soil (Singh et al., 2015). Moreover, the added urea fertilizer contains a high concentration of nitrogen (46%), which provides sufficient nitrogen for plant needs and enriches the soil. These results demonstrate the positive role of mineral fertilization in increasing ready nitrogen in the soil.

Table 2: Effect of soil amendment type, organic residue type, and NPK fertilizer application level on ready nitrogen in calcareous soil (mg kg soil⁻¹).

A	O	F			A x O
		F_0	F_1	F_2	
S	GM	i 40.78	f 49.26	abc 56.75	d 48.93
	VC	gh 45.55	e 52.78	abc 57.38	c 51.90
	JM	fgh 47.39	e 53.33	ab 58.66	bc 53.13
G	GM	h 44.55	de 53.78	ab 58.94	bc 52.42
	VC	fg 47.83	cde 54.75	ab 59.54	ab 54.04
	JM	f 48.85	abc 56.70	a 60.53	a 55.36
					$\bar{x}$O
F x O	GM	e 42.66	c 51.52	a 57.84	C 50.67
	VC	d 46.69	b 53.76	a 58.46	B 52.97
	JM	d 48.12	b 55.01	a 59.60	A 54.24
					$\bar{x}$A
F x A	S	f 44.57	d 51.79	b 57.60	B 51.32
	G	e 47.07	c 55.08	a 59.67	A 53.94
					$\bar{x}$
	$\bar{x}$F	C 45.82	B 53.43	A 58.63	52.63

Means with the same letters are not significantly different according to Duncan's Multiple Range Test at the 5% probability level.

(Havlin et al., 2014), which is in agreement with the findings of (Badawy et al., 2007), and also aligns with the results of (Al-Fallahi & Al-Kilani, 2017).

The results presented in Table 2 show a significant effect of soil amendment types on increasing the ready nitrogen concentration in calcareous soil. The gypsum (G) treatment outperformed the sulfur (S) treatment, which recorded (53.94) mg kg soil⁻¹, with an increase of (4.8%) compared to the sulfur treatment, which had the lowest mean ready nitrogen concentration in the soil, at (51.32) mg kg soil⁻¹. The increase in ready nitrogen concentration can be attributed to the role of gypsum in improving the biological properties of the soil, due to increased microbial activity (Luiz, 2022; Bhattacharjee et al., 2020), which contributes to biological nitrogen fixation, thus increasing the soil's nitrogen stock (Hamaad, 2014).

Table 2 indicates that the type of organic residue had a significant effect on the ready nitrogen concentration in the soil after harvest. The JM treatment gave the highest mean ready nitrogen concentration in the soil, reaching (54.24) mg kg soil⁻¹, with a significant increase of (6.58%) compared to the GM treatment, which recorded the lowest mean nitrogen concentration of (50.67) mg kg soil⁻¹. This can be attributed to the complex composition of the Jeevamrutha solution, which is nitrogen-enriched (Bhattacharjee & Uppaluri, 2023). Moreover, the organic solution enhances microbial activity (Girish, 2023), and therefore, adding the organic solution to the soil increases nitrogen concentration and helps prevent its loss due to the organic composition, which acts as a chelating agent for most nutrients. This result is consistent with the findings of (Ravi et al., 2022).

The results in Table 2 show that the interaction between the fertilization recommendation level and the type of soil amendment was significant, with the G2F treatment giving the highest mean nitrogen concentration of (59.67) mg kg soil⁻¹. The interaction between the fertilization recommendation level and the type of organic residue was not significant in most of the experimental treatments, as shown in Table 2. The F2JM treatment recorded the highest mean nitrogen concentration in the soil at (59.60) mg kg soil⁻¹. Additionally, the results indicated that the interaction between the types of soil amendments and organic residues resulted in an increase in ready nitrogen concentration in the soil, with the GJM treatment showing the highest mean at (55.36) mg kg soil⁻¹. Table 2 also shows that there were no significant differences in the triple interaction between the experimental treatments, with the F2GJM treatment recording the highest mean ready nitrogen concentration of (60.53) mg kg soil⁻¹, compared to the lowest mean nitrogen concentration in the soil, which was found in the F0SGM treatment at (40.78) mg kg soil⁻¹.

- Ready phosphorus extracted with 1% formic acid (mg kg⁻¹).

The results presented in Table 3 show that the level of NPK fertilizer application significantly affected the ready phosphorus concentration in both soils after harvest. The F2 phosphorus fertilizer treatment resulted in the highest ready phosphorus concentration in the soil, which was (31.63) mg kg soil^{-1}, with an increase of (20.93%) compared to the F0 non-fertilized treatment, which recorded (25.01) mg kg soil^{-1}. The latter concentration was higher than the ready phosphorus concentration in the soil before planting, which was (13.50) mg kg soil^{-1} (Table 1). This effect can be attributed to the increased levels of mineral fertilizer application, particularly the TSP fertilizer added to the soil, which releases phosphorus in a readily available form for absorption by plants. The remaining phosphorus in the soil becomes a reserve that benefits subsequent crops (Singh et al., 2015). This result is consistent with the findings of Sai & Paswan (2024).

Table 3: Effect of soil amendment type, organic residue type, and NPK fertilizer application level on ready phosphorus extracted with 1% formic acid (mg kg soil^{-1}).

A	O	F			A x O
		F_0	F_1	F_2	
S	GM	i 23.42	f 29.54	b-e 31.04	d 28.00
	VC	h 24.59	ef 30.03	bcd 31.23	c 28.61
	JM	gh 25.24	def 30.27	abc 31.50	bc 29.00
G	GM	gh 25.33	c-f 30.50	ab 31.71	bc 29.18
	VC	gh 25.51	b-e 30.92	ab 31.94	ab 29.45
	JM	g 25.98	bcd 31.20	a 32.37	a 29.85
					$\bar{x}$O
F x O	GM	e 24.38	c 30.02	ab 31.38	B 28.59
	VC	de 25.05	c 30.47	a 31.58	A 29.03
	JM	d 25.61	bc 30.73	a 31.94	A 29.43
					$\bar{x}$A
F x A	S	e 24.41	c 29.95	b 31.26	B 28.54
	G	d 25.61	b 30.87	a 32.01	A 29.50
					$\bar{x}$
	$\bar{x}$F	C 25.01	B 30.41	A 31.63	29.02

Means with the same letters are not significantly different according to Duncan's Multiple Range Test at the 5% probability level.

According to Almismar (2021) and AL-Migimia (2019), this effect may also be attributed to the increase in soil hydrogen levels due to the addition of urea, which leads to biological processes that may result in the dissolution of soil phosphorus and an increase in its availability. Lim et al. (2015) pointed out that the addition of nitrogen fertilizers helps to lower the soil pH, thus increasing the availability of certain elements such as phosphorus due to the release of hydrogen ions. This finding is consistent with the results of Mjbil (2022).

As shown in the results of Table 3, the significant effect of soil amendment types on the increase in available phosphorus concentration in the soil was observed. The G treatment outperformed the sulfur treatment, which recorded 29.50 mg kg^{-1} soil, with an increase of 3.25% compared to the S treatment, which recorded the lowest average of available phosphorus concentration in the soil (28.54 mg kg^{-1} soil). The increase in available phosphorus concentration in the soil can be attributed to the role of gypsum in improving the chemical and biological properties of the soil, which may lead to a reduction in the soil pH, thereby converting soil phosphorus into available forms (Prakash et al., 2023; Marcos et al., 2023). This result is consistent with the findings of Kumar et al. (2023) and Shaheen (2018).

Table 3 indicates that the type of organic waste significantly affected the concentration of available phosphorus in the soil at harvest. The JM treatment gave the highest average concentration of available phosphorus in the soil, which was 29.43 mg kg^{-1} soil, and this was not significantly different from the VC treatment, which recorded an average of 29.03 mg kg^{-1} soil. The JM treatment also showed a significant increase of 2.85% compared to the GM treatment, which recorded the lowest average available phosphorus concentration in the soil, at 28.59 mg kg^{-1} soil. This increase can be attributed to the organic solution in the JM treatment, which contains mineral elements, decomposable materials, and a diverse content of beneficial microorganisms. This leads to an increase in bacteria, fungi, and actinomycetes, as well as an increase in enzyme secretion in the soil, ultimately contributing to the increased availability of mineral nutrients in the soil (Aich & Dey, 2022). Chaithra (2018) reported similar results, noting a significant increase in N, P, and K content in sunflower plants due to the application of the Jeevamrutha solution, which resulted in an increase in available nutrients such as N, P, and K in the soil compared to treatments without the solution. This is due to the large microbial load present in the solution. These results are consistent with the findings of Ravi et al. (2022).

The results in Table 3 show that the two-way interaction between the fertilization recommendation level and the type of soil amendment was significant in most of the experimental treatments. The G2F treatment gave the highest average concentration of phosphorus in the soil, which was 32.01 mg kg^{-1} soil. The two-way interaction between the fertilization recommendation level and the type of organic material, however, was not significant in most of the experimental treatments (Table 3). The F2JM treatment recorded the highest average nitrogen concentration in the soil, which was 31.94 mg kg^{-1} soil. The above results also indicate that the two-way interaction between soil amendments and organic wastes led to an increase in available phosphorus concentration in the soil. The GJM treatment recorded the highest average phosphorus concentration, which was 29.85 mg kg^{-1} soil. Additionally, the results in Table 3 revealed no significant differences in the three-way interaction between the experimental treatments. The F2GJM treatment recorded the highest average available phosphorus concentration in the soil, which was 32.37 mg kg^{-1} soil, compared to the lowest average phosphorus concentration at the F0SGM treatment, which was 23.42 mg kg^{-1} soil.

- Readily available potassium in the soil (mg kg^{-1} soil).

The results in Table 4 show that the level of NPK fertilization significantly affected the concentration of available potassium in the soil after harvest. The F2 treatment (potassium fertilization) recorded the highest concentration of available potassium in the soil, which was 128.08 mg kg^{-1} soil, with an increase of 17.93% compared to the F0 treatment (no fertilization), which recorded 105.12 mg kg^{-1} soil. The latter also surpassed the available potassium concentration in the soil before planting, which was 91.50 mg kg^{-1} soil (Table 1). This increase can be attributed to the role of mineral fertilizers, which increase the potassium content in the soil as a result of higher levels of NPK fertilization (Singh et al., 2015). Moreover, the addition of potassium sulfate to the soil in stages helps in making potassium available for absorption by the plant and reduces leaching losses, thus increasing available potassium in the soil. This result is consistent with the findings of Sai & Paswan (2024). Additionally, the addition of urea and triple superphosphate fertilizers to the soil promotes vegetative growth and develops the root system, which in turn lowers the soil pH and increases the availability of potassium in the soil. These results highlight the positive role of mineral fertilization in increasing the proportion of available potassium in the soil (Yadav et al., 2010), and are consistent with the findings of Al-Migimiam (2019).

Table 4: Effect of soil amendment type, organic waste type, and NPK fertilizer addition level on available potassium in calcareous soil (mg kg^{-1} soil).

A	O	F			A x O
		F_0	F_1	F_2	
S	GM	i 96.47	d 119.81	abc 126.87	e 114.38
	VC	i 98.61	d 121.14	abc 127.17	e 115.64
	JM	h 102.00	c 124.80	ab 128.72	d 118.51
G	GM	g 106.88	bc 125.93	ab 127.95	c 120.25
	VC	f 111.99	bc 126.12	ab 128.26	b 122.12
	JM	e 114.78	abc 126.66	a 129.51	a 123.65
					$\bar{x}$O
F x O	GM	f 101.67	c 122.87	ab 127.41	C 117.32
	VC	e 105.30	c 123.63	a 127.72	B 118.88
	JM	d 108.39	b 125.73	a 129.11	A 121.08
					$\bar{x}$A
F x A	S	e 99.03	c 121.92	ab 127.59	B 116.18
	G	d 111.21	b 126.24	a 128.57	A 122.01
					$\bar{x}$
	$\bar{x}$F	C 105.12	B 124.08	A 128.08	119.09

Means that share the same letters are not significantly different according to the Duncan's multiple range test at a 5% probability level.

The results in Table 4 show the significant effect of soil amendment types on the increase in available potassium concentration in the soil. The G treatment outperformed the sulfur treatment, which recorded 122.01 mg kg^{-1} soil, with an increase of 4.78% compared to the S treatment, which recorded the lowest average available potassium concentration in the soil, at 116.18 mg kg^{-1} soil. This increase in available potassium concentration in the soil can be attributed to the role of gypsum in lowering the soil pH, thereby increasing the availability of potassium in the soil solution. This result is consistent with Kabibo (2014), who found an increase in available potassium concentration as a result of higher gypsum application rates, and with the findings of Bhattacharjee et al. (2020) and Prakash et al. (2023).

The results in Table 4 indicate that the type of organic waste significantly affected the concentration of available potassium in the soil after harvest. The JM treatment recorded the highest average available potassium concentration in the soil, which was 121.08 mg kg^{-1} soil, with a significant increase of 3.11% compared to the GM treatment, which recorded the lowest average potassium concentration in the soil at 117.32 mg kg^{-1} soil. The increase in available potassium in the soil is attributed to the abundance of mineral elements in the JM solution, which also contains organic acids that dissolve unavailable potassium in the soil (Saharan et al., 2023). Additionally, the solution contains a variety of beneficial soil microorganisms, which may contribute to the release of potassium into the soil solution or due to the activity of these organisms in decomposing organic materials containing various organic acids. This process may have assisted in releasing unavailable potassium into water-soluble forms that are available to plants (Chitra & Janaki, 1999). These results are consistent with the findings of Duraivadivel et al. (2022).

The results in Table 4 show that the two-way interaction between the fertilization recommendation level and the type of soil amendment was significant in most of the experimental treatments. The G2F treatment recorded the highest average concentration of potassium in the soil, which was 128.57 mg kg^{-1} soil. The two-way interaction between the fertilization recommendation level and the type of organic waste also showed an increase in available potassium concentration, with the highest average recorded in the F2JM treatment, which was 129.11 mg kg^{-1} soil. Furthermore, the results of the table indicate that the two-way interaction between the types of soil amendments and organic material led to an increase in available potassium concentration in the soil, with the GJM treatment recording the highest average of 123.65 mg kg^{-1} soil. The results in Table 4 also showed no significant differences in the three-way interaction between the experimental treatments. The F2GJM treatment recorded the highest average available potassium concentration in the soil, which was 129.51 mg kg^{-1} soil, compared to the lowest average potassium concentration recorded in the F0SGM treatment, which was 96.47 mg kg^{-1} soil.

-The total yield (tons per hectare).

Table 5 shows the effect of fertilization recommendation levels, types of soil amendments, and types of organic waste used in the experiment on the total yield of broccoli plants (tons ha^{-1}). Significant differences were observed between the fertilization levels in terms of the average total yield. The highest average total yield (27.38 tons ha^{-1}) was recorded at the 125% fertilization level (F2), while the lowest average total yield was recorded in the no fertilization treatment (F0), which was 16.43 tons ha^{-1}. The increase in total yield at the third level (F2) was 39.99%. The increase in total yield of broccoli is directly related to the increase in the size of the flower head, which is influenced by the NPK levels in the applied fertilization recommendation. These fertilizers play a vital role in plant metabolism by supplying mineral elements, leading to the accumulation of photosynthetic products from the leaves to the flower heads of the broccoli plant. This, in turn, increases the weight of the flower head and, consequently, the total yield per unit area. These results are in line with the findings of Bozkurt et al. (2011), Khoshnaw (2011), Jasim & Merhij (2013), and Mjbil (2022).

Table 5: Effect of soil amendment type, organic waste type, and NPK fertilizer addition level on the total yield of broccoli plants grown in calcareous soil (tons per hectare).

A	O	F			A x O
		F_0	F_1	F_2	
S	GM	i 13.67	f 21.67	cd 25.97	d 20.44
	VC	h 16.06	e 23.35	bc 26.74	c 22.05
	JM	h 16.68	e 24.45	ab 28.17	b 23.10
G	GM	h 15.94	e 23.47	bc 26.84	c 22.08
	VC	h 17.01	de 24.59	ab 27.98	b 23.19
	JM	g 19.22	bc 26.90	a 28.61	a 24.91
					$\bar{x}$O
	GM	h 14.80	e 22.57	bc 26.41	C 21.26
	VC	g 16.54	d 23.97	b 27.36	B 22.62

F x O	**JM**	f 17.95	c 25.67	a 28.39	A 24.00
					$\bar{x}$**A**
F x A	**S**	f 15.47	d 23.16	b 26.96	B 21.86
	G	e 17.39	c 24.99	a 27.81	A 23.39
					$\bar{x}$
	$\bar{x}$**F**	C 16.43	B 24.07	A 27.38	22.63

Means that share the same letters are not significantly different according to Duncan's multiple range test at a 5% probability level.

As for the effect of soil amendment types, Table 5 shows that the G and S treatments in calcareous soil recorded the highest averages of 23.39 and 21.86 tons ha^{-1}, respectively. These results show clear significant differences between soil amendment types in terms of total yield of broccoli plants, with a 6.54% increase in the G treatment compared to the S treatment. The effect of gypsum (G) added to calcareous soil significantly improved the total yield of broccoli plants. This increase in yield can be attributed to the improvement in individual plant yield, as the addition of gypsum positively affects soil properties and nutrient availability, leading to better vegetative growth. Consequently, the accumulated photosynthetic products in the flower heads of the broccoli plant increase, which results in higher weight and, thus, a higher total yield per unit area. These results are consistent with those of Kost et al. (2014), Subhradip et al. (2020), and Marcos et al. (2023).

As shown in Table 5, the effect of organic waste types was significant. The JM treatment recorded the highest average total yield of 24.00 tons ha^{-1}, significantly outperforming both VC and GM treatments with increases of 5.75% and 11.42%, respectively, compared to the GM treatment, which gave the lowest average of 21.26 tons ha^{-1}. This increase can be attributed to the factors related to the size of the flower head and its weight. As the size of the broccoli flower head increases, the total volume of the head also increases. This increase is associated with the accumulation of photosynthetic products such as proteins, carbohydrates, fibers, amino acids, vitamins, and other organic compounds in the flower head, which leads to an increase in the weight of the flower head and the individual plant yield. Consequently, this affects the total yield per hectare. These results are consistent with the findings of Kumar et al. (2022), Gopal & Gurusiddappa (2022), Duraivadivel et al. (2022), and Veeranna et al. (2023).

The two-way interaction between fertilization recommendation levels and soil amendment types resulted in the highest average total yield of broccoli at the F2G treatment, which was 27.81 tons ha^{-1}. The two-way interaction between fertilization recommendation levels and organic waste types, as shown in Table 5, revealed significant differences between some treatments, with the highest average recorded for the F2JM treatment, which was 28.39 tons ha^{-1}. The results in Table 5 also show the two-way interaction between soil amendment types and organic waste types, where the highest average total yield was recorded for the GJM treatment, which was 24.91 tons ha^{-1}. Furthermore, the results indicated a significant three-way interaction between fertilization recommendation levels, soil amendment types, and organic waste types. There were significant differences between some treatments regarding total plant yield, with the highest average recorded for the F2GJM treatment at 28.61 tons ha^{-1}, while the lowest average was recorded for the F0SGM treatment, which was 13.67 tons ha^{-1}.

DISCUSSION

In conclusion, our results indicate that the combination of NPK fertilizer, organic wastes, and soil amendments as part of soil fertility management, aimed at replenishing the nutrients removed by plants, led to an increase in total yield and the storage of mineral nutrients, particularly the major ones, in the soil after harvest for the subsequent season. The application of this approach was able to significantly improve soil fertility properties, as evidenced by the increases in total yield of broccoli plants and the levels of available nitrogen, phosphorus, and potassium in the soil after harvest. Based on this study, we recommend continuing the use of organic fertilizers, particularly those that add organic matter to the soil, such as green manures, or biological mass such as the JM organic solution and earthworm compost (VC), in combination with NPK fertilizers and gypsum, due to its effective role in improving certain chemical properties of the soil for broccoli cultivation in the studied region.

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