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Improving the Yield and Quality of Faba Bean Grown in Alkaline Soils Using Agricultural Gypsum, Organic Fertilizers and Cobalt

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RECLAIMING degraded soils, such as alkaline soils, is essential for sustainable agriculture and food security. So, a field experiment was conducted in the El-Serw region, Damietta, Egypt, to enhance the yield and quality of faba bean grown on alkaline soil using agricultural gypsum, organic fertilizers and cobalt. The experimental design included main plots treated with or without agricultural gypsum as gypsum requirements (GR; 4.2 Mg fed^{-1}), sub-plots receiving different types of organic fertilizers (control, farmyard manure compost, and plant residue compost at 20 m³ fed^{-1}), and sub-sub plots treated with varying rates of cobalt (0.0, 5 and 10 mg Co L^{-1}). Biochemical analyses at 70 days from sowing including malondialdehyde (MDA), peroxidase (POD), superoxide dismutase (SOD) and catalase (CAT) enzyme activities were measured. Concurrently, leaf nutrient content (NPK), chlorophyll and carotene levels were measured. At the harvest stage, yield components such as the number of pods per plant, pod weight and seed yield, along with seed protein, carbohydrate and total dissolved solids (TDS) content were assessed. Soil parameters like electrical conductivity (EC), N, P and K content were also measured. Results indicated that applying gypsum, organic fertilizers and spraying cobalt individually reduced MDA, POD, SOD and CAT levels, while enhancing leaf nutrient content, photosynthetic pigments and yield components compared to control groups. Furthermore, gypsum decreased soil EC, whereas organic fertilizers increased available soil N, P, and K, with plant residue compost showing superior effectiveness. The combination of gypsum application with plant residue compost and 10 mg L^{-1} cobalt spray achieved the highest overall performance. Generally, integrating gypsum, organic fertilization, and cobalt can significantly improve the biochemical and agronomic traits of faba beans in alkaline soils. Future research should explore the long-term impacts and optimization of these treatments for various crops and soil types.

Keywords: Alkalinity stress, Organo-fertilizers, Oxidative stress, malondialdehyde, peroxidase, superoxide dismutase, catalase.

1. Introduction

Soil degradation is a significant issue in many coastal regions, including Egypt, where saline and alkaline soils pose serious challenges to agricultural productivity **(Abdel Rahman *et al.* 2022).** Alkaline soils, characterized by high pH levels and poor nutrient availability, are prevalent in Egypt's coastal areas **(Abd El-Hady *et al.* 2024).** These soils can inhibit plant growth, reduce crop yields, and ultimately threaten food security. Effective reclamation strategies are essential to restore soil health and enhance agricultural productivity in these regions **(Alnaimy *et al.* 2023).**

Coastal regions in Egypt are increasingly affected by soil salinization and alkalization due to factors such as irrigation with saline water, poor drainage, and rising sea levels **(Abd El-Hamid *et al.* 2023; Kebede, 2023).** These conditions lead to the accumulation of soluble salts and sodium, which degrade soil structure and fertility. Reclaiming these degraded soils is vital to sustain agricultural production and ensure food security for the growing population. Alkaline soils typically have pH values above 8.5, which can limit the availability of essential nutrients like phosphorus, iron, and zinc **(Liu *et al.* 2024).** Excess sodium in alkaline soils can cause soil particles to disperse, leading to poor soil structure and reduced water infiltration. These soils often suffer from nutrient imbalances, which can affect plant growth and yield **(Guan *et al.* 2024).**

Faba bean (*Vicia faba*), a staple crop in Egypt, holds substantial nutritional and economic importance **(Elsherpiny and Kaney, 2023**). It is a primary source of protein for many Egyptians and plays a critical role in the diet and agriculture of the region. It is highly valued for its nutritional content, providing a rich

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source of fiber, vitamins, and minerals Enhancing the growth and yield of faba bean in alkaline soils could significantly benefit Egyptian agriculture and food systems **(Abdeen and Hefni, 2023).**

Agricultural gypsum (calcium sulphate, $CaSO_4$. $2H_2O$) is widely used in the reclamation of alkaline soils **(El-Henawy *et al.* 2024).** It works through several mechanisms, as it provides a source of calcium, which replaces sodium ions on soil particles, thereby improving soil structure and reducing soil pH. By enhancing soil structure, agricultural gypsum increases water infiltration and reduces surface crusting **(Al-Qaisi *et al.* 2024).** Its application can improve the availability of essential nutrients, promoting better plant growth and yield **(Jyothsna *et al.* 2024).**

Organic fertilizers, such as the compost of farmyard manure and plant residues, offer multiple benefits for soil health and crop productivity **(Mengmeng *et al.* 2024).** They provide a slow-release source of essential nutrients (NPK) to plants. Additionally, they enhance soil structure by increasing organic matter content, improving soil aeration, and water-holding capacity. Also, they stimulate microbial activity in the soil, enhancing nutrient cycling and soil fertility **(Turabi *et al.* 2024).**

Cobalt (Co) is a micronutrient that plays a vital role in plant growth and development **(Elshamly *et al.* 2024).** Cobalt plays a vital role in the growth of plants under stress conditions such as salinity and sodicity by acting as an essential micronutrient that enhances plant resilience **(Inayat *et al.* 2024).** It is a crucial nutrient for nitrogen fixation in leguminous plants, helping them to maintain growth and productivity in adverse conditions. Cobalt mitigates the negative effects of salinity and sodicity by improving enzymatic activities and antioxidant defenses, which protect plant cells from oxidative damage **(Alhammad *et al.* 2023).** Additionally, cobalt aids in the synthesis of essential molecules like vitamin B12 and enhances the uptake of other nutrients thereby promoting better overall plant health and stress tolerance **(Faiyad and AbdEL-Azeiz, 2024)**.

Therefore, this study aims to (1) valuate the effects of agricultural gypsum on the yield and quality of faba beans grown in alkaline soils, (2) assess the impact of different organic fertilizers on soil fertility and faba bean productivity, (3) investigate the potential benefits of cobalt on faba bean growth and stress tolerance, (4) determine the combined effects of agricultural gypsum and organic fertilizers on soil health and crop performance, and (5) provide recommendations for effective soil reclamation practices to enhance agricultural productivity in coastal regions of Egypt.

2. Materials and Methods

2.1. Experimental site

Throughout two consecutive seasons (2022/23 and 2023/24), an experimental fieldwork was conducted on a privately owned farm situated in El-Serw region, Damietta, Egypt (coordinates: 31°14′19″N 31°39′14″E).

2.2. Soil sampling and applied materials

The properties of the initial soil, organic fertilizers and agricultural gypsum were determined based on the methodology outlined by **Tandon (2005).** The studied soil had a high pH of 8.70 (suspension 1:2.5) and an electrical conductivity (EC) of 3.78 dSm^{-1}, indicating alkaline conditions. The exchangeable sodium percentage (ESP) was 16.32, reflecting significant soil sodicity. Nutrient analysis revealed low levels of available nitrogen (N) at 22.02 mg kg^{-1} and phosphorus (P) at 4.05 mg kg^{-1}, with potassium (K) moderately available at 194.2 mg kg^{-1}. The organic matter content was 1.00%. The soil texture consisted of 33% sand, 48% clay, and 19% silt. These properties highlight the need for effective soil reclamation strategies to improve soil fertility and enhance crop productivity.

The compost used in the study comprised two types: compost of farmyard manure (FYM) and derived from plant residues. The composting process for both plant residues and farmyard manure was conducted on the experimental land following the established protocol outlined by **Misra *et al.* (2003).** Plant compost was made from banana plant residues. Both types of organic fertilizers were composted in the experimental field six months before the start of the experiment. This protocol involved several key steps to ensure proper decomposition and conversion of organic materials into compost. These composts were characterized based on several key properties. The pH of the FYM compost was recorded at 6.3 in a suspension ratio of 1:10, while the plant residue compost exhibited a slightly lower pH of 6.1 under the same conditions. Electrical conductivity (EC) measurements indicated values of 4.98 dSm^{-1} for FYM compost and 4.040 dSm^{-1} for plant residue compost, reflecting their respective levels of soluble salts. The organic matter content of the composts was notably high, with FYM compost containing 29.7% organic matter and plant residue compost containing 30.96%. Total carbon (C) content, an important indicator of soil organic carbon, was measured at 17.3% for FYM compost and 18.00% for plant residue compost. Additionally, the composts differed slightly in their total nitrogen (N) content, with FYM compost containing 1.2% N and plant residue compost containing 1.5% N. The C:N ratio, a crucial parameter influencing microbial activity and nutrient availability, was calculated as 14.4 for FYM compost and 12 for plant residue compost. These characteristics highlight the nutrient-rich nature of the composts, making them valuable amendments for improving soil fertility and promoting plant growth in agricultural systems.

The agricultural gypsum utilized in the study was procured from Al-Shafii Agricultural Investment Company, a reputable supplier in the Egyptian commercial market. Gypsum sourced from reliable suppliers ensures quality and purity, which are essential for its effectiveness as a soil amendment in agricultural applications. This agricultural gypsum was characterized by several key properties. In a suspension of 1:5, the pH of the gypsum suspension was measured to be 7.75. The sulfur content of the gypsum was recorded at 17.88 g 100 g^{-1}. The gypsum also contained a significant amount of calcium, with a content of 22.92 g 100g^{-1}. Electrical conductivity (EC) measurements indicated a value of 2.5 dS m^{-1} for the gypsum solution, reflecting its salinity level. Finally, the purity of the gypsum was determined to be 98.30%. This high purity level ensures that the gypsum is free from contaminants or impurities that could potentially interfere with its effectiveness as a soil amendment. Overall, these characteristics demonstrate the suitability of the agricultural gypsum for improving soil structure, enhancing nutrient availability, and promoting plant growth in agricultural systems.

The used source of cobalt in the current study was the cobalt sulphate (36% Co), which sourced from Sigma Company.

2.3. Experimental design and treatments

The experimental design was a split-split plot. Main plots were treated either with or without agricultural gypsum as gypsum requirements (GR, 4.2 Mg fed^{-1}). Sub-plots received different types of organic fertilizers; a control, farmyard manure compost and plant residue compost at 20 m³ fed^{-1}. Sub-sub plots were treated with varying rates of cobalt (0.0, 5, and 10 mg CoL^{-1}). Fig1 illustrates the flowchart of this research work.

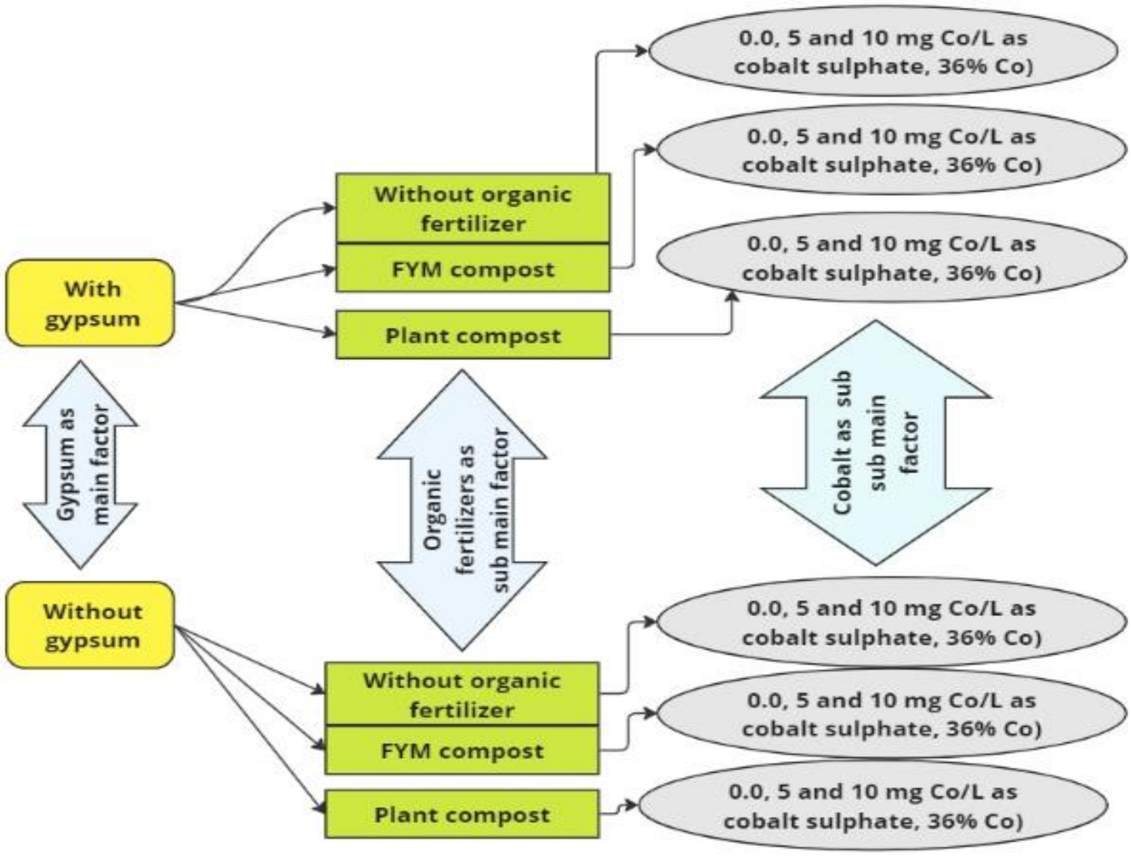

Fig. 1. Flowchart of the current research work.

2.4. Applying date of the studied substances

For the gypsum treatments, three months before sowing, the agricultural gypsum was added according to the studied treatments (4.2 Mg fed^{-1}) then the soil was irrigated. Irrigation was continued until the soil reached its saturation limit, with water levels about 10 cm higher. Irrigation process was repeated every 15 days to eliminate excess sodium from the soil. For the compost treatments, farmyard manure compost and plant residue compost were applied to the plots two weeks before cultivation. Both the agricultural gypsum and organic fertilizers were thoroughly mixed with the top layer of soil in a single application. A standard solution was made by dissolving a specific amount of cobalt sulphate in a solvent to achieve a particular concentration. This standard solution was then used to prepare various concentrations for the study. The foliar application of cobalt was performed 30 days after sowing and repeated three times at 14-day intervals using a hand sprayer until the saturation point was reached, with a volume of 600 L ha^{-1}.

2.5. Cultivation and harvesting

Each sub-sub plot measured 3 x 3 meters. Faba bean seeds (Giza 716, an early cultivar) were sown on October 23rd during both studied seasons, directly by hand, with 2 seeds per hill under a flooding irrigation system. The recommended seed rate was almost 55kg fed^{-1}. The effective nitrogen dose (15 kg N fed^{-1}), in the form of urea (46.5% N), was applied 15 days after sowing and before the first irrigation. All plots received calcium superphosphate (6.6% P) at a rate of 25 kg P per feddan and potassium sulfate (39.8% K) at a rate of 40 kg K per feddan. Standard agronomic practices for faba bean were followed according to the guidelines set by the Egyptian Ministry of Agriculture. Harvesting was implemented on April 14th during both investigated seasons.

2.6. Measurement traits

After 70 days from sowing, random samples of faba bean plants were collected for analysis. Chlorophyll content was measured using a SPAD meter, providing a non-destructive assessment of chlorophyll concentration in the leaves. Carotene content was determined spectrophotometrically *via* the acetone 80% method following the protocol established by **Porra *et al.* (1989).** Additionally, nitrogen content was quantified using the Kjeldahl method, which involves digestion with sulfuric acid and subsequent distillation (**Walinga *et al.* 2013**). Phosphorus levels were assessed colorimetrically, utilizing a method outlined by **Walinga *et al.* (2013),** which extracts phosphorus from the sample and measures its concentration based on a color reaction. Potassium content was determined via flame photometry, a technique also described by **Walinga *et al.* (2013)**, which measures the intensity of light emitted by potassium atoms in a flame, providing insight into the potassium concentration in the plant tissues. At the same time, malondialdehyde (MDA), an indicator of lipid peroxidation, was quantified using a spectrophotometric method based on the reaction with thiobarbituric acid **(Valenzuela, 1991).** Also, the activities of peroxidase (POD), superoxide dismutase (SOD) and catalase (CAT) enzymes were determined following established protocols **(Alici and Arabaci, 2016).**

At harvest, the following yield components, including No. of pods per plant, pod weight (g), 100-seed weight (g) and seed yield (ton/ha) were measured. .

Seed quality parameters were measured using various established methods according to the **AOAC (2000)** after harvest. Protein content was determined using the Kjeldahl method, which involves digesting the sample in sulfuric acid to convert nitrogen into ammonium sulfate, followed by neutralization and distillation to quantify the nitrogen content then multiplying the nitrogen percentage by a factor of 6.25. Carbohydrate content was assessed using the phenol-sulfuric acid method, a colorimetric technique where carbohydrates react with phenol and sulfuric acid to produce a measurable color change. Total Dissolved Solids (TDS) were measured with a refractometer, an instrument that evaluates the concentration of dissolved substances in the sample based on the refractive index. Fiber content was analyzed using the Van Soest method.

Soil samples were obtained from each sub subplot at the harvest stage and subjected to laboratory analysis for various parameters based on the methodology outlined by **Tandon (2005).** Nitrogen content was determined using the Kjeldahl method. Phosphorus levels were measured using the Olsen method, which extracts P from the soil with sodium bicarbonate and then quantifies it colorimetrically. Potassium concentrations were assessed *via* flame photometry, a technique that detects the intensity of light emitted by potassium atoms in a flame. Soil Electrical Conductivity (EC) was evaluated using a conductivity meter, which measures the ability of the soil solution to conduct electrical current, providing an indication of ion concentration and soil salinity.

2.7. Statistical analyses

Statistical analysis was conducted *via* CoStat version 6.303, copyrighted from 1998 to 2004 (**Gomez and Gomez, 1984).**

3. Results

3.1. Biochemical analyses at 70 days

Tables 1 and 2 show the effect of agricultural gypsum and various compost sources, combined with cobalt on oxidative performance (MDA, POD, SOD, and CAT) of faba bean plants grown in alkaline soil 70 days post-sowing during both studied seasons. The data illustrate that the application of agricultural gypsum significantly influenced the oxidative performance of faba bean plants. Plants treated with agricultural gypsum showed a notable reduction in oxidative stress markers compared to the control (without gypsum). Specifically, Malondialdehyde (MDA) levels decreased from 8.28 µmol g^{-1} FW in the control group to 5.69 µmol g^{-1} FW with gypsum treatment in first season. Similarly, peroxidase (POD) activity reduced from 3.15 to 2.24 unit mg^{-1} protein^{-1}, superoxide dismutase (SOD) activity decreased from 1.99 to 1.12 unit mg^{-1}protein^{-1}, and catalase (CAT) activity lowered from 0.374 to 0.312 unit mg^{-1} protein^{-1}. The reductions were statistically significant at the 5% level, indicating a substantial impact of gypsum on reducing oxidative stress in alkaline soil conditions.

Organic fertilizers also had a significant effect on the oxidative performance of the faba bean plants. Without organic fertilization, MDA levels were at 7.91 µmol g^{-1} FW. This value decreased to 6.92 µmol g^{-1} FW with farmyard manure compost (FYMC) and further to 6.12 µmol g^{-1}FW with plant residue compost (PRC). Similar trends were observed for POD, SOD and CAT activities, which showed significant reductions with the application of FYMC and PRC compared to the control groups. POD decreased from 2.96 to 2.71 and 2.42 unit mg^{-1} protein^{-1}, SOD from 1.89 to 1.57 and 1.21 unit mg^{-1} protein^{-1}, and CAT from 0.361 to 0.344 and 0.323 unit mg^{-1} protein^{-1} for FYMC and PRC, respectively. These reductions suggest that organic fertilizers, particularly PRC, enhance the antioxidant defense system of faba bean plants.

Cobalt application rates had a notable effect on oxidative markers. Without cobalt (0.0 mg CoL^{-1}), MDA levels were 7.27 µmol g^{-1} F.W. With 5.0 mg CoL^{-1}, MDA levels decreased to 7.01 µmol.g^{-1} F.W, and further to 6.67 µmol g^{-1} FW with 10.0 mg CoL^{-1}. Similarly, POD activity decreased from 2.79 to 2.70 and 2.59 unit mg^{-1} protein^{-1}, SOD from 1.67 to 1.56 and 1.44 unit mg^{-1} protein^{-1}, and CAT from 0.347 to 0.345 and 0.337 unit mg^{-1} protein^{-1} with increasing cobalt concentrations. These findings indicate that cobalt, at appropriate levels, can enhance the antioxidant capacity of faba bean plants, reducing oxidative damage.

The interaction between agricultural gypsum, organic fertilizers and cobalt rates revealed complex but significant patterns. In the absence of agricultural gypsum and organic fertilization, the highest MDA levels were observed (up to 9.99 µmol g^{-1} FW), with corresponding high levels of POD, SOD, and CAT activities. However, with the combined application of gypsum and organic fertilizers, particularly with higher cobalt rates, the oxidative stress markers were significantly reduced. For instance, the combination of agricultural gypsum, PRC and 10.0 mg CoL^{-1} cobalt resulted in the lowest MDA levels (4.80 µmol.g^{-1} F.W), along with the lowest POD (1.82 unit mg^{-1} protein^{-1}), SOD (0.64 unit mg^{-1} protein^{-1}), and CAT (0.293 unit mg^{-1} protein^{-1}) activities. Overall, the results demonstrate that agricultural gypsum and organic fertilizers, along with appropriate cobalt supplementation, significantly improve the oxidative performance of faba bean plants in alkaline soils. These treatments reduce oxidative stress markers, suggesting enhanced antioxidant defense mechanisms. The most effective combination observed was agricultural gypsum with plant residue compost and 10.0 mg CoL^{-1} cobalt, which consistently showed the lowest levels of MDA, POD, SOD, and CAT, indicating reduced oxidative stress and improved plant health. The same trend was achieved during both studied seasons.

Table 1. Effect of agricultural gypsum and organic fertilizers, combined with cobalt on biochemical analyses (MDA, POD, SOD, and CAT) of faba bean plants grown in alkaline soil 70 days post-sowing (2022/2023 season).

Treatments			**MDA**	**POD**	**SOD**	**CAT**
			μmol g^{-1}FW	**unit $mg^{-1}$$protein^{-1}$**		
Main factor: Individual effect of agricultural gypsum						
Without agricultural gypsum (Control)			8.28a	3.15a	1.99a	0.374a
With agricultural gypsum			5.69b	2.24b	1.12b	0.312b
F-test			**	**	**	**
Sub main factor: Individual effect of organic fertilizers						
Without organic fertilization (Control)			7.91a	2.96a	1.89a	0.361a
Farmyard manure compost (FYMC)			6.92b	2.71b	1.57b	0.344b
Plant residue compost (PRC)			6.12c	2.42c	1.21c	0.323c
F-test			**	**	**	**
Sub sub main factor: Individual effect of cobalt rates						
0.0 mg CoL^{-1}			7.27a	2.79a	1.67a	0.347a
5.0 mg CoL^{-1}			7.01b	2.70b	1.56b	0.345b
10.0 mg CoL^{-1}			6.67c	2.59c	1.44c	0.337c
F-test			**	**	**	**
Interaction						
Without agricultural gypsum (Control)	Without organic fertilization	0.0 mg CoL^{-1}	9.99	3.48	2.43	0.402
		5.0 mg CoL^{-1}	9.65	3.36	2.33	0.399
		10.0 mg CoL^{-1}	8.70	3.27	2.21	0.390
	FYMC	0.0 mg CoL^{-1}	8.31	3.24	2.12	0.378
		5.0 mg CoL^{-1}	8.12	3.18	2.01	0.375
		10.0 mg CoL^{-1}	7.94	3.12	1.86	0.371
	PRC	0.0 mg CoL^{-1}	7.54	3.03	1.75	0.358
		5.0 mg CoL^{-1}	7.23	2.93	1.62	0.353
		10.0 mg CoL^{-1}	7.00	2.74	1.58	0.339
With agricultural gypsum	Without organic fertilization	0.0 mg CoL^{-1}	6.63	2.65	1.54	0.328
		5.0 mg CoL^{-1}	6.35	2.55	1.49	0.328
		10.0 mg CoL^{-1}	6.14	2.44	1.35	0.323
	FYMC	0.0 mg CoL^{-1}	5.94	2.33	1.27	0.318
		5.0 mg CoL^{-1}	5.78	2.24	1.18	0.317
		10.0 mg CoL^{-1}	5.45	2.14	1.00	0.304
	PRC	0.0 mg CoL^{-1}	5.19	2.02	0.91	0.300
		5.0 mg CoL^{-1}	4.95	1.96	0.75	0.296
		10.0 mg CoL^{-1}	4.80	1.82	0.64	0.293
F-test			**	**	**	**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 2. Effect of agricultural gypsum and organic fertilizers, combined with cobalt on biochemical analyses (MDA, POD, SOD, and CAT) of faba bean plants grown in alkaline soil 70 days post-sowing (2023/2024 season).

Treatments			**MDA**	**POD**	**SOD**	**CAT**
			μmol g^{-1}FW	**unit mg^{-1}protein^{-1}**		
Main factor: Individual effect of agricultural gypsum						
Without agricultural gypsum (Control)			8.12a	3.07a	1.92a	0.361a
With agricultural gypsum			5.58b	2.20b	1.10b	0.305b
F-test			**	**	**	**
Sub main factor: Individual effect of organic fertilizers						
Without organic fertilization (Control)			7.76a	2.89a	1.82a	0.350a
Farmyard manure compost (FYMC)			6.79b	2.64b	1.53b	0.333b
Plant residue compost (PRC)			5.99c	2.36c	1.19c	0.316c
F-test			**	**	**	**
Sub sub main factor: Individual effect of cobalt rates						
0.0 mg CoL^{-1}			7.14a	2.73a	1.62a	0.337a
5.0 mg CoL^{-1}			6.87b	2.64b	1.51b	0.335b
10.0 mg CoL^{-1}			6.53c	2.53c	1.41c	0.327c
F-test			**	**	**	**
Interaction						
Without agricultural gypsum (Control)	Without organic fertilization (Control)	0.0 mg CoL^{-1}	9.83	3.37	2.32	0.386
		5.0 mg CoL^{-1}	9.47	3.26	2.21	0.382
		10.0 mg CoL^{-1}	8.51	3.18	2.12	0.374
	FYMC	0.0 mg CoL^{-1}	8.16	3.15	2.04	0.363
		5.0 mg CoL^{-1}	7.98	3.09	1.93	0.361
		10.0 mg CoL^{-1}	7.78	3.03	1.83	0.355
	PRC	0.0 mg CoL^{-1}	7.40	2.97	1.72	0.350
		5.0 mg CoL^{-1}	7.07	2.87	1.59	0.345
		10.0 mg CoL^{-1}	6.84	2.70	1.55	0.333
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	6.52	2.61	1.50	0.322
		5.0 mg CoL^{-1}	6.24	2.51	1.46	0.321
		10.0 mg CoL^{-1}	6.01	2.41	1.32	0.316
	FYMC	0.0 mg CoL^{-1}	5.82	2.30	1.23	0.311
		5.0 mg CoL^{-1}	5.66	2.20	1.15	0.311
		10.0 mg CoL^{-1}	5.34	2.11	0.98	0.299
	PRC	0.0 mg CoL^{-1}	5.10	2.00	0.89	0.293
		5.0 mg CoL^{-1}	4.83	1.90	0.74	0.290
		10.0 mg CoL^{-1}	4.71	1.76	0.63	0.287
F-test			**	**	**	**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

3.2 Leaf chemical contents and photosynthetic pigments at 70 days

Tables 3 and 4 illustrate the effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on photosynthetic pigments and chemical constituents in faba bean leaf tissues grown in alkaline soil 70 days post-sowing during both studied seasons. The application of agricultural gypsum significantly improved the photosynthetic pigments and chemical constituents of faba bean leaf tissues. Compared to the control (without gypsum), plants treated with gypsum exhibited higher SPAD readings for chlorophyll (45.02 vs. 41.89) and increased carotene content (0.349 mg g^{-1} vs. 0.314 mg g^{-1}). Additionally, essential nutrient concentrations were higher in gypsum-treated plants, with nitrogen (N) at 4.23%, phosphorus (P) at 0.454%, and potassium (K) at 2.96%, compared to the control values of 3.72%, 0.376%, and 2.35%, respectively. These differences were statistically significant at the 5% level, indicating that gypsum amendment enhances the nutritional status and photosynthetic efficiency of faba bean plants grown in alkaline soil.

Organic fertilizers had a substantial impact on the photosynthetic pigments and chemical constituents of the plants. Without organic fertilization, the SPAD reading for chlorophyll was 42.21, which increased to 43.67 with Farmyard Manure Compost (FYMC) and further to 44.48 with Plant Residue Compost (PRC). Carotene content also followed a similar trend, increasing from 0.321 mg g^{-1} in the control to 0.333 mg g^{-1} with FYMC and 0.341 mg g^{-1} with PRC. Correspondingly, the concentrations of N, P and K were highest in PRC-treated plants (4.16%, 0.441%, and 2.89%, respectively), followed by FYMC (3.98%, 0.418%, and 2.61%) and the control (3.78%, 0.387%, and 2.47%). These results highlight the effectiveness of organic fertilizers, particularly PRC, in improving the nutrient content and photosynthetic performance of faba bean plants.

Cobalt application at different rates also significantly affected the photosynthetic pigments and chemical constituents. At 0.0 mg CoL^{-1}, the SPAD reading for chlorophyll was 43.01, which increased to 43.52 with 5.0 mg CoL-1 and to 43.82 with 10.0 mg CoL^{-1}. Carotene content increased from 0.328 mg g^{-1} at 0.0 mg CoL-1 to 0.331 mg g^{-1} at 5.0 mg CoL^{-1} and 0.336 mg g^{-1} at 10.0 mg CoL^{-1}. Nutrient concentrations also improved with higher cobalt rates, with N increasing from 3.88% to 4.04%, P from 0.407% to 0.424%, and K from 2.60% to 2.72% across the increasing cobalt rates. These increases were statistically significant, suggesting that cobalt supplementation enhances the photosynthetic pigment concentration and nutrient uptake in faba bean plants.

The interaction effects of agricultural gypsum, organic fertilizers and cobalt rates showed complex yet significant improvements in photosynthetic pigments and nutrient contents. In the absence of gypsum and organic fertilization, the lowest values were observed across all parameters. For example, the SPAD reading was 39.68 with 0.0 mg CoL^{-1}, which increased to 41.01 with 10.0 mg CoL^{-1}. However, the most substantial improvements were obtained with the combined application of agricultural gypsum, PRC and the highest cobalt rate (10.0 mg CoL^{-1}). This combination resulted in the highest SPAD reading of 45.83, carotene content of 0.367 mg g^{-1}, N content of 4.56%, P content of 0.490%, and K content of 3.30%. These significant increases suggest a synergistic effect of gypsum, organic fertilizers, and cobalt on enhancing the photosynthetic efficiency and nutrient status of faba bean plants in alkaline soils.

Table 3. Effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on photosynthetic pigments and chemical constituents in faba bean leaf tissues grown in alkaline soil 70 days post-sowing (2022/2023 season).

Treatments			Chlorophyll,	Carotene,	N, %	P, %	K, %
Main factor: Individual effect of agricultural gypsum							
Without agricultural gypsum (Control)			41.89b	0.314b	3.72b	0.376b	2.35b
With agricultural gypsum			45.02a	0.349a	4.23a	0.454a	2.96a
F-test			**	**	**	**	**
Sub main factor: Individual effect of organic fertilizers							
Without organic fertilization (Control)			42.21c	0.321c	3.78c	0.387c	2.47c
Farmyard manure compost (FYMC)			43.67b	0.333b	3.98b	0.418b	2.61b
Plant residue compost (PRC)			44.48a	0.341a	4.16a	0.441a	2.89a
F-test			**	**	**	**	**
Sub sub main factor: Individual effect of cobalt rates							
0.0 mg CoL^{-1}			43.01b	0.328c	3.88c	0.407c	2.60c
5.0 mg CoL^{-1}			43.52a	0.331b	4.00b	0.416b	2.65b
10.0 mg CoL^{-1}			43.82a	0.336a	4.04a	0.424a	2.72a
F-test			**	**	**	**	**
Interaction							
Without agricultural gypsum (Control)	Without organic fertilization	0.0 mg CoL^{-1}	39.68	0.300	3.34	0.339	2.10
		5.0 mg CoL^{-1}	40.71	0.306	3.59	0.354	2.13
		10.0 mg CoL^{-1}	41.01	0.310	3.63	0.362	2.18
	FYMC	0.0 mg CoL^{-1}	41.27	0.314	3.68	0.371	2.27
		5.0 mg CoL^{-1}	42.33	0.314	3.75	0.379	2.31
		10.0 mg CoL^{-1}	42.74	0.322	3.81	0.388	2.39
	PRC	0.0 mg CoL^{-1}	42.83	0.319	3.83	0.392	2.52
		5.0 mg CoL^{-1}	42.90	0.321	3.90	0.400	2.60
		10.0 mg CoL^{-1}	43.51	0.322	3.92	0.404	2.70
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	43.50	0.330	3.97	0.415	2.79
		5.0 mg CoL^{-1}	43.86	0.336	4.06	0.421	2.77
		10.0 mg CoL^{-1}	44.50	0.343	4.10	0.435	2.83
	FYMC	0.0 mg CoL^{-1}	44.91	0.347	4.16	0.448	2.85
		5.0 mg CoL^{-1}	45.40	0.350	4.23	0.456	2.91
		10.0 mg CoL^{-1}	45.34	0.353	4.25	0.463	2.96
	PRC	0.0 mg CoL^{-1}	45.88	0.357	4.31	0.477	3.04
		5.0 mg CoL^{-1}	45.92	0.360	4.47	0.485	3.19
		10.0 mg CoL^{-1}	45.83	0.367	4.56	0.490	3.30
F-test			**	**	**	**	**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 4. Effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on photosynthetic pigments and chemical constituents in faba bean leaf tissues grown in alkaline soil 70 days post-sowing (2023/2024 season).

Treatments			Chlorophyll, SPAD reading	Carotene, mgg^{-1}	N, %	P, %	K, %
Main factor: Individual effect of agricultural gypsum							
Without agricultural gypsum (Control)			41.25b	0.303b	3.62b	0.364b	2.26b
With agricultural gypsum			44.39a	0.342a	4.15a	0.446a	2.90a
F-test			**	**	**	**	**
Sub main factor: Individual effect of organic fertilizers							
Without organic fertilization (Control)			41.58c	0.311c	3.70c	0.377c	2.40c
Farmyard manure compost (FYMC)			42.93b	0.323b	3.89b	0.405b	2.55b
Plant residue compost (PRC)			43.94a	0.333a	4.07a	0.432a	2.80a
F-test			**	**	**	**	**
Sub sub main factor: Individual effect of cobalt rates							
0.0 mg CoL^{-1}			42.36b	0.319c	3.80c	0.396c	2.52c
5.0 mg CoL^{-1}			42.88a	0.322b	3.90b	0.405b	2.58b
10.0 mg CoL^{-1}			43.21a	0.327a	3.95a	0.413a	2.65a
F-test			**	**	**	**	**
Interaction							
Without agricultural gypsum (Control)	Without organic fertilization (Control)	0.0 mg CoL^{-1}	39.09	0.288	3.24	0.326	2.02
		5.0 mg CoL^{-1}	39.95	0.293	3.48	0.339	2.05
		10.0 mg CoL^{-1}	40.36	0.297	3.52	0.347	2.10
	FYMC	0.0 mg CoL^{-1}	40.58	0.301	3.57	0.356	2.18
		5.0 mg CoL^{-1}	41.58	0.302	3.65	0.364	2.22
		10.0 mg CoL^{-1}	41.94	0.308	3.70	0.371	2.29
	PRC	0.0 mg CoL^{-1}	42.28	0.312	3.75	0.383	2.42
		5.0 mg CoL^{-1}	42.46	0.314	3.82	0.391	2.50
		10.0 mg CoL^{-1}	42.99	0.316	3.87	0.396	2.60
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	42.94	0.324	3.92	0.407	2.69
		5.0 mg CoL^{-1}	43.34	0.328	3.99	0.417	2.73
		10.0 mg CoL^{-1}	43.80	0.336	4.05	0.429	2.79
	FYMC	0.0 mg CoL^{-1}	44.03	0.340	4.10	0.439	2.81
		5.0 mg CoL^{-1}	44.60	0.342	4.16	0.447	2.86
		10.0 mg CoL^{-1}	44.85	0.347	4.19	0.455	2.92
	PRC	0.0 mg CoL^{-1}	45.25	0.348	4.24	0.465	3.00
		5.0 mg CoL^{-1}	45.33	0.353	4.32	0.474	3.09
		10.0 mg CoL^{-1}	45.33	0.359	4.39	0.482	3.19
F-test			**	**	**	**	**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

The results indicate that agricultural gypsum, organic fertilizers and cobalt collectively and individually improve the photosynthetic pigments and chemical constituents of faba bean leaf tissues. Agricultural gypsum consistently enhanced chlorophyll and carotene contents, as well as essential nutrients (NPK). Organic fertilizers, especially PRC, significantly boosted these parameters. Cobalt, at appropriate rates, further enhanced the plant's photosynthetic pigments and nutrient uptake. The interaction effects underscored the benefits of integrating these treatments, with the highest improvements observed with a combination of gypsum, PRC, and 10.0 mg CoL-1 cobalt. These findings suggest that these amendments are effective strategies for improving the growth and nutritional quality of faba bean plants in alkaline soils. The obtained results of the second season were similar to those of the first season.

Yield and its components at harvest stage

Data of Tables from 5 and 6 indicate that the impact of agricultural gypsum amendment, organic fertilizers and cobalt rates on yield and its components of faba bean is significant. With gypsum, the number of pods per plant increased significantly in both seasons. In 2022/2023, it increased from 15.52 to 26.07 and in 2023/2024 from 13.33 to 23.93. Pod Weight increased with gypsum application from 18.11g to 22.50g in 2022/2023 and from 17.51g to 21.97g in 2023/2024. Gypsum increased the seed weight from 78.99g to 87.08g (2022/2023) and from 77.55g to 85.90g (2023/2024). Seed yield was improved significantly with gypsum from 1.89 ton/ha to 2.36 ton ha^{-1} (2022/2023) and from 1.83 ton/ha to 2.31 ton ha^{-1} (2023/2024).

Plant residue compost (PRC) resulted in the highest number of pods per plant in both seasons (24.61 and 22.06 respectively). PRC had the highest pod weight (21.96g in 2022/2023 and 21.25g in 2023/2024). PRC consistently improved seed weight over other treatments (85.38g in 2022/2023 and 84.28g in 2023/2024). PRC yielded the highest seed production (2.28 ton/ha in 2022/2023 and 2.23 ton/ha in 2023/2024). The lowest values of all aforementioned traits were achieved with control treatment (without organic fertilization).

No. of pods per plant increased with higher cobalt rates, with 10.0 mg CoL^{-1} showing the best results (21.78 in 2022/2023 and 19.72 in 2023/2024). Similarly, higher pod weights were recorded with 10.0 mg CoL^{-1} (20.83g in 2022/2023 and 20.26g in 2023/2024). 100-seed weight increased with cobalt application, with 10.0 mg CoL^{-1} being the most effective (83.84g in 2022/2023 and 82.55g in 2023/2024). The highest seed yields were recorded with 10.0 mg CoL^{-1} (2.18 ton ha^{-1} in 2022/2023 and 2.13 ton ha^{-1} in 2023/2024).

The quality of faba bean seeds in terms of protein, carbohydrates, total dissolved solids (TDS), and fiber content showed notable variations based on treatments (Tables 7 and 8).

Protein content increased significantly with gypsum, reaching 20.63% in 2022/2023 and 20.35% in 2023/2024. Also, gypsum slightly increased carbohydrate content, with minor but consistent improvements (57.79% in 2022/2023 and 56.63% in 2023/2024). TDS and fiber improved with gypsum application, with TDS rising from 3.17% to 4.00% and fiber from 11.02% to 11.51% in 2022/2023.

PRC resulted in the highest protein content (20.01% in 2022/2023 and 19.76% in 2023/2024).also, this organic treatment led to the highest carbohydrate content (57.61% in 2022/2023 and 56.41% in 2023/2024). PRC also improved TDS and fiber content compared to other treatments.

On the other hand, the highest protein content was achieved with 10.0 mg CoL^{-1} (19.17% in 2022/2023 and 18.88% in 2023/2024). On the contrary, no significant change was observed in carbohydrate content across cobalt rates. Additionally, TDS and fiber content improved with higher cobalt rates, particularly at 10.0 mg CoL^{-1}.

Overall, it can be noticed from the data in Tables from 5 to 8 that the application of agricultural gypsum, organic fertilizers, and cobalt positively impacts the yield and quality of faba bean grown in alkaline soil. The combination of gypsum and plant residue compost, along with the higher cobalt rate (10.0 mg CoL^{-1}), yields the best results in terms of both productivity and seed quality.

Table 5. Effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on yield and its components of faba bean grown in alkaline soil at harvest stage (2022/2023 season).

Treatments			**No. of pods plant^{-1}**	**Pod weight, g**	**100 seed weight, g**	**Seed yield, ton ha^{-1}**
Main factor: Individual effect of agricultural gypsum						
Without agricultural gypsum (Control)			15.52b	18.11b	78.99b	1.89b
With agricultural gypsum			26.07a	22.50a	87.08a	2.36a
F-test			**	**	**	**
Sub main factor: Individual effect of organic fertilizers						
Without organic fertilization (Control)			17.56c	18.63c	80.74c	1.97c
Farmyard manure compost (FYMC)			20.22b	20.32b	82.99b	2.13b
Plant residue compost (PRC)			24.61a	21.96a	85.38a	2.28a
F-test			**	**	**	**
Sub sub main factor: Individual effect of cobalt rates						
0.0 mg CoL^{-1}			19.50b	19.73c	82.28b	2.07b
5.0 mg CoL^{-1}			21.11a	20.34b	82.99b	2.12b
10.0 mg CoL^{-1}			21.78a	20.83a	83.84a	2.18a
F-test			**	**	**	**
Interaction						
Without agricultural gypsum (Control)	Without organic fertilization (Control)	0.0 mg CoL^{-1}	10.33	15.64	77.41	1.67
		5.0 mg CoL^{-1}	12.67	16.48	77.83	1.72
		10.0 mg CoL^{-1}	12.67	17.16	78.01	1.78
	FYMC	0.0 mg CoL^{-1}	13.67	17.63	77.81	1.84
		5.0 mg CoL^{-1}	16.00	18.22	78.53	1.89
		10.0 mg CoL^{-1}	16.00	18.75	79.70	1.97
	PRC	0.0 mg CoL^{-1}	18.00	19.29	80.37	2.01
		5.0 mg CoL^{-1}	20.00	19.94	80.22	2.04
		10.0 mg CoL^{-1}	20.33	19.86	81.07	2.10
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	22.67	20.28	82.17	2.15
		5.0 mg CoL^{-1}	23.00	20.82	83.93	2.22
		10.0 mg CoL^{-1}	24.00	21.37	85.10	2.27
	FYMC	0.0 mg CoL^{-1}	24.67	21.84	86.38	2.32
		5.0 mg CoL^{-1}	25.00	22.32	87.21	2.35
		10.0 mg CoL^{-1}	26.00	23.16	88.28	2.41
	PRC	0.0 mg CoL^{-1}	27.67	23.71	89.53	2.46
		5.0 mg CoL^{-1}	30.00	24.27	90.22	2.48
		10.0 mg CoL^{-1}	31.67	24.69	90.85	2.57
F-test			**	**	**	**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 6. Effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on yield and its components of faba bean grown in alkaline soil at harvest stage (2023/2024 season).

Treatments			No. of pods plant^{-1}	Pod weight, g	100 seed weight, g	Seed yield, ton ha^{-1}
Main factor: Individual effect of agricultural gypsum						
Without agricultural gypsum (Control)			13.33b	17.51b	77.55b	1.83b
With agricultural gypsum			23.93a	21.97a	85.90a	2.31a
F-test			**	**	**	**
Sub main factor: Individual effect of organic fertilizers						
Without organic fertilization (Control)			15.39c	18.20c	79.41c	1.91c
Farmyard manure compost (FYMC)			18.44b	19.77b	81.50b	2.07b
Plant residue compost (PRC)			22.06a	21.25a	84.28a	2.23a
F-test			**	**	**	**
Sub sub main factor: Individual effect of cobalt rates						
0.0 mg CoL^{-1}			17.50b	19.19c	80.90c	2.02b
5.0 mg CoL^{-1}			18.67ab	19.76b	81.73b	2.07ab
10.0 mg CoL^{-1}			19.72a	20.26a	82.55a	2.13a
F-test			**	**	**	**
Interaction						
Without agricultural gypsum (Control)	Without organic fertilization (Control)	0.0 mg CoL^{-1}	10.67	15.05	76.02	1.59
		5.0 mg CoL^{-1}	10.33	15.97	76.09	1.66
		10.0 mg CoL^{-1}	10.67	16.60	76.27	1.71
	FYMC	0.0 mg CoL^{-1}	11.00	17.07	76.45	1.78
		5.0 mg CoL^{-1}	13.00	17.51	77.07	1.82
		10.0 mg CoL^{-1}	14.67	18.05	77.80	1.88
	PRC	0.0 mg CoL^{-1}	15.00	18.57	78.74	1.97
		5.0 mg CoL^{-1}	16.67	19.17	79.48	2.01
		10.0 mg CoL^{-1}	18.00	19.58	80.07	2.05
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	19.67	20.04	81.27	2.11
		5.0 mg CoL^{-1}	20.00	20.51	82.95	2.17
		10.0 mg CoL^{-1}	21.00	21.03	83.87	2.22
	FYMC	0.0 mg CoL^{-1}	23.00	21.54	84.69	2.26
		5.0 mg CoL^{-1}	24.00	22.01	85.66	2.31
		10.0 mg CoL^{-1}	25.00	22.45	87.32	2.38
	PRC	0.0 mg CoL^{-1}	25.67	22.89	88.23	2.39
		5.0 mg CoL^{-1}	28.00	23.40	89.15	2.43
		10.0 mg CoL^{-1}	29.00	23.87	90.00	2.53
F-test			**	**	**	**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 7. Effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on seed quality of faba bean grown in alkaline soil at harvest stage (2022/2023 season).

Treatments			Protein, %	Carbohydrates, %	TDS, %	Fiber, %
Main factor: Individual effect of agricultural gypsum						
Without agricultural gypsum (Control)			16.96b	57.02a	3.17b	11.02b
With agricultural gypsum			20.63a	57.79a	4.00a	11.51a
F-test			**	*	**	**
Sub main factor: Individual effect of organic fertilizers						
Without organic fertilization (Control)			17.49c	57.10b	3.29c	11.08c
Farmyard manure compost (FYMC)			18.87b	57.52ab	3.58b	11.26b
Plant residue compost (PRC)			20.01a	57.61a	3.89a	11.45a
LSD at 5%			**0.23**	**0.44**	**0.05**	**0.09**
Sub sub main factor: Individual effect of cobalt rates						
0.0 mg CoL^{-1}			18.42c	57.22a	3.48c	11.20b
5.0 mg CoL^{-1}			18.79b	57.40a	3.59b	11.26ab
10.0 mg CoL^{-1}			19.17a	57.60a	3.69a	11.33a
F-test			**	*	**	**
Interaction						
Without agricultural gypsum (Control)	Without organic fertilization (Control)	0.0 mg CoL^{-1}	15.22	56.52	2.73	10.73
		5.0 mg CoL^{-1}	15.56	57.00	2.91	10.86
		10.0 mg CoL^{-1}	16.02	57.17	2.99	10.89
	FYMC	0.0 mg CoL^{-1}	16.54	57.20	3.11	11.00
		5.0 mg CoL^{-1}	17.11	57.24	3.19	11.02
		10.0 mg CoL^{-1}	17.50	57.81	3.26	11.08
	PRC	0.0 mg CoL^{-1}	17.98	56.66	3.38	11.12
		5.0 mg CoL^{-1}	18.09	56.80	3.48	11.21
		10.0 mg CoL^{-1}	18.61	56.79	3.51	11.29
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	18.99	57.08	3.58	11.27
		5.0 mg CoL^{-1}	19.31	57.32	3.71	11.33
		10.0 mg CoL^{-1}	19.85	57.52	3.81	11.42
	FYMC	0.0 mg CoL^{-1}	20.33	57.48	3.87	11.47
		5.0 mg CoL^{-1}	20.83	57.65	3.95	11.48
		10.0 mg CoL^{-1}	20.93	57.71	4.14	11.53
	PRC	0.0 mg CoL^{-1}	21.47	58.38	4.24	11.63
		5.0 mg CoL^{-1}	21.82	58.42	4.31	11.69
		10.0 mg CoL^{-1}	22.10	58.58	4.41	11.74
F-test			**	**	**	**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 8. Effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on seed quality of faba bean grown in alkaline soil at harvest stage (2023/2024 season).

Treatments			**Protein, %**	**Carbohydrates, %**	**TDS, %**	**Fiber, %**
Main factor: Individual effect of agricultural gypsum						
Without agricultural gypsum (Control)			16.65b	55.07b	3.07b	10.81b
With agricultural gypsum			20.35a	56.63a	3.91a	11.28a
F-test			**	**	**	**
Sub main factor: Individual effect of organic fertilizers						
Without organic fertilization (Control)			17.21c	55.31c	3.22c	10.88c
Farmyard manure compost (FYMC)			18.54b	55.84b	3.49b	11.04b
Plant residue compost (PRC)			19.76a	56.41a	3.77a	11.22a
F-test			**	**	**	**
Sub sub main factor: Individual effect of cobalt rates						
0.0 mg CoL^{-1}			18.11c	55.68a	3.40c	10.98b
5.0 mg CoL^{-1}			18.50b	55.85a	3.49b	11.05ab
10.0 mg CoL^{-1}			18.88a	56.03a	3.59a	11.09a
F-test			**	*	**	**
Interaction						
Without agricultural gypsum (Control)	Without organic fertilization (Control)	0.0 mg CoL^{-1}	14.95	54.24	2.65	10.53
		5.0 mg CoL^{-1}	15.21	54.54	2.82	10.65
		10.0 mg CoL^{-1}	15.66	54.76	2.89	10.72
	FYMC	0.0 mg CoL^{-1}	16.25	54.99	3.01	10.79
		5.0 mg CoL^{-1}	16.78	55.07	3.07	10.81
		10.0 mg CoL^{-1}	17.08	55.22	3.14	10.86
	PRC	0.0 mg CoL^{-1}	17.61	55.50	3.26	10.90
		5.0 mg CoL^{-1}	17.92	55.58	3.36	10.99
		10.0 mg CoL^{-1}	18.38	55.78	3.46	11.01
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	18.78	55.97	3.54	11.06
		5.0 mg CoL^{-1}	19.08	56.08	3.66	11.13
		10.0 mg CoL^{-1}	19.56	56.28	3.75	11.17
	FYMC	0.0 mg CoL^{-1}	19.93	56.34	3.82	11.20
		5.0 mg CoL^{-1}	20.46	56.62	3.90	11.26
		10.0 mg CoL^{-1}	20.70	56.80	4.01	11.29
	PRC	0.0 mg CoL^{-1}	21.16	57.02	4.09	11.41
		5.0 mg CoL^{-1}	21.56	57.22	4.16	11.46
		10.0 mg CoL^{-1}	21.90	57.34	4.27	11.52
F-test			**	**	**	**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Soil properties at harvest

Based on the results in Table 9 and Fig 2, it can be noticed that gypsum application decreased soil electrical conductivity (EC) (Fig 2). This indicates that gypsum helps in reducing soil salinity, improving the overall soil environment for plant growth. On the other hand, organic fertilizers increase the available soil nitrogen. Among the types of organic fertilizers, Farmyard Manure Compost (FYMC) and Plant Residue Compost (PRC) had significant positive effects. Organic fertilizers also increase the available soil phosphorus. PRC showed the highest effectiveness in increasing phosphorus levels. While the overall increase in available potassium was not significant among treatments, the use of organic fertilizers maintained adequate potassium levels in the soil, with slight improvements observed with PRC.

Table 9. Effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on available soil nutrients at harvest stage during season of 2022/2023.

Treatments			**N, mg kg^{-1}**	**P, mg kg^{-1}**	**K, mg kg^{-1}**
Main factor: Individual effect of agricultural gypsum					
Without agricultural gypsum (Control)			44.75b	7.84b	209.87a
With agricultural gypsum			44.91a	8.29a	210.10a
F-test			**	**	*
Sub main factor: Individual effect of organic fertilizers					
Without organic fertilization (Control)			44.81b	7.93c	209.73a
Farmyard manure compost (FYMC)			44.91a	8.07b	210.20a
Plant residue compost (PRC)			44.78b	8.19a	210.02a
F-test			**	**	*
Sub sub main factor: Individual effect of cobalt rates					
0.0 mg CoL^{-1}			44.86a	8.10a	209.88a
5.0 mg CoL^{-1}			44.86a	8.07b	210.00a
10.0 mg CoL^{-1}			44.78a	8.02c	210.07a
F-test			*	**	*
Interaction					
Without agricultural gypsum (Control)	Without organic fertilization (Control)	0.0 mg CoL^{-1}	44.86	7.75	209.64
		5.0 mg CoL^{-1}	44.82	7.72	209.61
		10.0 mg CoL^{-1}	44.72	7.66	209.47
	FYMC	0.0 mg CoL^{-1}	44.95	7.87	210.08
		5.0 mg CoL^{-1}	44.83	7.82	210.45
		10.0 mg CoL^{-1}	44.87	7.81	210.76
	PRC	0.0 mg CoL^{-1}	44.55	7.98	209.41
		5.0 mg CoL^{-1}	44.62	8.00	209.71
		10.0 mg CoL^{-1}	44.57	7.94	209.73
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	44.85	8.20	209.60
		5.0 mg CoL^{-1}	44.98	8.16	209.92
		10.0 mg CoL^{-1}	44.62	8.09	210.17
	FYMC	0.0 mg CoL^{-1}	44.92	8.37	210.01
		5.0 mg CoL^{-1}	44.94	8.30	209.99
		10.0 mg CoL^{-1}	44.95	8.25	209.92
	PRC	0.0 mg CoL^{-1}	45.01	8.42	210.55
		5.0 mg CoL^{-1}	44.96	8.42	210.31
		10.0 mg CoL^{-1}	44.95	8.38	210.38
F-test			**	**	*

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

Table 10. Effect of agricultural gypsum amendment and organic fertilizers, combined with cobalt on available soil nutrients at harvest stage during season of 2023/2024.

Treatments			**N, mg kg^{-1}**	**P, mg kg^{-1}**	**K, mg kg^{-1}**
Main factor: Individual effect of agricultural gypsum					
Without agricultural gypsum (Control)			43.57b	7.51b	206.54a
With agricultural gypsum			43.97a	7.89a	207.09a
F-test			**	**	*
Sub main factor: Individual effect of organic fertilizers					
Without organic fertilization (Control)			43.65b	7.58c	206.63b
Farmyard manure compost (FYMC)			43.78ab	7.70b	206.86a
Plant residue compost (PRC)			43.89a	7.82a	206.95a
F-test			**	**	**
Sub sub main factor: Individual effect of cobalt rates					
0.0 mg CoL^{-1}			43.82a	7.74a	206.93a
5.0 mg CoL^{-1}			43.78a	7.70b	206.75a
10.0 mg CoL^{-1}			43.72a	7.66c	206.77a
F-test			*	**	*
Interaction					
Without agricultural gypsum (Control)	Without organic fertilization (Control)	0.0 mg CoL^{-1}	43.49	7.44	206.41
		5.0 mg CoL^{-1}	43.49	7.38	206.35
		10.0 mg CoL^{-1}	43.43	7.35	206.20
	FYMC	0.0 mg CoL^{-1}	43.60	7.56	206.63
		5.0 mg CoL^{-1}	43.60	7.52	206.44
		10.0 mg CoL^{-1}	43.53	7.47	206.61
	PRC	0.0 mg CoL^{-1}	43.73	7.65	206.93
		5.0 mg CoL^{-1}	43.67	7.63	206.66
		10.0 mg CoL^{-1}	43.64	7.59	206.59
With agricultural gypsum	Without organic fertilization (Control)	0.0 mg CoL^{-1}	43.90	7.79	207.05
		5.0 mg CoL^{-1}	43.83	7.77	206.92
		10.0 mg CoL^{-1}	43.79	7.73	206.87
	FYMC	0.0 mg CoL^{-1}	44.04	7.93	207.34
		5.0 mg CoL^{-1}	43.98	7.90	207.02
		10.0 mg CoL^{-1}	43.92	7.86	207.11
	PRC	0.0 mg CoL^{-1}	44.18	8.05	207.23
		5.0 mg CoL^{-1}	44.10	8.01	207.09
		10.0 mg CoL^{-1}	44.05	7.97	207.21
F-test			**	**	*

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

***NS=Non significant**

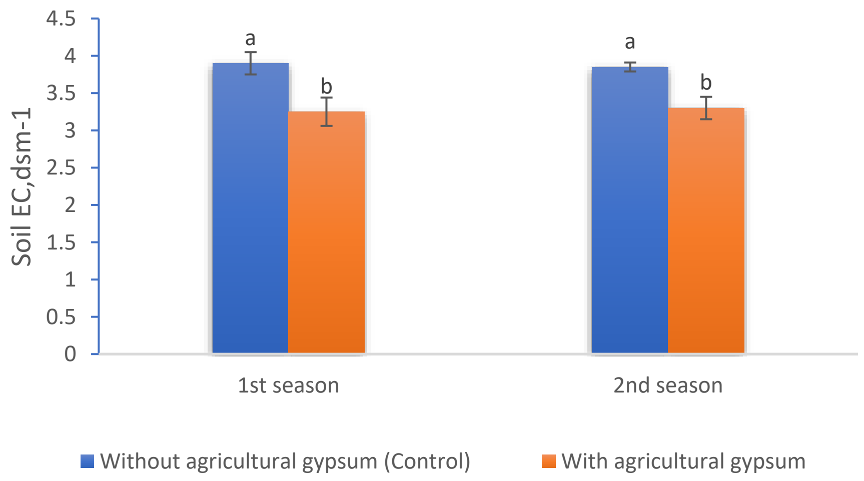

Fig. 2. Effect of agriclural gypsum treatments on soil EC during both studied seasons (2022/23-2023/24).

Gypsum application significantly increased soil phosphorus but had a negligible effect on nitrogen and potassium. Both FYMC and PRC significantly increased soil phosphorus, with PRC being the most effective. FYMC also showed a slight increase in nitrogen. The cobalt application did not have a significant effect on the nitrogen and potassium levels but slightly decreased phosphorus with increasing rates. generally, it can be said that gypsum was effective in reducing soil EC and marginally increasing available phosphorus. Organic fertilizers were effective in increasing available soil nutrients, particularly phosphorus and nitrogen, with PRC showing superior effectiveness. Cobalt had No significant effect on the major soil nutrients. These findings suggest a synergistic approach where gypsum and organic fertilizers, particularly PRC, can be used to enhance soil fertility and reduce salinity, promoting better crop yields in alkaline soils.

4. Discussion

The experiment demonstrated that applying gypsum, organic fertilizers, and cobalt significantly reduced malondialdehyde (MDA) levels in plant tissues. MDA is a marker of oxidative stress and its reduction indicates decreased lipid peroxidation and cell membrane damage. The application of gypsum improves soil structure and reduces soil pH and exchangeable sodium percentage (ESP) by replacing sodium ions with calcium ions, thus mitigating the detrimental effects of sodium on plant roots and enhancing water and nutrient uptake. This alleviation of soil salinity stress directly contributes to the reduction of MDA in plant tissues (**El-Henawy *et al.* 2024).**

Organic fertilizers, such as farmyard manure (FYM) compost and plant residue compost, enhance soil organic matter, microbial activity, and the availability of essential nutrients (NPK) **(Mengmeng *et al.* 2024).** These improvements in soil health and fertility promote robust plant growth and enhance the plant's innate antioxidant defense mechanisms, reducing the need for plants to overproduce stress-related enzymes such as peroxidase (POD), polyphenol oxidase (PPO), and catalase (CAT). Consequently, the self-production of these antioxidant enzymes decreases due to the positive role of the studied supplements in mitigating stress conditions.

Cobalt (Co) is involved in various metabolic processes, including the synthesis of vitamin B12 and chlorophyll. Its application enhances overall plant health, leading to improved nutrient uptake and photosynthesis, reflected in higher levels of chlorophyll and carotene **(Elshamly *et al.* 2024).** The alkaline soil conditions may have contributed to an increase in the production of free radicals within the plants, leading to potential damage to plant cells. To counteract this oxidative stress, faba bean plants typically elevate the production of antioxidant enzymes such as peroxidase (POD), superoxide dismutase (SOD), and catalase (CAT). These enzymes play a crucial role in scavenging free radicals, thus protecting plant cells from oxidative damage. In the control treatments, the highest values of POD, SOD, and CAT were observed, indicating a significant response to the oxidative stress induced by the alkaline soil. However, the application of cobalt, gypsum, and organic fertilization led to a gradual decrease in the levels of these enzymes. This reduction suggests that these treatments effectively mitigated the stress conditions, thereby lowering the need for the plants to produce high levels of antioxidant enzymes **(Elshamly *et al.* 2024).** Cobalt, along with gypsum and organic fertilizers, likely improved the overall soil conditions and plant health. Gypsum helps to ameliorate the soil structure and reduce salinity, while organic fertilizers enhance soil fertility and nutrient availability. Consequently, these treatments collectively contributed to creating a more favorable environment for faba bean plant growth, reducing oxidative stress, and thereby lowering the plants' reliance on their internal antioxidant defense mechanisms **(Alhammad *et al.* 2023;Faiyad and AbdEL-Azeiz, 2024)**.

At harvest, the integrated application of gypsum, organic fertilizers, and cobalt improved yield components such as the number of pods per plant, pod weight, and seed yield. Enhanced leaf nutrient content (NPK), chlorophyll, and carotenoid levels indicate better photosynthetic efficiency and nutrient assimilation. These factors contribute to higher seed protein, carbohydrate content, and total dissolved solids (TDS), reflecting improved nutritional quality and market value of the produce.

Gypsum's role in replacing sodium with calcium in the soil improves soil structure and permeability, facilitating better root growth and nutrient absorption **(Al-Qaisi *et al.* 2024; Jyothsna *et al.* 2024)**. Organic fertilizers like FYM compost and plant residue compost increase soil organic matter and microbial activity, which in turn enhances the availability and uptake of nitrogen, phosphorus, and potassium (NPK). The organic matter from these composts also improves soil aeration and water retention, creating a more favorable environment for root development and microbial activity **(Turabi *et al.* 2024).**

Cobalt's role in improving the general state of the plant and its root system leads to enhanced root zone activity, promoting the availability and uptake of NPK **(Inayat *et al.* 2024).**The synergistic effects of these treatments result in a healthier, more resilient plant capable of achieving higher yields and better quality produce, thus contributing to sustainable agriculture and food security**(Alhammad *et al.* 2023;Faiyad and AbdEL-Azeiz, 2024)**.

5. Conclusion

The obtained results demonstrated that the application of agricultural gypsum, organic fertilizers, and cobalt can significantly improve the yield and quality of faba bean grown in alkaline soils. Gypsum effectively reduced soil electrical conductivity (EC), improving soil structure and nutrient availability. This treatment alone led to better plant growth and higher yields. Both farmyard manure compost and plant residue compost increased the availability of soil nitrogen (N), phosphorus (P), and potassium (K), with plant residue compost showing superior results. These organic amendments also enhanced the overall soil fertility and crop performance. Spraying cobalt, particularly at a rate of 10 mgL^{-1}, improved the physiological and biochemical responses of faba bean. This treatment increased the content of chlorophyll, carotene, and essential nutrients in the leaves while reducing oxidative stress markers such as malondialdehyde (MDA), peroxidase (POD), polyphenol oxidase (PPO), and catalase (CAT). The highest overall performance in terms of yield and quality was achieved with the combination of gypsum application, plant residue compost, and 10 mgL^{-1} cobalt spray. These results underscore the potential of an integrated soil reclamation approach that combines chemical, organic and nanotechnological interventions to enhance the productivity of crops in challenging soil conditions.

Based on the findings of this study, it is recommended to apply gypsum at rates equivalent to the soil's gypsum requirement to improve soil structure and reduce salinity. Additionally, using organic fertilizers such as plant residue compost at a rate of 20 m³/fed can enhance soil fertility and nutrient availability. Furthermore, applying cobalt at a rate of 10 mg/L can enhance plant growth, nutrient uptake, and stress tolerance. Generally, combining gypsum, organic fertilizers, and cobalt yields the best results in improving crop yield and quality. It is also advisable to explore the potential of these treatments on other crops and soil types to develop comprehensive soil management guidelines. By adopting these recommendations, farmers can enhance the productivity of faba bean and other crops in alkaline soils, contributing to improved food security and sustainable agricultural practices in the coastal regions of Egypt.

Conflicts of interest

Authors have declared that no competing interests exist. The authors contributed equally to put the research methodology and implementing it at all stages.

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