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Enhancing Soybean Productivity in Saline Soil Conditions: Synergistic Effects of Organic Fertilizer and Proline Co-Application

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EFFICIENTLY optimizing strategic crop production in Egypt's degraded soils is imperative to address the nutritional gap and ensure food security. Consequently, a field trial was conducted over two consecutive summer seasons (2022 and 2023) to evaluate the potential impact of various organic fertilization sources as the main plots on soybean plant cultivated in soil with an EC value of 6.45 dsm^{-1}. The organic treatments included a control group without organic fertilizers **(I_0),** farmyard manure (FYM) compost **(I_1),** plant residues (PR) compost **(I_2)** and chicken manure (ChM) compost **(I_3)**. Additionally, the subplots were designated for foliar applications of proline amino acid, with three groups: **F_0** (without foliar application, serving as the control), **F_1** (proline at a rate of 60 mg L^{-1}), and **F_2** (proline at a rate of 100 mg L^{-1}). The study assessed various parameters at two stages: 80 days from sowing, focusing on growth indicators such as plant height, foliage fresh and dry leaf weights, and chlorophyll content and antioxidant indicators. At the harvest stage, yield-related parameters and quality aspects like the number of pods per plant, seed yield, oil, protein, carbohydrates, along with the analysis of soil nutrient availability. The results obtained illustrated that ChM compost (**I_3**) proved to be the most effective organic source in promoting optimal performance under salinity conditions, as evidenced by superior growth indicators, yield-related parameters, and quality. Following closely was PR compost **(I_2),** with FYM compost **(I_1)** ranking third, while the control group (without organic fertilizers) exhibited the lowest performance. In addition, the findings highlight the positive impact of proline amino acid on enhancing plant tolerance to salinity stress, with performance improvements correlating with increased proline levels. The sequence of proline treatments, ranked from most effective to least, was **F_2**, followed by **F_1**, then **F_0** (without proline). Analyzing soil fertility at the harvest stage, all organic sources positively influenced the availability of N, P, and K, with ChM compost (**I_3)** demonstrating superior effects. The influence of proline was nearly negligible in this aspect. Overall, the combined treatment of **I_3 x F_2** emerged as the most distinguished among the various interactions studied. Therefore, integrated approaches that combine optimal organic fertilization practices with proline applications, such as the studied combination of ChM compost and proline, should be promoted for enhanced soybean production. Ongoing research is essential to refine and expand these recommended practices for a comprehensive and sustainable approach to soybean cultivation in challenging soil conditions.

Keywords: Degraded soils, Chicken manure, Farmyard manure, Compost and Proline.

1. Introduction

Soil salinity is a formidable impediment to global agricultural sustainability, exerting deleterious effects on plant growth and productivity. Elevated concentrations of soluble salts, notably sodium chloride, disrupt the intricate balance of water and nutrient uptake by plant roots, leading to osmotic stress, ion toxicity, and compromised cellular functions **(Munns *et al.* 2020).** Despite these challenges, the imperative to cultivate saline lands persists, driven by the pressing need to expand agricultural frontiers to meet the escalating demands for food production **(Elsherpiny 2023).**

The paradox lies in the recognition that while soil salinity threatens crop health, it is imperative to manage and cultivate such lands efficiently to harness their potential for agriculture. Effective management strategies are crucial to mitigate salinity's negative impacts and unlock the latent agricultural productivity of these challenging soils. Among these strategies, organic fertilization emerges as a pivotal tool in ameliorating the adverse effects of salinity (**Abou Hussien *et al.* 2020).**

Organic fertilization, through the incorporation of organic amendments such as farmyard manure (FYM), chicken manure (ChM), and plant residues (PR) compost, assumes a central role in enhancing soil

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structure, water retention, and nutrient availability. In saline lands, where conventional fertilization practices may exacerbate salt accumulation, the judicious application of organic matter becomes paramount **(Elbaalawy *et al.* 2023).**

Furthermore, recognizing the need for innovative approaches to enhance plant tolerance to salinity, the study incorporates proline amino acid as a potential solution. Proline, known for its osmoprotectant properties, is pivotal in alleviating the physiological stress induced by salinity. By investigating the impact of varying through foliar applications **(Abd-Elzaher *et al.* 2022; Abdeen and Hefni, 2023).**

Soybeans, chosen as this study's focal crop have economic and nutritional significance. As a versatile legume, soybeans contribute substantially to global protein and oil production, playing a crucial role in human and livestock nutrition. Understanding and enhancing soybean performance under saline conditions is thus not only imperative for global food security **(Elsherpiny *et al.* 2023).**

Considering these considerations, the overarching goal of this experiment is to provide a comprehensive understanding of the interplay between organic fertilization, proline amino acid application, and soybean cultivation in saline soils. Through meticulous evaluation of growth indicators, yield-related parameters, and soil nutrient dynamics, the study aspires to contribute practical insights toward developing sustainable and integrated approaches for soybean production in regions grappling with soil salinity. The aim is to devise strategies that optimize yields, ensuring agricultural resilience and nutritional security in the face of escalating salinity challenges.

2. Material and Methods

A field trial was conducted under a split plot design with three replicates over two consecutive summer seasons (2022 and 2023) to evaluate the potential impact of various organic fertilization sources as the main plots on soybean plant cultivated in soil with an electric conductivity (EC) value of 6.45 dSm^{-1}. These sources included a control group without organic fertilizers **(I_0),** farmyard manure (FYM) compost at a rate of 10 ton fed^{-1} **(I_1),** plant residues (PR) compost at a rate of 10 ton fed^{-1} **(I_2)** and chicken manure (ChM) compost a rate of 10 ton fed^{-1} (**I_3**). Additionally, the subplots were designated for foliar applications of proline amino acid, with three groups: **F_0** (without foliar application, serving as the control), **F_1** (proline at a rate of 60 mg L^{-1}), and **F_2** (proline at a rate of 100 mg L^{-1}).

Experimental location

The research was conducted on a private farm in Met Antar village, Talkha district, El-Dakahlia Governorate, Egypt, with coordinates 31°4'54"N - 31°24'4"E.

Soil sampling and compost sources traits

Before the experimental study, soil samples were gathered from 30 cm depth. These samples underwent air-drying, sieving through a 2 mm sieve, and analysis of their characteristics. The soil properties before the experimental study are presented in Table 1. The characteristics of the studied compost sources are also shown in Table 1. All analyses were conducted according to the methodologies outlined by **Tandon (2005).**

Table 1. Properties of the initial soil and the studied compost sources (The data presented in this Table is the combined data over both studied seasons).

Property	Initial soil	ChM compost	FYM compost	Plant compost
pH	8.2 (suspension 1:2.5)	6.16 (suspension 1:10)	6.43 (suspension 1: 10)	6.25 (suspension 1: 10)
EC, dSm^{-1}	6.45	3.52	3.56	3.49
Total C, %	/	17.69	19.69	19.88
Total N, %	/	1.130	1.08	1.13
C:N ratio	/	15.65	18.23	17.59
Available N	51.20	/	/	/
Available P	10.25	/	/	/
Available K mg kg^{-1}	210.0	/	/	/
Fe	/	1.20	0.85	0.99
Zn	/	27.0	22.3	24.2
Mn		110	98.2	104.3
Organic matter,%	1.360	30.42	33.86	34.10
Sand	24.00	/	/	/
Clay	49.00	/	/	/
Silt	27.00	/	/	/
Textural	Clay	/	/	/

Compost preparation

Plant residues, specifically rice straw, animal residues from cows and sheep and poultry waste, were acquired to serve as representations of plant compost, farmyard manure (FYM), and chicken manure (ChM) compost, respectively. The composting procedure for these three types was initiated six months before the commencement of the field experiment at the experimental site, according to instructions of **Inckel *et al.* (2005).**

Soybean seeds

Soybean seeds "***Glycine max* L. Cv Giza 111**", were obtained from agricultural research center ARS.

Proline

Proline amino acid was purchased from the commercial market in Egypt and then dissolved in distilled water to achieve the desired concentrations.

Experimental set up

The experimental plot, spanning 120 m^2, underwent an addition of calcium superphosphate (6.6%P) at a rate of 150 kg fed^{-1} before ploughing. Additionally, all examined compost sources were applied before ploughing by designated treatments. On the 26th of May in both study seasons, seeds were manually sown after inoculation with rhizobium at a rate of 38 kg fed^{-1} (2-3 seeds $hill^{-1}$). At sowing time, a nitrogen dose of 15.0 kg urea fed^{-1} (46% N) was uniformly distributed across all plots. After 20 days from sowing, plant thinning was conducted to retain one soybean plant per hill. Potassium sulfate (48% K_2O) was introduced in two equal installments, with a basal application of 50 kg fed^{-1} and the remaining half applied two months after sowing. Proline was sprayed three times during the experiment, following the studied rates, at 35, 50, and 65 days from cultivation, using a volume of 490 L fed^{-1}.The agricultural practices were done in line with the recommendations of the ARS, Egypt. Harvesting occurred 120 days after sowing (25th of September).

Measurement traits

At 75 (flowering stage) and 120 days after sowing (harvest time), three plants were randomly sampled from each replicate to estimate the characteristics presented in Table 2.

Statistical analysis

Statistical analyses were performed utilizing CoStat version 6.303 copyrighted (1998-2004), as documented by **Gomez and Gomez (1984),** following the methodology detailed by **Duncan (1995).**

Table 2. Methods, formula, and references of measurements.

Measurements	Methods and formula	References
After 75 days of sowing soybean plants		
Proline content (µgg^{-1} FW)	Colourimetric measurement	**Ábrahám *et al.* (2010)**
Malondialdehyde (MDA, µmol.g^{-1} FW)	Spectrophotometrically	**Mendes *et al.* (2009)**.
Peroxidase (POX, unit mg^{-1} $protein^{-1}$), and superoxide (SOD, unit mg^{-1} $protein^{-1}$)	Spectrophotometrically	**Alici and Arabaci (2016)**
Plant height (cm), foliage fresh and dry weights (g $plant^{-1}$)	Manually and visually	**----------------**
Digested plant samples for NPK	Mixed of $HClO_4 + H_2SO_4$	**Jones and Case (1990)**
N, P, K (%)	Micro-kjeldahl, spectrophotometrically and flame photometer, respectively	**Walinga *et al.* (2013)**
Chlorophyll pigment levels (a and b, mg g^{-1})	Spectrophotometrically using acetone	**Branisa *et al.* (2014)**
At the harvest stage (After 120 days from sowing soybean plants)		
No. of pods $plant^{-1}$, pod and seed weights (g $plant^{-1}$), seed yield (Kg fed^{-1})	**Manually and visually**	**----------------**
Protein, carbohydrates and oil (%)		**A.O.A.C (2000)**
Available soil N, P, K (mg kg^{-1})	Micro-kjeldahl, spectrophotometrically and flame photometer, respectively	**Tandon (2005)**

3. Results

Enzymatic and non-enzymatic antioxidants

Table 3 depicts the impact of different compost sources and varying proline concentrations on the proline content (µg.g^{-1} FW), malondialdehyde (MDA, µmolg^{-1} FW), peroxidase enzyme activity (POX, unit mg^{-1} protein^{-1}), and superoxide dismutase (SOD, unit mg^{-1} protein^{-1}) levels in soybean leaves after 75 days from sowing in the 2022 and 2023 seasons. The results reveal that soybean plants cultivated without compost exhibited the highest values for both proline and MDA. Conversely, including any compost source led to a reduction in both proline and MDA levels, with ChM compost demonstrating the lowest values, followed by plant compost and FYM compost. On the other hand, the optimal treatment for achieving maximum peroxidase enzyme activity (POX, unit mg^{-1} protein^{-1}) and superoxide dismutase (SOD, unit mg^{-1} protein^{-1}) values was ChM compost, followed by plant compost then FYM compost, and lately the control treatment, which received no compost source. In terms of proline treatments, it can be noticed from Table 2 that all studied traits, except MDA indicator, gradually increased as the proline rate increased from 0.0 to 60 then100 mg L^{-1}. Regarding the MDA, indicator, its value gradually decreased as the proline rate increased from 0.0 to 60 then 100 mg L^{-1}. Generally, the combined application of ChM compost and proline spray at a rate of 100 mg L^{-1} demonstrated the most effective performance under salinity conditions.

Growth criteria and chemical constituents

The impact of different compost sources and proline rates on the performance of soybean plants grown on saline soil was significant, as reflected in various growth criteria [plant height (cm), foliage fresh and dry weights (g plant^{-1})], (Table 4) and leaf chemical constituents (N, P, K ,%) along with chlorophyll pigment levels (a and b, mg g^{-1}) (Table 5). The data of Tables 4 and 5 illustrated that ChM compost (**I_3**) proved to be the most effective organic source in promoting optimal performance under salinity conditions, as evidenced by superior growth and chemical indicators. Following closely was PR compost **(I_2),** with FYM compost **(I_1)** ranking third, while the control group (without organic fertilizers) exhibited the lowest performance. In addition, the findings highlight the positive impact of proline amino acid on enhancing plant tolerance to salinity stress, with performance improvements correlating with increased proline levels. The sequence of proline treatments, ranked from most effective to least, was **F_2**, followed by **F_1**, and lastly, **F_0** (without proline). Overall, the combined treatment of **I_3 x F_2** emerged as the most superior among the various interactions studied.

Yield and its components

The impact of diverse compost sources and proline rates on parameters related to yield (No. of pods plant^{-1}, pod and seed weights in g plant^{-1}, seed yield in Kg fed^{-1}) and quality (protein, carbohydrates, and oil in %) is presented in Tables 6 and 7, respectively. The results indicate that ChM compost **(I_3)** was the most effective organic source in promoting optimal performance under salinity conditions, as demonstrated by superior yield-related parameters and quality. Following closely was PR compost **(I_2),** with FYM compost **(I_1)** ranking third, while the control group (without organic fertilizers) exhibited the lowest performance.

Moreover, the findings underscore the positive impact of proline amino acid in enhancing plant tolerance to salinity stress, with performance improvements corresponding to increased proline levels. The sequence of proline treatments, ranked from most effective to least, was **F_2**, followed by **F_1**, and lastly, **F_0** (without proline). Overall, the combined treatment of **I_3 x F_2** emerged as superior among the various interactions studied, showcasing comprehensive enhancements in yield-related parameters and quality.

Table 3. Effect of various compost sources and proline on leaves proline content, MDA indicator and plant's self-production of enzymatic antioxidants (POX and SOD) at a period of 75 days from soybean plant's life during seasons of 2022 and 2023.

Treatments	Proline ($\mu g g^{-1}$ FW)		Malondialdehyde (MDA) ($\mu mol\ g^{-1}$ FW)		Peroxidase (POX) (unit mg^{-1} protein^{-1})		Superoxide (SOD) (unit mg^{-1} protein^{-1})	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Compost treatments								
I_0: Without	8.22a	8.41a	12.37a	12.55a	1.552d	1.611d	43.68d	44.19d
I_1: FYM compost	8.01b	8.17b	11.14b	11.31b	2.080c	2.164c	46.97c	47.50c
I_2: Plant compost	7.96bc	8.05b	10.70c	10.90c	2.423b	2.469b	49.44b	50.01b
I_3: ChM compost	7.85c	8.04b	9.79d	9.92d	2.714a	2.819a	51.65a	52.40a
LSD 5%	**0.13**	**0.14**	**0.20**	**0.20**	**0.036**	**0.042**	**0.59**	**0.42**
Proline treatments								
F_0: Without	7.60b	7.73c	11.35a	11.52a	2.103c	2.166c	47.30c	47.67c
F_1: Proline (60 mg L^{-1})	8.15a	8.32b	10.88b	11.06b	2.190b	2.272b	47.88b	48.53b
F_2: Proline (100 mg L^{-1})	8.28a	8.46a	10.77b	10.94b	2.284a	2.359a	48.64a	49.38a
LSD 5%	**0.17**	**0.10**	**0.17**	**0.14**	**0.022**	**0.026**	**0.45**	**0.60**
Interaction								
I x F (LSD 5%)	**0.34**	**0.21**	**0.34**	**0.27**	**0.044**	**0.052**	**0.90**	**1.21**
I_0 **F_0**	7.72de	7.90e	12.84a	13.03a	1.470k	1.526k	42.46f	42.84g
F_1	8.34ab	8.51b	12.25b	12.41b	1.565j	1.625j	43.98e	44.48f
F_2	8.61a	8.82a	12.03b	12.21b	1.621i	1.683i	44.61e	45.25f
I_1 **F_0**	7.60e	7.74ef	11.49c	11.65c	1.937h	2.016h	46.31d	46.72e
F_1	8.16bc	8.35bcd	10.99d	11.14d	2.077g	2.160g	46.45d	46.97e
F_2	8.26bc	8.42bc	10.95de	11.14d	2.225f	2.316f	48.15c	48.82d
I_2 **F_0**	7.55e	7.59f	10.82de	11.01de	2.390e	2.411e	48.99bc	49.22cd
F_1	8.15bc	8.26cd	10.66de	10.91de	2.407e	2.486d	49.53b	50.36bc
F_2	8.17bc	8.30cd	10.62e	10.79e	2.473d	2.510d	49.81b	50.45b
I_3 **F_0**	7.52e	7.67f	10.24f	10.38f	2.614c	2.713c	51.42a	51.91a
F_1	7.95cd	8.16d	9.63g	9.79g	2.712b	2.817b	51.54a	52.30a
F_2	8.09bc	8.29cd	9.48g	9.60g	2.816a	2.928a	52.00a	52.99a

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

Table 4. Effect of various compost sources and proline on growth criteria at a period of 75 days from soybean plant's life during seasons of 2022 and 2023.

Treatments	Plant height (cm)		Foliage fresh weight (g $plant^{-1}$)		Foliage dry weight (g $plant^{-1}$)	
	1st	2nd	1st	2nd	1st	2nd
Compost treatments						
I_0: Without	77.22d	79.60d	52.16d	52.78d	13.40d	13.68d
I_1: FYM compost	83.72c	86.31c	56.77c	57.64c	14.47c	14.75c
I_2: Plant compost	87.82b	90.72b	59.13b	60.26b	14.93b	15.22b
I_3: ChM compost	93.23a	95.93a	62.18a	62.95a	15.60a	15.90a
LSD 5%	**1.06**	**0.17**	**0.99**	**0.86**	**0.41**	**0.13**
Proline treatments						
F_0: Without	84.90b	87.55b	56.82c	57.62c	14.43b	14.71b
F_1: Proline (60 mg L^{-1})	85.10b	87.60b	57.45b	58.32b	14.57ab	14.85b
F_2: Proline (100 mg L^{-1})	86.50a	89.27a	58.42a	59.29a	14.80a	15.10a
LSD 5%	**0.93**	**1.19**	**0.36**	**0.68**	**0.36**	**0.21**
Interaction						
I x F (LSD 5%)	**1.87**	**2.37**	**0.72**	**1.36**	**0.71**	**0.41**
I_0 **F_0**	77.63f	79.97ef	51.34i	51.98i	13.27g	13.55g
F_1	75.61g	78.01f	51.93i	52.62hi	13.35g	13.60g
F_2	78.43f	80.83e	53.21h	53.75h	13.59fg	13.89g
I_1 **F_0**	82.24e	84.91d	56.18g	57.01g	14.23ef	14.51f
F_1	83.02e	85.56d	56.66g	57.57g	14.48de	14.71ef
F_2	85.90d	88.44c	57.48f	58.36fg	14.70cde	15.02de
I_2 **F_0**	87.77c	90.49bc	58.61e	59.61ef	14.89b-e	15.17d
F_1	88.08c	90.45bc	59.02e	60.08de	14.90b-e	15.23cd
F_2	34.29cd	91.21b	59.78d	61.09cd	14.99bcd	15.27cd
I_3 **F_0**	87.62b	94.83a	61.14c	61.88bc	15.32abc	15.61bc
F_1	93.68ab	96.37a	62.19b	63.02ab	15.56ab	15.86ab
F_2	94.05a	96.59a	63.20a	63.95a	15.94a	16.21a

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

Table 5. Effect of various compost sources and proline on leaf chemical constituents and chlorophyll pigment at a period of 75 days from soybean plant's life during seasons of 2022 and 2023.

Treatments		N		P		K		Chlorophyll a		Chlorophyll b	
		(%)						(mg g^{-1})			
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Compost treatments											
I_0: Without		3.64d	3.80d	0.356d	0.371d	2.29d	2.41d	0.899d	0.938d	0.621d	0.645d
I_1: FYM compost		3.93c	4.10c	0.393c	0.411c	2.74c	2.78c	1.002c	1.044c	0.659c	0.687c
I_2: Plant compost		4.36b	4.44b	0.411b	0.429b	2.91b	2.97b	1.049b	1.094b	0.689b	0.710b
I_3: ChM compost		4.66a	4.83a	0.431a	0.447a	3.10a	3.26a	1.092a	1.136a	0.719a	0.747a
LSD 5%		**0.07**	**0.04**	**0.010**	**0.10**	**0.02**	**0.03**	**0.022**	**0.032**	**0.020**	**0.012**
Proline treatments											
F_0: Without		4.06c	4.20c	0.393b	0.410b	2.69b	2.77c	0.994c	1.037c	0.659c	0.684c
F_1: Proline (60 mg L^{-1})		4.16b	4.31b	0.396b	0.412b	2.77a	2.86b	1.010b	1.052b	0.673b	0.699b
F_2: Proline (100 mg L^{-1})		4.23a	4.38a	0.404a	0.421a	2.83a	2.92a	1.028a	1.070a	0.683a	0.709a
LSD 5%		**0.05**	**0.10**	**0.003**	**0.003**	**0.06**	**0.04**	**0.010**	**0.011**	**0.003**	**0.009**
Interaction											
I x F		LSD 5%									
		0.10	**0.12**	**0.006**	**0.006**	**0.13**	**0.08**	**0.020**	**0.001**	**0.002**	**0.018**
I_0	**F_0**	3.57h	3.72h	0.355g	0.370g	2.12g	2.23h	0.874j	0.910l	0.605l	0.626i
	F_1	3.65gh	3.81gh	0.356g	0.371g	2.35f	2.47g	0.893j	0.932k	0.624k	0.650h
	F_2	3.71g	3.87g	0.359g	0.373g	2.41f	2.53g	0.931i	0.971j	0.633j	0.659h
I_1	**F_0**	3.87f	4.03f	0.388f	0.406f	2.71e	2.74f	0.986h	1.028i	0.650i	0.678g
	F_1	3.96ef	4.11ef	0.389f	0.405f	2.73e	2.77ef	1.004gh	1.046h	0.660h	0.688fg
	F_2	3.98e	4.16de	0.403e	0.422e	2.78de	2.82e	1.018fg	1.058g	0.668g	0.696efg
I_2	**F_0**	4.21d	4.28d	0.406de	0.423de	2.86cd	2.91d	1.038ef	1.087f	0.680f	0.704def
	F_1	4.39c	4.47c	0.411d	0.429d	2.91c	2.97cd	1.051de	1.095e	0.689e	0.711cde
	F_2	4.48c	4.56c	0.418c	0.436c	2.96bc	3.02c	1.059cd	1.102d	0.697d	0.715cd
I_3	**F_0**	4.58b	4.76b	0.426b	0.442b	3.07ab	3.21b	1.078bc	1.124c	0.702c	0.729bc
	F_1	4.65ab	4.83ab	0.429b	0.445b	3.08ab	3.25ab	1.093ab	1.137b	0.720b	0.746b
	F_2	4.74a	4.91a	0.438a	0.455a	3.16a	3.33a	1.104a	1.147a	0.734a	0.767a

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

Table 6. Effect of various compost sources and proline on soybean yield and its components during seasons of 2022 and 2023.

Treatments		No. of pods $plant^{-1}$		Pods weight		Seeds weight		Seed yield	
				(g $plant^{-1}$)				(Kg fed^{-1})	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd
Compost treatments									
I_0: Without		58.11d	61.22d	45.26d	45.88d	23.87c	24.34d	1302.00d	1322.44d
I_1: FYM compost		72.00c	74.89c	51.53c	52.33c	27.55b	28.00c	1496.67c	1519.44c
I_2: Plant compost		77.78b	82.78b	57.02b	57.20b	28.59b	30.46b	1579.78b	1617.89b
I_3: ChM compost		85.56a	90.00a	61.83a	62.78a	31.73a	32.58a	1676.33a	1700.78a
LSD 5%		**3.74**	**2.41**	**0.35**	**0.49**	**1.50**	**0.28**	**9.16**	**9.32**
Proline treatments									
F_0: Without		70.58c	74.50b	52.61b	53.45c	27.62a	28.54b	1479.17b	1504.92c
F_1: Proline (60 mg L^{-1})		73.25b	76.50b	53.93ab	54.50b	27.93a	28.81ab	1521.75a	1544.25b
F_2: Proline (100 mg L^{-1})		76.25a	80.67a	55.19a	55.70a	28.25a	29.19a	1540.17a	1571.25a
LSD 5%		**2.29**	**2.53**	**1.50**	**0.75**	***NS**	**0.42**	**38.46**	**15.33**
Interaction									
I x F		LSD 5%							
		4.57	**5.05**	**3.01**	**1.50**	**1.90**	**0.84**	**76.93**	**30.65**
I_0	**F_0**	54.67f	58.00i	43.23g	43.89g	23.67f	24.22e	1269.33f	1283.33h
	F_1	57.67ef	60.00i	45.75fg	46.31f	23.76f	24.26e	1311.33f	1328.67g
	F_2	62.00e	65.67h	46.79f	47.45f	24.18f	24.53e	1325.33f	1355.33g
I_1	**F_0**	70.00d	72.00g	50.44e	51.27e	27.29e	27.77d	1466.67e	1496.00f
	F_1	72.00d	74.67fg	50.93e	51.60e	27.59e	27.98d	1507.67de	1523.67ef
	F_2	74.00d	78.00ef	53.23de	54.12d	27.76de	28.24d	1515.67de	1538.67e
I_2	**F_0**	74.00d	81.00de	55.80cd	56.76c	29.48de	30.03c	1558.00cd	1595.33d
	F_1	79.00c	82.33cde	57.16c	57.22c	30.10cd	30.63c	1579.33cd	1611.33d
	F_2	80.33bc	85.00bcd	58.10bc	57.64c	26.19bc	30.74c	1602.00c	1647.00c
I_3	**F_0**	83.67b	87.00bc	60.96ab	61.88b	31.29abc	32.14b	1622.67bc	1645.00c
	F_1	84.33ab	89.00ab	61.89a	62.88ab	31.57ab	32.35b	1688.67ab	1713.33b
	F_2	88.67a	94.00a	62.65a	63.58a	32.34a	33.24a	1717.67a	1744.00a

Means within a row followed by a different letter (s) are statistically different at a 0.05 level.
*NS= non-significant.

Table 7. Effect of various compost sources and proline on the quality of soybean seeds during seasons of 2022 and 2023

Treatments		Protein		Carbohydrates		Oil	
		(%)					
		1st	2nd	1st	2nd	1st	2nd
Compost treatments							
I_0: Without		27.33d	27.80d	21.78d	22.30d	20.67d	21.06d
I_1: FYM compost		29.39c	30.04c	23.20c	23.76c	22.65c	23.08c
I_2: Plant compost		30.70b	31.35b	24.07b	24.70b	23.70b	24.16b
I_3: ChM compost		32.43a	33.02a	25.07a	25.64a	24.34a	24.89a
LSD 5%		**0.97**	**0.48**	**0.33**	**0.21**	**0.36**	**0.13**
Proline treatments							
F_0: Without		29.26b	29.80c	23.10c	23.62b	22.55b	22.96c
F_1: Proline (60 mg L^{-1})		30.09a	30.73b	23.59b	24.17a	22.79b	23.24b
F_2: Proline (100 mg L^{-1})		30.55a	31.13a	23.90a	24.50a	23.18a	23.70a
LSD 5%		**0.47**	**0.37**	**0.28**	**0.34**	**0.27**	**0.19**
Interaction							
I x F		LSD 5%					
		0.95	**0.75**	**0.57**	**0.68**	**0.54**	**0.37**
I_0	F_0	25.76i	26.14i	21.24i	21.76i	20.24h	20.60i
	F_1	27.95h	28.51h	21.76hi	22.23hi	20.57h	20.97i
	F_2	28.27gh	28.73h	22.32gh	22.90gh	21.20g	21.62h
I_1	F_0	29.05fg	29.66g	22.89fg	23.34fg	22.31f	22.66g
	F_1	29.27f	29.96fg	23.22ef	23.83ef	22.52f	22.96g
	F_2	29.86ef	30.50ef	23.48de	24.11de	23.12e	23.63f
I_2	F_0	30.42de	31.03de	23.83cd	24.35cde	23.51de	23.90ef
	F_1	30.66de	31.40d	24.10bc	24.78bcd	23.73cd	24.16de
	F_2	31.04cd	31.62cd	24.29bc	24.96bc	23.86bcd	24.43cd
I_3	F_0	31.80bc	32.36bc	24.42b	25.04b	24.14abc	24.66bc
	F_1	32.46ab	33.04ab	25.27a	25.84a	24.34ab	24.88ab
	F_2	33.04a	33.67a	25.52a	26.03a	24.53a	25.12a

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

Post-harvest soil analysis

Table 8 and Figs 1, 2, 3 illustrate the impact of various compost sources and proline on soil available nutrients *i.e.*, N, P and K (mg kg^{-1}) after harvest. It can be noticed that all organic sources positively influenced the availability of N, P, and K, with ChM compost **(I_3)** demonstrating superior effects. In other words, the highest values of soil available nutrients *i.e.*, N, P and K (mg kg^{-1}) were realized with ChM compost, followed by plant compost then FYM compost, and lately the control treatment, which received no compost source. The influence of proline was nearly negligible in this aspect.

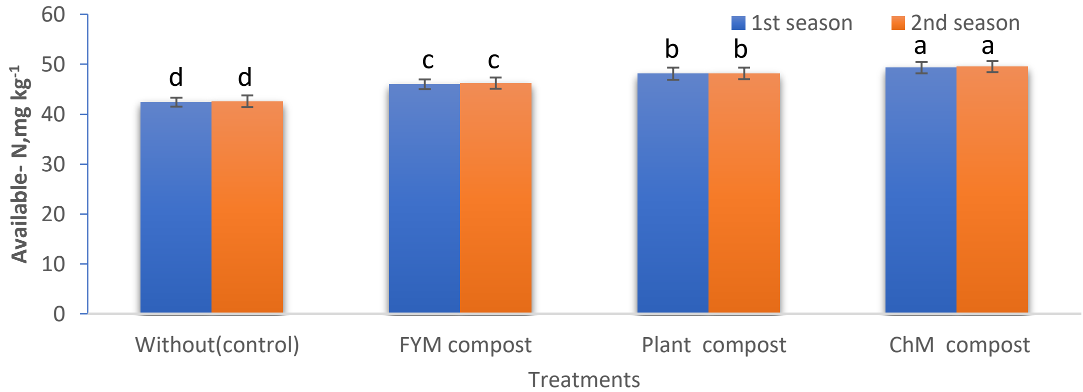

Fig. 1. The individual effect of various compost sources on soil available nitrogen after harvest during seasons of 2022 and 2023

Table 8. Effect of various compost sources and proline on soil nutrient availability after harvest during seasons of 2022 and 2023

Treatments		Available- N (mg kg^{-1})		Available - P (mg kg^{-1})		Available - K (mg kg^{-1})	
		1st	2nd	1st	2nd	1st	2nd
Compost treatments							
I_0: Without		42.40d	42.58d	10.32d	10.75c	230.07d	232.82c
I_1: FYM compost		45.99c	46.23c	10.71c	10.80c	236.92c	240.76b
I_2: Plant compost		48.10b	48.17b	10.96b	11.10b	241.90b	246.32a
I_3: ChM compost		49.35a	49.54a	11.35a	11.81a	245.96a	248.81a
LSD 5%		**0.83**	**1.08**	**0.10**	**0.08**	**0.30**	**4.30**
Proline treatments							
F_0: Without		46.86a	46.92a	10.94a	11.23a	240.03a	243.25a
F_1: Proline (60 mg L^{-1})		46.51ab	46.73ab	10.81ab	11.09ab	238.78a	242.32a
F_2: Proline (100 mg L^{-1})		46.02b	46.24b	10.76b	11.02b	237.33a	240.96a
LSD 5%		**0.69**	**0.52**	**0.13**	**0.20**	**NS**	**NS**
Interaction							
I x F		**LSD 5%**					
		1.38	**1.03**	**0.26**	**0.40**	**6.42**	**4.63**
I_0	F_0	42.89f	43.05d	10.48fg	10.92bc	233.00d	235.29de
	F_1	42.82fg	42.97d	10.28gh	10.71cd	229.90e	232.74ef
	F_2	41.49g	41.71e	10.19h	10.63d	227.31f	230.44f
I_1	F_0	46.40de	46.58c	10.76de	10.87bc	237.48b	241.61bc
	F_1	45.93e	46.27c	10.70def	10.81bc	237.45b	241.21c
	F_2	45.65e	45.83	10.67ef	10.72cd	235.82c	239.45cd
I_2	F_0	48.58abc	48.33cb	11.04bc	11.19b	242.74a	246.33a
	F_1	48.02bc	48.16b	10.95cd	11.08bc	241.81a	246.40a
	F_2	47.71cd	48.02b	10.88cde	11.02bc	241.16a	246.23ab
I_3	F_0	49.56a	49.71a	11.46a	11.94a	246.91a	249.78a
	F_1	49.28ab	49.52a	11.31a	11.76a	245.97a	248.92a
	F_2	49.21ab	49.38a	11.28ab	11.72a	245.02a	247.71a

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
***NS= non-significant**

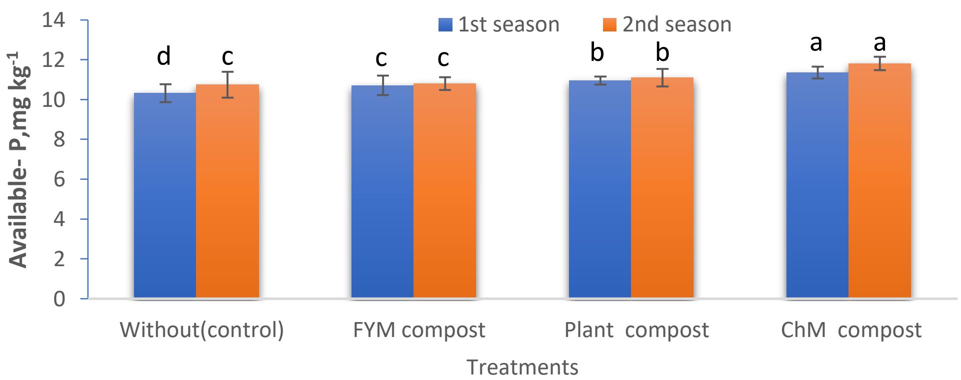

Fig. 2. The individual effect of various compost sources on soil available phosphorus after harvest during seasons of 2022 and 2023.

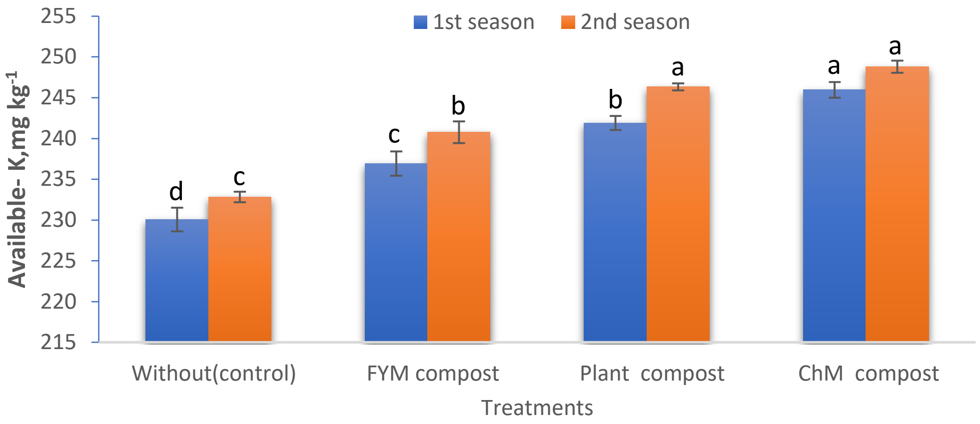

Fig. 3. The individual effect of various compost sources on soil available potassium after harvest during seasons of 2022 and 2023.

4. Discussion

Enzymatic and non-enzymatic antioxidants

Soybean plants cultivated without compost exhibited elevated levels of proline and malondialdehyde (MDA). This suggests that in the absence of organic amendments, the plants experienced heightened stress, leading to an accumulation of proline as an osmo-protectant and an increase in MDA, indicating oxidative damage **(Hnilickova *et al.* 2021).** The introduction of compost sources, including ChM, plant compost, and FYM compost reduced proline and MDA levels. This implies that the organic amendments played a role in mitigating salinity-induced stress, potentially by enhancing the plant's ability to manage osmotic stress and reducing oxidative damage **(Khatun *et al.* 2019).**

ChM compost emerged as the most effective in promoting peroxidase enzyme activity (POX) and superoxide dismutase (SOD) levels, indicating a robust antioxidant defense mechanism. This is likely due to bioactive compounds and beneficial microorganisms in ChM compost, enhancing the plant's capacity to scavenge reactive oxygen species (ROS) and alleviate oxidative stress **(Ait-El-Mokhtar *et al.* 2022).**

The gradual increase in enzymatic antioxidant activities with the rise in proline concentration suggests a positive correlation between proline application and the plant's ability to activate enzymatic antioxidant defenses. This aligns with the well-known role of proline as an osmo-protectant and its involvement in cellular protection against oxidative stress **(Ibrahim *et al.* 2019).** The most effective performance under salinity conditions was observed with the combined application of ChM compost and proline spray at a rate of 100 mg L^{-1}. This suggests a synergistic effect between the organic amendment and proline in enhancing the plant's adaptive mechanisms to salinity stress. ChM compost likely provided a conducive soil environment, while proline further fortified the plant's stress tolerance through osmo-protection and antioxidant activities.

Growth criteria and chemical constituents

In salinity stress, the notable performance differences observed in soybean plants subjected to different compost sources and proline rates can be attributed to several scientific factors. ChM compost (**I_3**) emerged as the most effective organic source, likely due to its rich nutrient content and beneficial microbial populations, collectively facilitating improved nutrient uptake and utilization by soybean plants under salinity conditions. This enhanced nutrient availability positively influenced growth criteria such as plant height and foliage weights (**Ossai 2021; Elbaalawy *et al.* 2023).** Additionally, ChM compost may have contributed to a more favorable soil environment, mitigating the detrimental effects of salinity on plant growth. The positive impact of proline amino acid further enhanced the plants' tolerance to salinity stress, with the proline treatments revealing a dose-dependent response **(Abd-Elzaher *et al.* 2022; Abdeen and Hefni, 2023)**. The combination of ChM compost and the highest proline treatment (**F_2**) exhibited a synergistic effect, demonstrating the most superior performance by concurrently addressing nutrient availability, osmo-protection, and antioxidant functions crucial for soybean adaptation to saline soils.

Yield and its components

The observed outcomes regarding soybean yield and its components under salinity stress can be elucidated by various scientific factors influenced by diverse compost sources and proline rates. ChM compost (**I_3**) exhibited superiority as an organic source, likely due to its ability to enhance soil fertility and nutrient availability. The beneficial microorganisms present in ChM compost may have contributed to nutrient mobilization and uptake by the soybean plants, counteracting the adverse effects of salinity on yield-related parameters. Proline amino acid, known for its osmo-protective and antioxidant properties, played a crucial role in enhancing plant tolerance to salinity stress, as evidenced by the positive correlation between increased proline levels and improved yield components**(Abd-Elzaher *et al.* 2022; Abdeen and Hefni, 2023)**. The combination of ChM compost and the highest proline treatment (**F_2**) demonstrated a synergistic effect, showcasing comprehensive enhancements in yield-related parameters and soybean produce quality. These findings emphasize the importance of integrated approaches, combining optimal organic fertilization practices with proline applications, to maximize soybean productivity under challenging salinity conditions.

Post-harvest soil analysis

The positive influence of organic sources, particularly ChM compost **(I_3),** on soil nutrient availability can be attributed to multiple mechanisms. ChM compost likely had a higher nutrient content, providing an enriched source of nitrogen (N), phosphorus (P), and potassium (K) to the soil. This can be attributed to the composition of chicken manure, which is inherently rich in essential nutrients. Organic composts harbor beneficial microorganisms contributing to nutrient cycling and mineralization (**Biratu *et al.* 2018**). These microorganisms in ChM compost might have facilitated the release of N, P, and K from organic matter in the soil, making these nutrients more available to plants. The incorporation of organic composts improves soil structure and water retention. This enhancement of soil physical properties might have contributed to better nutrient availability by creating a more favorable environment for root development (**Adekiya *et al.* 2020**).

The nearly negligible influence of proline on soil nutrient availability suggests that its primary role might be in enhancing plant tolerance to salinity stress rather than directly affecting soil nutrient dynamics. Proline's primary functions as an osmo-protectant and antioxidant might not directly influence soil nutrient concentrations.

5. Conclusion

Based on the study's findings, it is recommended to prioritize using ChM compost (**I_3**) for soybean cultivation in saline soils due to its remarkable efficacy. Further exploration of the long-term effects and sustainability of different organic fertilization sources is encouraged. Proline amino acid applications, especially at higher concentrations (**F_2**), should be considered to enhance soybean plant tolerance to salinity stress. Integrated approaches that combine optimal organic fertilization practices with proline applications, such as the studied combination of ChM compost and **F_2** proline, should be promoted for enhanced soybean production. Ongoing research is essential to refine and expand these recommended practices for a comprehensive and sustainable approach to soybean cultivation in challenging soil conditions.

Conflicts of interest

The authors have declared that no competing interests exist.

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