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Integrating compost and foliar boron nutrition with mineral nitrogen fertilization improves productivity, quality, and nutrient acquisition of sugar beet

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ADEQUATE and balanced crop nutrition is essential for realizing yield potential of sugar beet (*Beta vulgaris* L.). Over-reliance on the mineral nitrogen (N) fertilizers poses environmental risks, while boron (B) deficiency also limits productivity. Field studies were conducted over two seasons to evaluate combinations of mineral N fertilizer, compost, and foliar B nutrition on sugar beet. Treatments included four compost-mineral N ratios (100% recommended nitrogen dose (RND) as urea, 75% RND + 25% RND as compost, 50% RND + 50% RND as compost, and 100% RND as compost) and four foliar B regimes (0, Milano 15%, Borax 11%, and Boric acid 17% B sprays). Integrating compost supplying 25-50% N enhanced root and sugar yields over sole urea, likely by providing balanced nutrition. Foliar B increased yields, with the maximum at Boric acid 17% B indicating sub-optimal crop B status. Boric acid spraying combined with higher mineral N increased yields synergistically. Incorporating compost improves quality parameters like sucrose content and sugar recovery. Foliar B augmented the quality response, benefiting sucrose accumulation and purity through physiological regulation. An integrated nutrient strategy combining compost and foliar B with mineral N is suggested for promoting productivity and quality in sugar beet.

Keywords: Sugar beet, compost, foliar boron, mineral nitrogen, yield, quality.

1. Introduction

Sugar beet *(Beta vulgaris* L.) is a major sugar-producing crop grown in temperate zones all over the world. Egypt is one of the major sugar beet growing countries seeking to enhance productivity through optimized agronomic practices (FAOSTAT, 2021). Nitrogen is often a yield-limiting nutrient and sugar beet requires adequate nitrogen supply for high yields (Mosaad et al., 2022; Varga et al., 2022). Though mineral nitrogen fertilizers are commonly applied, its excessive use poses environmental risks including soil acidification and groundwater contamination (Ju et al., 2007; Tyagi et al., 2022). Integrating organic amendments like compost could allow partial substitution of mineral nitrogen, in addition to promoting soil health and sustainability (Agegnehu et al., 2016; Elbaalawy et al., 2023; Liu et al., 2021).

Boron is another essential micronutrient influencing sugar beet development and quality (El-Hafiz & Elmahdy, 2023; Enan et al., 2023; Tayyab et al., 2022). It facilitates sugar transport, cell wall structure and metabolism of nitrogen and carbohydrates (Enan et al., 2023; Song et al., 2022, 2023; Tayyab et al., 2022). Marginal boron deficiency is widespread among crops due to boron inadequate in soil and immobility in the phloem (Brown et al., 2002; Kohli et al., 2023; Nejad & Etesami, 2020; Wimmer et al., 2019). Foliar boron application helps overcome limited mobility in the soil-plant system thereby enhancing productivity (El-hady, 2017; Ibrahim et al., 2020; Faiyad et al. 2023).

There have been few studies evaluating combination of compost, mineral nitrogen fertilizer and foliar boron nutrition in sugar beet. Their interaction effects on productivity, quality and nutrient uptake are unclear. The present study tested the hypothesis that partially replacing mineral nitrogen with compost integrated with foliar boron application can improve yields, processing quality and nutrient acquisition in sugar beet compared to their sole applications. Field experiments over two seasons investigated growth, yield attributes, quality parameters and nutritional status of sugar beet under different compost-mineral nitrogen combinations and boron nutrition regimes.

2. Materials and Methods

2.1. Experimental Site Description

Field experiments were carried out at the El-Serw Agriculture Research Station in Damietta Governorate, Egypt (31°22' N, 31°64' E) under the

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auspices of the Agricultural Research Center during the 2019/2020 and 2020/2021 seasons. The soil at the experimental site has a clayey texture and a slightly alkaline pH (Table 1).

Table 1. Soil physical and chemical parameters of the tested soils prior to sugar beet production during the seasons 2019/2020 and 2020/2021.

Soil properties	2019/2020 season	2020/2021 season
Particle size distribution (%)		
Coarse Sand	10.50	10.70
Fine Sand	11.50	11.30
Silt	20.50	20.50
Clay	57.50	57.50
Texture Class	Clayey	Clayey
Chemical properties		
pH (1:2.5)	8.40	8.20
EC dS m^{-1}	3.50	3.20
OM %	0.98	0.88
Available Nutrients (mg kg soil $^{-1}$)		
Nitrogen (N)	32.00	32.00
Phosphorus (P)	8.40	8.42
Potassium (K)	450.00	465.00

2.2. Experimental design and crop management

The experiments were designed as a strip plot with three replications. The vertical plots included four mineral nitrogen and compost combination treatments: 100% RND as urea (100%NM), 75% RND as urea + 25% RND as compost (75%NM+25%NC), 50% RND as urea + 50% RND as compost (50%NM+50%NC), and 100% RND as compost (100%NC). Four foliar boron treatments were used in the horizontal plots: control (water spray B0), Milano 15% B (B1), borax 11% B (B2), and boric acid 17% B (B3). During the growing season, the boron treatments were applied twice (Fig 1). The chemical analysis of the compost used in both seasons is shown in Table 2.

Table 2. Pooled chemical analysis of compost used in both seasons.

pH 1:10	EC (1:10) dS m^{-1}	O.M	O.C	N	P	K	C/N ratio	Fe	Mg	Cu	Zn	Cd
		%						(mg kg^{-1})				
6.62	4.35	31.0	19.35	1.25	0.45	0.72	15.48	63.3	26.6	5.65	18.55	0.95

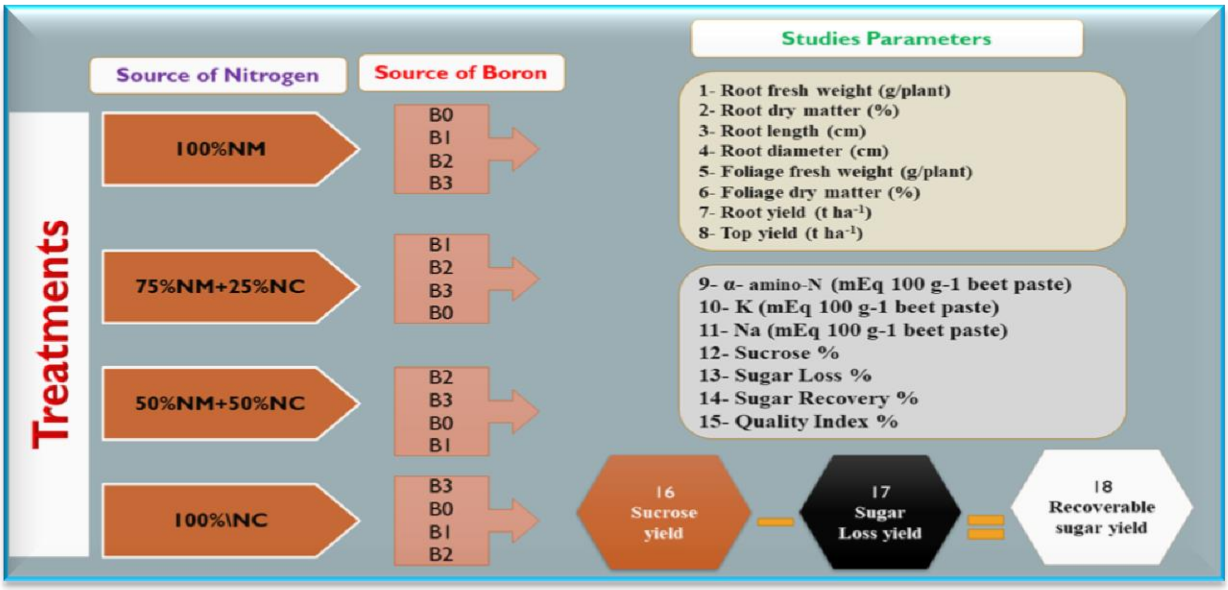

Fig. 1. General description of the study (abbreviations):
RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano (15 % B), B2= Borax (11 % B), and B3= Boric acid (17 % B)

In the first and second seasons, the sugar beet variety Zwan poly sowing took place on the 15th and 18th of October, respectively. All cultural practices including fertilization with phosphorus and potassium were done as per recommendations. The compost and 50% urea were incorporated into soil before sowing while the remaining 50% urea was side dressed at later growth stages (Power & Prasad, 1997).

2.3. Measurements

At harvest (190 days from sowing), five plants were randomly selected from each plot. Root and shoot fresh weights were recorded and samples were oven dried to estimate dry matter percentage. Root length and diameter were measured.

A random sample of roots from each plot was obtained to determine root quality parameters, which included:

Concentrations of alpha-amino nitrogen (alpha-amino-N) as well as Na and K were calculated using an Automation BV Analyzer IIG16-12-99, 9716JP/ Groningen / Holland as defined by (A.O.A.C. 2005). Concentrations were calculated as (mEq 100 g^{-1} beet paste). Sucrose content was determined using the Saccharometer in fresh sugar beet root samples using the method described by (A.O.A.C. 2005). The percentage of sugar loss was determined using the following formula (Cooke & Scott, 2012):

Sugar loss % = 0.29 + (0.343 × (K% + Na %)) + 0.094 α-amino-N

The percentage of sugar recovery was studied using the following equation by (Cooke & Scott, 2012):

1. Sugar Loss Percentage

Sugar Loss %=0.29+(0.343×(K%+Na %))+0.094×α-amino-N

2. Percentage of Sugar Recovery

Percentage of Sugar Recovery (%)=Percentage of(Sucrose−Sugar Loss)

3. Sugar Quality Index Percentage

Sugar Quality Index %=(Percentage of Sugar Recovery×100)/Sucrose %

4. Sucrose Yield

Sucrose Yield (t/ha)=(Root Yield (t/ha)×Sucrose %)/100

5. Recoverable Sugar Yield

Recoverable Sugar Yield (t/ha)= (Root Yield (t/ha)×Sugar Recovery %)/100

6. Sugar Loss Yield

Sugar Loss Yield (t/ha) =(Root Yield (t/ha)×Sugar Loss %)/100

2.4. Statistical analyses

The strip-plot design was analyzed using analysis of variance (Steel & Torrie, 1980). Means were statistically differentiated using Duncan's multiple range test at 5% level of significance (Snedecor & Cochran, 1989). SPSS (v. 24, IBM Inc., Chicago, II, USA) software was used for analysis.

3. Results

3.1. Growth parameters of sugar beet

Mineral nitrogen combined with compost exhibited a significant ($p \leq 0.01$) influence on root fresh weight, dry matter percentage, root length, and diameter (Table 3). The 100NM treatment produced the most root fresh weight (769.29 and 802.99 g/plant), root dry mater percentage (24.76 and 24.74%) and root length (32.95 and 34.22 cm) in the first and second seasons, respectively, which was significantly higher than the 75NM+25NC, 50NM:50NC, and 100NC treatments. The root fresh weight decreased as the compost ratio in the nitrogen source increased. Similarly, 100NM resulted in the largest root diameter (10.66 and 11.51 cm in the first and second seasons, respectively), which was significantly bigger than all other treatments. With increasing compost ratio, root dry matter percentage and length fell marginally but dramatically.

Foliar application of boron increased root fresh weight, length and diameter compared to the control without boron, with boric acid at 17% B resulting in the highest values, significantly greater than other boron sources.

The interaction between nitrogen source and boron application was not significant for any of the root parameters, indicating their effects were mostly independent.

The treatments showed similar directional effects on foliage fresh weights and dry matter percentages as observed for the root parameters (Table 4). The 100NM treatment resulted in the highest foliage fresh weight, significantly greater than all other treatments, which decreased progressively and significantly with increasing ratio of compost. Foliage dry matter percentage was highest with 100NM and lowest with 100NC, with all treatments differing significantly.

Foliar boron application significantly increased both foliage fresh weights and dry matter percentages over the control. Boric acid application led to the highest foliage fresh weight (267.71 and 279.13 g/plant) and dry matter percentage (15.43%

and 15.36%), statistically greater than those of other boron treatments. The interaction between nitrogen source and boron application was not significant for the foliage parameters.

3.2. Root, top and sugar yields

As shown in Table 5, root, top and sugar yields followed the same trends as fresh weights, with 100NM having the highest yields (71.61, 71.69 t/ha for root yields in first and second seasons), significantly greater than all other treatments. The yields showed a decreasing trend with increasing ratio of compost in nitrogen fertilization.

Boron application markedly increased root, top and sugar yields over the control without boron. Maximum yields were obtained by boric acid treatment, which were significantly higher than those from other boron sources.

The interaction between nitrogen treatments and boron application was significant for root, top and sugar yields, indicating synergistic effects. As shown in Figures 2 and 3, differences between boron treatments depended on the nitrogen source - the highest incremental gains were observed when boron (as boric acid) was combined with higher ratios of mineral fertilizers (100NM and 75NM:25NC) while lower yields were obtained from combinations with higher compost ratios (50NM:50NC and 100NC).

3.3. Chemical compositions of sugar beet

The effect of treatments on amino-N, potassium, and sodium concentrations (mEq $100g^{-1}$ beet paste) is presented in Table 6. Alpha amino-N concentration showed a decreasing trend with increasing ratio of compost, with 100NM resulting in the highest concentration (2.707 and 2.715 mEq $100g^{-1}$ beet paste) which was significantly greater than other treatments. While potassium concentration was lowest with 100NC treatment and highest with 50NM+50NC and 100NM in the first and second seasons, respectively. Sodium concentration was unaffected by nitrogen source but showed a slight increasing trend with foliar boron application up to 0.132 mEq/100g beet paste with boric acid treatment.

Boron application increased amino-N concentrations compared to the control, with boric acid resulting in significantly higher concentration than Milano across both seasons. Potassium concentration also increased with foliar boron but differences between boron treatments were mostly non-significant. The interaction between nitrogen source and boron application was not significant for any of all chemical compositions of sugar beet.

3.4. Quality parameters of sugar beet

Quality parameters Sucrose content such as sucrose, sugar recovery and quality index showed an increasing trend while sugar loss decreased significantly with increasing ratio of compost in nitrogen fertilization. Maximum sucrose content was obtained with 100NC (17.81% and 17.85%) which was significantly higher than other treatments (Table 7). Recoverable sugar yield was highest with 75NM+25NC treatment (Table 8).

Boron application significantly enhanced quality parameters compared to the control without boron. The highest sucrose content (17.84% and 17.79%), sugar recovery and quality index along with lowest sugar loss was obtained with boric acid treatment. Statistical analysis across both seasons showed boric acid resulted in significantly higher sucrose content, sugar loss and sugar recovery percentage than borax and Milano.

Sucrose yield and recoverable sugar yield was highest with 75NM+25NC treatment, while the highest sugar loss yield was obtained with 100NM (Table 8). The control without boron had the lowest sucrose yield, recoverable sugar yield and sugar loss yield. Boric acid application led to significantly higher sucrose yield, recoverable sugar yield and sugar loss yield over other boron treatments with mostly significant.

The interaction between nitrogen source and boron application had a pronounced effect on all three sugar yield parameters as evident from Figures 4, 5 and 6. Maximum sucrose yield was obtained from combination of boric acid spraying with higher ratios of mineral fertilization (75NM:25NC and 100NM) while lower yields resulted from combinations with higher compost (50NM:50NC and 100NC). Similarly, recoverable sugar yield was highest for boric acid × 100NM combination. Sugar loss yield showed a proportional increase with higher nitrogen application for each boron treatment.

Table 3. Root fresh weights/plant, foliage dry matter percentages, root length and diameter of sugar beet as affected by combination between mineral nitrogen fertilizer + compost and foliar spraying with boron sources as well as their interaction during 2019/2020 and 2020/2021 seasons.

Treatments	Root fresh weight (g/plant)		Root dry matter (%)		Root length (cm)		Root diameter (cm)	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Combination between mineral nitrogen fertilizer and compost								
100NM	769.29 a	802.99 a	24.76 a	24.74 a	32.95 a	34.22 a	10.66 a	11.51 a
75NM+25NC	718.79 b	736.19 b	24.62 b	24.72 b	32.70 b	33.73 b	10.59 b	11.41 b
50NM+50NC	675.94 c	700.04 c	24.60 c	24.72 b	31.96 c	32.93 c	10.10 c	10.63 c
100NC	613.14 d	630.24 d	24.20 d	24.26 c	31.20 d	31.96 d	9.93 d	10.51 d
F-test	**	**	**	**	**	**	**	**
Foliar spraying with boron								
B0	635.05 d	648.48 d	24.25 d	24.31 d	31.55 d	32.41 d	9.72 d	10.34 d
B1	658.50 c	686.28 c	24.37 c	24.50 c	31.79 c	32.61 c	10.13 c	10.75 c
B2	742.85 a	747.48 b	24.67 b	24.77 b	32.59 b	33.66 b	10.53 b	11.35 b
B3	740.75 b	787.23 a	24.89 a	24.87 a	32.87 a	34.15 a	10.90 a	11.61 a
F-test	**	**	**	**	**	**	**	**
Interaction								
F-test	ns	ns	ns	ns	ns	ns	ns	ns

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

Table 4. Foliage fresh weights/plant and foliage dry matter percentages of sugar beet as affected by combination between mineral nitrogen fertilizer + compost and foliar spraying with boron sources as well as their interaction during 2019/2020 and 2020/2021 seasons.

Treatments	Foliage fresh weight (g/plant)		Foliage dry matter (%)	
	1st	2nd	1st	2nd
Combination between mineral nitrogen fertilizer and compost				
100NM	263.86 a	278.23 a	15.17 a	15.08 a
75NM+25NC	241.81 b	251.08 b	15.01 b	14.96 b
50NM+50NC	236.96 c	249.28 c	14.95 c	14.88 c
100NC	211.46 d	221.63 d	14.60 d	14.50 d
F-test	**	**	**	**
Foliar spraying with boron				
B0	213.26 d	221.73 d	14.49 d	14.43 d
B1	218.16 c	231.08 c	14.65 c	14.64 c
B2	254.96 b	268.28 b	15.16 b	15.01 b
B3	267.71 a	279.13 a	15.43 a	15.36 a
F-test	**	**	**	**
Interaction				
F-test	ns	ns	ns	ns

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

Table 5. Root, top yields (t ha^{-1}) of sugar beet as affected by combination between mineral nitrogen fertilizer + compost and foliar spraying with boron sources as well as their interaction during 2019/2020 and 2020/2021 seasons.

Treatments	Root yield (t ha^{-1})		Top yield (t ha^{-1})	
	1st	2nd	1st	2nd
Combination between mineral nitrogen fertilizer and compost				
100NM	71.61 a	71.69 a	23.36 a	24.70 a
75NM+25NC	70.24 b	70.60 b	22.69 b	24.46 b
50NM+50NC	69.21 c	68.16 c	20.86 c	21.85 c
100NC	66.68 d	66.69 d	20.20 d	20.92 d
F-test	**	**	**	**
Foliar spraying with boron				
B0	66.73 d	66.84 d	20.46 cd	22.20 d
B1	68.71 c	68.15 c	20.69 c	22.28 c
B2	70.57 b	70.56 b	22.57 b	22.96 b
B3	71.72 a	71.61 a	23.39 a	24.50 a
F-test	**	**	**	**
Interaction				
F-test	*	*	*	**

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

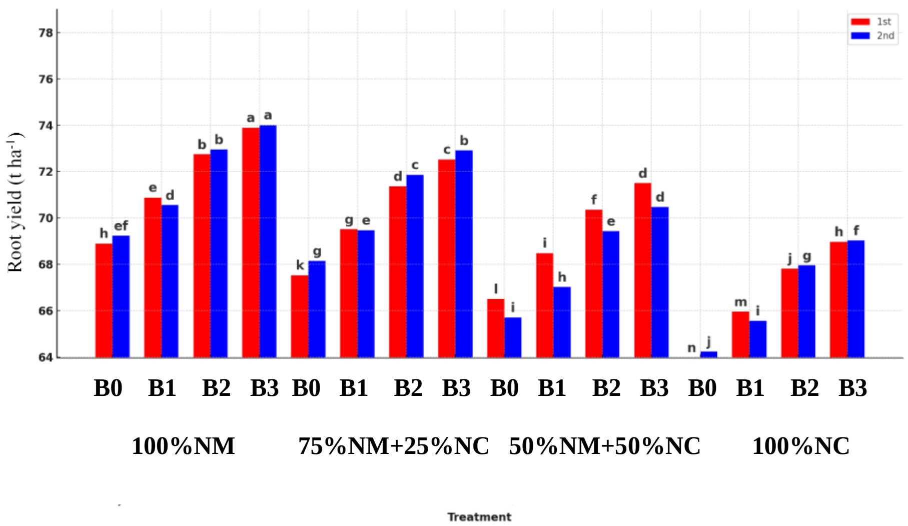

Fig. 2. The interaction effect between mineral nitrogen fertilizer + compost and foliar spraying with boron sources on sugar beet root yield (t ha^{-1}) during 2019/2020 and 2020/2021 seasons.

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

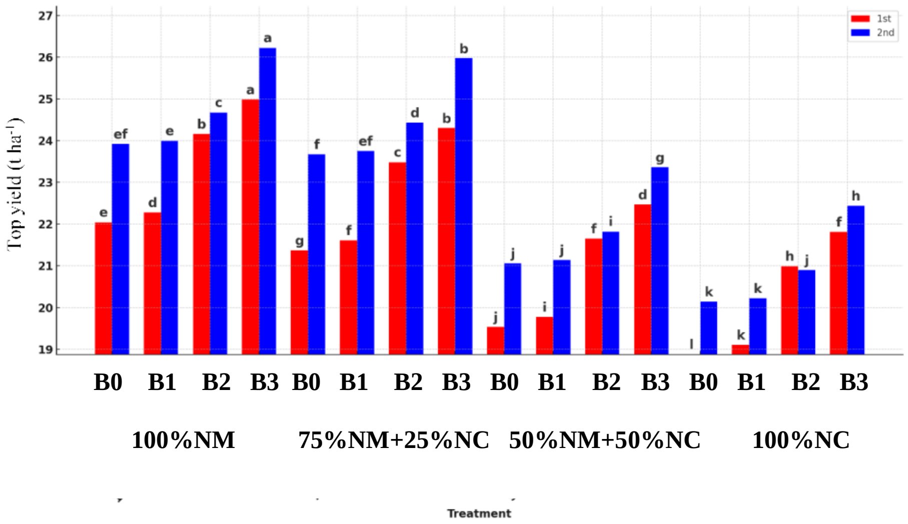

Fig. 3. The interaction effect between mineral nitrogen fertilizer + compost and foliar spraying with boron sources on sugar beet top yield (t ha^{-1}) during 2019/2020 and 2020/2021 seasons.

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

Table 6. Alfa amino-N, K and Na concentration (mEq 100 g^{-1} beet paste) of sugar beet as affected by combination between mineral nitrogen fertilizer + compost and foliar spraying with boron sources as well as their interaction during 2019/2020 and 2020/2021 seasons.

Treatments	α- amino-N		K		Na	
	Concentration (mEq 100 g^{-1} beet paste)					
	1st	2nd	1st	2nd	1st	2nd
Combination between mineral nitrogen fertilizer and compost						
100NM	2.707 a	2.715 a	3.008 b	2.982 a	0.130 a	0.129 b
75NM+25NC	2.614 b	2.618 b	2.973 c	2.933 b	0.130 a	0.130 a
50NM+50NC	2.556 c	2.566 c	3.071 a	2.918 c	0.129 b	0.128 c
100NC	2.407 d	2.362 d	2.636 d	2.598 d	0.128 c	0.128 c
F-test	**	**	**	**	*	*
Foliar spraying with boron						
B0	2.344 d	2.302 d	2.618 a	2.585 a	0.127 d	0.127 d
B1	2.525 c	2.531 c	3.017 a	2.867 a	0.128 c	0.128 c
B2	2.644 b	2.644 b	2.996 a	2.947 a	0.129 b	0.130 b
B3	2.769 a	2.785 a	3.057 a	3.032 a	0.130 a	0.132 a
F-test	**	**	ns	ns	**	**
Interaction						
F-test	ns	ns	ns	ns	ns	ns

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

Table 7. Sucrose, sugar loss, sugar recovery and quality index percentage of sugar beet as affected by combination between mineral nitrogen fertilizer + compost and foliar spraying with boron sources as well as their interaction during 2019/2020 and 2020/2021 seasons.

Treatments	Sucrose %		Sugar Loss %		Sugar Recovery %		Quality Index %	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Combination between mineral nitrogen fertilizer and compost								
100NM	16.73 d	16.72 c	1.62 b	1.61 a	15.11 c	15.11 d	90.31 d	90.36 d
75NM+25NC	17.28 c	17.30 b	1.60 c	1.59 b	15.68 b	15.72 c	90.74 b	90.83 c
50NM+50NC	17.29 b	17.31 b	1.63 a	1.58 c	15.67 b	15.73 b	90.59 c	90.90 b
100NC	17.81 a	17.85 a	1.46 d	1.45 d	16.35 a	16.40 a	91.78 a	91.90 a
F-test	**	**	**	**	**	**	**	**
Foliar spraying with boron								
B0	16.83 d	16.92 d	1.45 d	1.44 d	15.38 d	15.49 c	91.36 a	91.50 a
B1	17.08 c	17.01 c	1.60 c	1.56 c	15.47 c	15.45 d	90.58 d	90.84 c
B2	17.37 b	17.46 b	1.61 b	1.59 b	15.76 b	15.87 b	90.72 c	90.86 b
B3	17.84 a	17.79 a	1.64 a	1.64 a	16.20 a	16.15 a	90.78 b	90.79 d
F-test	**	**	**	**	**	**	**	**
Interaction								
F-test	ns	ns	ns	ns	ns	0.01	0.01	0.01

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

Table 8. Sucrose, sugar loss and recoverable sugar yield (t ha^{-1}) of sugar beet as affected by combination between mineral nitrogen fertilizer + compost and foliar spraying with boron sources as well as their interaction during 2019/2020 and 2020/2021 seasons.

Treatments	Sucrose yield (t ha^{-1})		Sugar loss yield (t ha^{-1})		Recoverable sugar yield (t ha^{-1})	
	1st	2nd	1st	2nd	1st	2nd
Combination between mineral nitrogen fertilizer and compost						
100NM	11.99 b	12.00 b	0.40 a	0.40 a	10.83 d	10.84 c
75NM+25NC	12.14 a	12.22 a	0.39 b	0.39 b	11.02 a	11.10 a
50NM+50NC	11.98 c	11.80 d	0.40 a	0.38 c	10.85 c	10.73 d
100NC	11.89 d	11.91 c	0.35 c	0.35 d	10.91 b	10.95 b
F-test	**	**	**	**	**	**
Foliar spraying with boron						
B0	11.23 d	11.30 d	0.35 d	0.35 d	10.26 d	10.34 d
B1	11.73 c	11.58 c	0.39 c	0.38 c	10.62 c	10.52 c
B2	12.25 b	12.32 b	0.40 b	0.39 b	11.12 b	11.19 b
B3	12.79 a	12.73 a	0.41 a	0.41 a	11.61 a	11.56 a
F-test	**	**	**	**	**	**
Interaction						
F-test	**	**	**	**	**	**

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

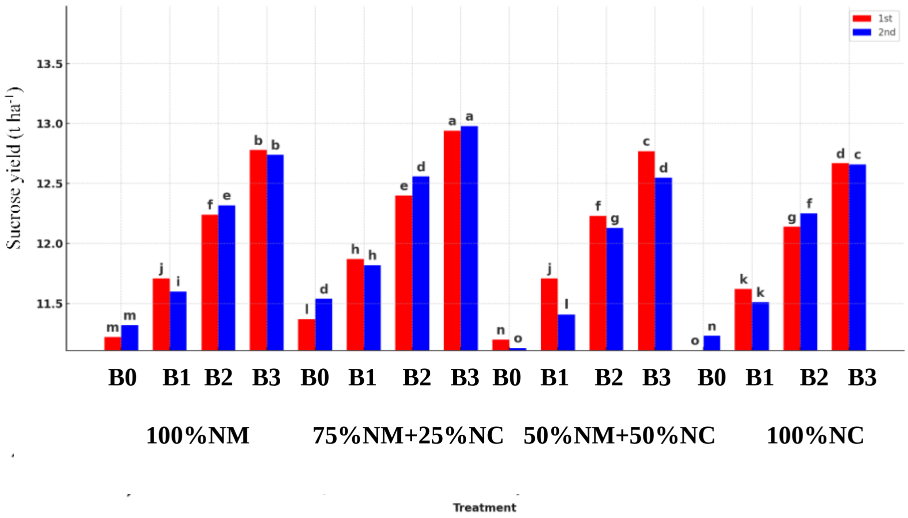

Fig. 4. The interaction effect between mineral nitrogen fertilizer + compost and foliar spraying with boron sources on sucrose yield (t ha^{-1}) during 2019/2020 and 2020/2021 seasons.

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

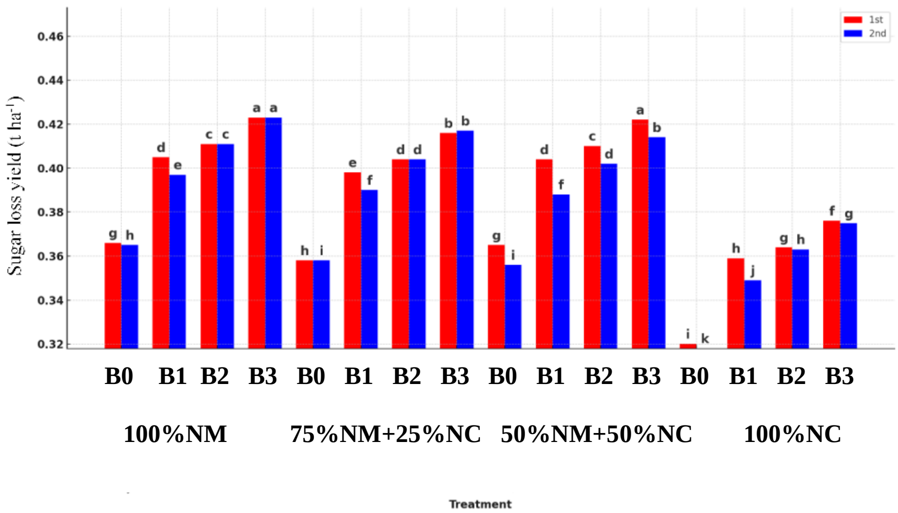

Fig. 5. The interaction effect between mineral nitrogen fertilizer + compost and foliar spraying with boron sources on sugar loss yield (t ha^{-1}) during 2019/2020 and 2020/2021 seasons.

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

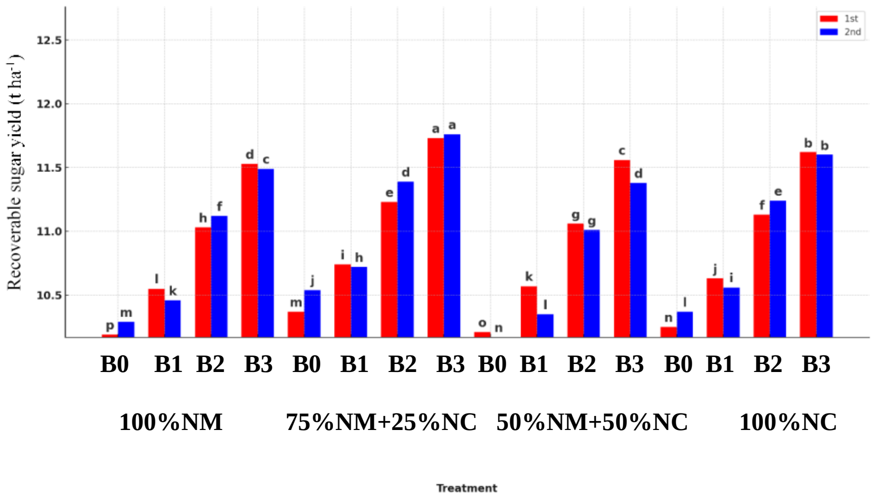

Fig. 6. The interaction effect between mineral nitrogen fertilizer + compost and foliar spraying with boron sources on recoverable sugar yield (t ha^{-1}) during 2019/2020 and 2020/2021 seasons.

RND = Nitrogen Recommended Dose.
100NM= 100% of RND as mineral, 75NM+25NC= 75% of RND as mineral + 25% of RND as compost, 50NM+50NC= 50% of RND as mineral + 50% of RND as compost and 100NC= 100% of RND as compost.
B0= without Boron, B1= Milano, 15 % B, B2= Borax, 11 % B and B3= Boric acid, 17 % B.

Discussion

Integrating compost with mineral nitrogen fertilization promoted vegetative growth as well as root and sugar yields of sugar beet compared to sole application of either nutrient source. Combining compost up to 50% substitution of recommended nitrogen requirement along with the residual mineral nitrogen resulted in yields comparable to 100% mineral nitrogen. The compost likely provided a balanced nutrient supply while also improving soil health and nutrient retention capacity over the long-term (Abou Hussien et al., 2020; Diacono & Montemurro, 2011; Hussein et al., 2022). Simultaneous application of organic and inorganic nitrogen sources has been found beneficial for crop yield through synergistic mechanisms in earlier studies (Agegnehu et al., 2016; Rigby et al., 2016; Farid et al. 2023).

Foliar boron nutrition further enhanced productivity over the compost-mineral nitrogen combinations, confirming the widespread boron deficiency among crops globally (Ahmad et al., 2012; Rerkasem et al., 2020). As an immobile micronutrient, boron requires adequate external supply through fertilization to meet metabolic demands particularly during rapid plant growth (Brdar-Jokanović, 2020; Goldbach & Wimmer, 2007). The highest boron rate from boric acid resulted in maximum yields, indicating potential sub-optimal crop boron status despite no visual deficiency symptoms (Ahmad et al., 2012; Reid, 2014).

Significant interactions between nitrogen source and boron treatments on yields can be ascribed to their interdependent roles in plant metabolism. Boron aids nitrogen assimilation and protein synthesis (Hajiboland & Farhanghi, 2010). The relatively higher incremental yield gains from boron under high mineral nitrogen regimes suggests their coordinated impact on metabolic pathways regulating crop productivity.

Quality parameters Incorporation of compost as partial substitute for mineral fertilizer enhanced quality parameters like sucrose content and processing efficiency. The sustained nitrogen release from composts (Tejada et al., 2010) possibly minimized protein accumulation and associated impurities as opposed to excess mineral nitrogen (Paungfoo-Lonhienne et al., 2008). Improved soil health from long-term compost amendments including porosity, drainage and microbial activity might also favor sucrose storage and purity (Meena et al., 2023).

Foliar boron nutrition further upgraded quality indices through positive impacts on sucrose metabolism, transport and compartmentalization (Farooq et al., 2018; Ghai & Dhillon, 2022). The significant interactions demonstrate interdependent functioning of boron and nitrogen in determination of sucrose accumulation patterns. Adequate boron availability under high nitrogen conditions likely promoted sucrose synthesis over competing pathways for nitrogenous compounds (Fuertes-Mendizábal et al., 2020; Marschner, 2011; Rengel et al., 2022).

Conclusion

The study demonstrates beneficial integration of compost and foliar B nutrition with mineral N fertilization for improving productivity, processing quality and nutrient efficiency of sugar beet. Applying compost to meet 25-50% of crop N demand along with residual mineral N ensures yields comparable to 100% mineral N. Foliar B sprays, especially at 17% concentration further enhance the yield levels and quality. The integrated strategy can be adopted for sustainable sugar beet cultivation with lowered reliance on mineral N fertilizers. Location-specific nutrient rate calibration through multi-location trials is suggested. Incorporating compost with mineral N fertilizer improved growth, root and sucrose yields of sugar beet over their sole applications by allowing balanced nutrient supply. Foliar B nutrition augmented the yield stimulus induced by compost-mineral N combinations and also enhanced quality parameters related to sucrose accumulation and purity. Significant interactions between compost-N treatments and B nutrition demonstrates their interdependent and synergistic functioning in sugar beet crop metabolism regulation. The integrated nutrient management approach can promote productivity, profitability, and sustainability.

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Author contribution

Ali K. Seadh (AKS), Ahmed S. Abdelhamied (ASA) and Ibrahim S. M. Mosaad (ISMM) contributed to the study conception and design. AKS and ISMM conducted the experiments and analyzed the data together with ASA. All authors contributed to the writing of the manuscript with IM as the lead. All authors reviewed and approved the final manuscript.

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