



Wheat productivity and micronutrients availability in soil by the use of chemical and organic fertilizers under alkaline calcareous conditions

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Abstract

Integrated use of chemical fertilizers and manures may be a promising option to promote growth, yield and nutrient contents in plant tissues. The current study aimed to evaluate the effect of chemical fertilizer of zinc (Zn), iron (Fe) and boron (B) along with manures, compost, and PGPR on yield and grain quality of wheat (*Triticum aestivum* L.) under alkaline calcareous conditions. Experimental plan comprised of soil addition (SA), foliar spray (FS), SA+FS of Zn, Fe and B in the form of nanoparticles (NPs) and bulk salt (BS) in combination with farmyard manure (FYM), poultry manure (PM), press mud (PrM), compost and plant growth promoting rhizobacteria (PGPR), making ten treatments. Results revealed that chemical fertilizers either alone or in combination with manures, compost and/or PGPR markedly improved the grain yield and quality, highest improvement with SA+FS+FYM+PM+PrM+compost+PGPR (Integrated Application). The said treatment maximally improved the grain yield by 26% and 21.51%, chlorophyll contents 50% and 47.50%, photosynthetic rate 41.77% and 25.58%, and stomatal conductance 86.36% and 68.0% with NPs and BS, respectively compared to the control. Grain Zn concentration was improved by 177% and 144%, Fe 146% and 111%, B 343% and 237%, carbohydrates 26.11% and 21.27%, protein 25.1% and 20.64%, fiber 14.40% and 10.46% with Integrated Application in case of NPs and BS, respectively compared to the control. The plant available Zn in soil was increased by 269% and 183%, Fe 372% and 325%, and B 213% and 115% with Integrated Application in case of NPs and BS, respectively, compared to the control. However, highest benefit cost ratio was found 1.976 and 2.056 with SA+FS+PrM in case of NPs and BS, respectively. In conclusion, Zn, Fe and B in the form of SA+FS along with manures, compost and PGPR could be recommended to optimize grain yield and quality of wheat under alkaline calcareous conditions.

Keywords: Bulk salt, chemical fertilizers, compost, grain quality, grain yield, manures, micronutrients, nanoparticles, PGPR

Introduction

Adequate and balance supply of plant nutrients is key to profitable and sustainable agriculture for meeting global food security (Singh *et al.*, 2024). Micronutrients are the integral component of plant nutrition owing to their involvement in plant growth and developmental processes, particularly enzyme activation, hormonal balance, water use efficiency, photosynthesis, carbohydrate metabolism, protein synthesis, pollination, flowering and fruit set (Hasanuzzaman *et al.*, 2020; Azam *et al.*, 2022). Among micronutrients, zinc (Zn), iron (Fe) and boron (B) are the most limiting micronutrients, and the

deficiencies of Zn and Fe are highly prevalent in humans (Semida *et al.*, 2021). It has been reported that about 1/3rd world population is suffering from Zn and Fe deficiencies (Rehman *et al.*, 2020). The major health disorders caused by micronutrient deficiencies may include poor mental abilities, anxiety, abortion, depression, impaired immunity, reduced work ability and reduced oxygen transport (Morton *et al.*, 2023). Nutrient deficiency disorders in humans could be mainly linked to poor nutrient contents in edible crops. Wheat is the major staple food in Pakistan which is found deficient in micronutrients due to its cultivation on soils that are deficient in micronutrients including Zn, Fe and B (Hussain *et al.*, 2018; Hassan *et al.*, 2020).

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Low utilization efficiency of micronutrients owing to alkaline calcareous conditions necessitates the supplementing of chemical fertilizers with organic fertilizers, manures, and compost (Sher *et al.*, 2022). Khodaei-Joghhan *et al.* (2018) reported that organic fertilizers and manures may improve the nutrient supply by releasing the nutrients through mineralization, and reducing their precipitation by binding the precipitating agents. In addition, organic fertilizers and manures might help to improve soil structural stability, water holding capacity, aeration, cation exchange capacity, hydraulic conductivity, and microbial activities, all these contribute to better plant growth, yield and quality (Mohan *et al.*, 2024). Shehzad *et al.* (2023) reported that manures often contain high amount of macro and micronutrients which become available on decomposition, and play an important role to meet nutrient requirements of growing plants. Additionally, cost of production can be reduced to greater extent by the integrated application of inorganic fertilizers with manures, compost and plant growth promoting rhizobacteria (PGPR) (Shehzad *et al.* (2022).

Integrated application of chemical fertilizers, compost, press mud (PrM) and manures improved soil fertility status by releasing nutrients through mineralization, reducing nutrient precipitation/ fixation by binding fixing agents, and improving soil properties. Dhaliwal *et al.* (2023) found that better soil and plant health brought about by the addition of farmyard manure (FYM) might be attributed to enhanced microbial activity, root penetration, cation exchange capacity, retention of nutrients and water, thereby contributing to enhanced crop yield and quality. Kumari *et al.* (2024) reported that FYM could play an important role in regulating soil pH, besides it contains a lot of nitrogen (N), phosphorus (P), potassium (K), and micronutrients which confirmed their role for improving plant growth, yield, and soil characteristics. Seddik *et al.* (2016) also reported that FYM application at appropriate rate may play an important role to improve plant mineral composition and yield components of tomato and pea under alkaline calcareous conditions by regulating better nutrient supply in soil.

The combined application of micronutrient fertilizers and poultry manure (PM) may also be an important strategy to enhance nutrient supply to plants, particularly under alkaline calcareous conditions. Adekiya *et al.* (2019) reported that appropriate addition of PM could enhance micronutrient status of soil, and improve the soil characteristics, particularly structural stability, aeration, water and nutrient holding capacities. Press mud (PrM), a byproduct of sugarcane industry also known as filters cake and filter mud. It can be used as good source of organic manure, effectively supplying nutrients, and also functioning as a conditioner for

improving soil properties (Sharma *et al.*, 2019). According to Krishnaveni *et al.* (2020), PrM may improve nutrients supply and use efficiency under alkaline calcareous conditions because of its high nutrient contents, and reducing the fixation of applied fertilizers. Integrated application of chemical fertilizer and compost can also provide an important strategy for improving nutrient supply in soil as well as plant growth, yield and quality characteristics (Xu *et al.*, 2017). Its application as organic amendment is considered cost effective and environmental friendly because it greatly reduced greenhouse gas emissions, in addition to improving fertilizer use efficiency (Eboibi *et al.*, 2021).

PGPR are considered important to improve soil properties, nutrients solubility and bioavailability with a subsequent improvement in crop productivity (Hasan *et al.*, 2024). PGPR can benefit the crop growth and development by nitrogen fixation, nutrients solubilization, breakdown of crop residues and making phytohormones (He *et al.*, 2019). Backer *et al.* (2018) reported that PGPR may contribute to plant growth by promoting nutrient mobilization in soil, production of plant growth regulators, protecting plants against phytopathogens, and improving soil properties. The efficiency of applied micronutrient fertilizers for improving plant growth and development can be enhanced by using nanoparticle (NPs) (Rizwan *et al.*, 2017; Faizan *et al.*, 2020). NPs being smaller in size and with higher surface area per unit mass could be more effective for promoting seed germination, growth, physiological and reproductive processes compared to bulk salt (BS) (Tariverdizadeh *et al.*, 2021; Mazhar *et al.*, 2023).

The effect of integrated application of chemical fertilizers, manures, compost and PGPR on plant growth, nutrient availability in soil, and uptake by plants may vary greatly depending upon the nature and properties of soil, source and application method of fertilizer, nature of manure, and crop species (Ali *et al.*, 2020; Sher *et al.*, 2022). The current study was planned to evaluate the role of integrated use of Zn, Fe and B as NPs and BS through soil addition (SA), foliar spray (FS), SA+FS in combination with FYM, PM, PrM, compost and PGPR to affect growth, yield, physiological, and grain quality characteristics of wheat (*Triticum aestivum* L.) as well as plant available concentration of Zn, Fe and B in soil under alkaline calcareous conditions.

Material and Methods

Characterization of experimental soil

A field experiment was conducted during 2022-23 to evaluate the role of soil and foliar application of Zn, Fe and



B in combination with FYM, PM, PrM, compost, and PGPR on growth, yield and grain quality characteristics of wheat (*Triticum aestivum* L.) under alkaline calcareous soil. The GPS coordinates of experimental site were 30° 27' N longitude, 71° 50' E latitude, and 129 m altitude. Prior to experimentation, soil samples were collected from 0-15 cm soil depth, and analyzed for various physicochemical properties according to the methods described by Richards (1954). Experimental soil was loamy having pH 8.03, ECe 1.17 dS m⁻¹, organic matter 0.71%, CaCO₃ 11.10%, saturation percentage 31.10, total N 0.042%, available P 6.98 mg kg⁻¹, extractable K 176.4 mg kg⁻¹, DTPA extractable Zn 0.26 mg kg⁻¹, DTPA extractable Fe 4.84 mg kg⁻¹, and DTPA-sorbitol extractable B 0.47 mg kg⁻¹.

2.2. Experimental plan and growth conditions

Experimental plan comprised of SA, FS, SA+FS of Zn, Fe and B in the form of NPs and BS in combination with FYM, PM, PrM, compost and PGPR making ten treatments which are detailed below;

1	Control (no addition of Zn, Fe, B and manures)	Control
2	Soil addition of Zn 20 kg ha ⁻¹ +Fe 10 kg ha ⁻¹ +B 2 kg ha ⁻¹	SA
3	Foliar spray of Zn 0.5%+Fe 0.5%+B 0.2%	FS
4	SA of Zn-Fe-B at 20-10-2 kg ha ⁻¹ +FS of Zn-Fe-B at 0.5-0.5-0.2%	SA+FS
5	SA+FS+FYM at 10 ton ha ⁻¹	SA+FS+FYM
6	SA+FS+PM at 5 ton ha ⁻¹	SA+FS+PM
7	SA+FS+ PrM at 5 ton ha ⁻¹	SA+FS+PrM
8	SA+FS+Compost at 5 ton ha ⁻¹	SA+FS+Comp
9	SA+FS+PGPR	SA+FS+PGPR
10	SA+FS+FYM+PM+PrM+Comp+PGPR	Integrated Application

Experiment was planned according to split plot design under factorial arrangement. Each treatment was replicated for five times. Zn was used as ZnO-NPs and ZnSO₄.H₂O. B was supplied as B-NPs and H₃BO₃. Fe was supplied as Fe-NPs and FeSO₄.7H₂O. ZnO-NPs were prepared according to the method proposed by Ahamed *et al.* (2016), B-NPs in accordance with Kocakuşak *et al.* (1996), and Fe₂O₃-NPs by co-precipitation method as described by Ba-Abbad *et al.* (2022). Manures and compost were analysed for various chemical characteristics following the procedure described by Peters *et al.* (2003). The selected chemical characteristics of manures and compost are presented in Table 1.

The seed bed was prepared by ploughing and planking at field capacity. Manures and compost were incorporated into the respective plots according to treatment plan about 30 days prior to sowing. Healthy and uniform seeds of wheat cultivar DilKash-21 was sown in the 1st week November 2022 using 150 kg ha⁻¹ seed rate by hand seed drill. The seeds of respective treatment were inoculated by soaking them in PGPR suspension after sterilizing with ethanol solution. Recommended fertilizers in terms of N 150 kg ha⁻¹ in the form of urea, P 100 kg ha⁻¹ P₂O₅ as single superphosphate and K 60 kg ha⁻¹ K₂O in the form of potassium sulfate were applied. Whole of P₂O₅, K₂O and 1/3rd N were applied at the time of sowing, while remaining N in two equal splits, 30 and 60 days after germination. Weeding was done manually. Irrigation was made with canal water at crown root initiation, tillering, booting, flowering, milking and dough stages.

Physiological characteristics measurement

The physiological characteristics were measured during 9th week after germination using the 4th topmost leaf. Stomatal conductance (Gs), photosynthesis (Pn), and transpiration rate (Tr) were measured using IRGA (CI-340 hand-held) following the procedure described by Yang *et al.* (2021). Chlorophyll contents were measured following the method described by Arnon (1949) using spectrophotometer (DU730 UV-Vis Spectrophotometer; Beckman Coulter, USA).

Ion concentration determination

During the 9th week after germination, three plants were harvested from each replication and combined to get composite plant sample. These plant samples were washed, dried in an oven (EYELA WFO-600ND; Tokyo Rikaikai Co., Ltd., Tokyo, Japan) at 70°C till constant weight. For Zn and Fe determination, plant samples were digested by wet digestion method as described by Miller (1998), and ion concentration was measured on atomic absorption spectrophotometry (Z-8200 Polarized Zeeman AAS; Hitachi, Japan). For B determination, plant samples were digested by dry ashing method described by Haynes (1980). B determination was made on spectrophotometer (DU730 UV-Vis Spectrophotometer; Beckman Coulter, USA). After harvesting and threshing, the grains were digested by dry ashing method as described by Haynes (1980) for the determination of Zn, Fe and B. Estimation for Zn and Fe was done on atomic absorption spectrophotometry (Z-8200 Polarized Zeeman AAS; Hitachi, Japan) while, B on spectrophotometer (DU730 UV-Vis Spectrophotometer; Beckman Coulter, USA).



Table 1: Chemical characteristics of manures and compost used in the experimentation

Characteristic	Farmyard manure	Poultry manure	Press mud	Compost
Total N (%)	1.47	1.62	1.84	1.81
Available phosphorus (mg kg ⁻¹)	6.29	7.94	5.77	6.78
Available potassium (mg kg ⁻¹)	152.14	167.70	126.56	118.67
Electrical conductivity (dS m ⁻¹)	2.71	2.56	1.42	2.82
pH	6.48	6.23	6.39	7.81
Dry Matter (%)	33.70	36.10	35.73	34.10
Moisture (%)	61.80	42.28	57.26	38.28
Zinc (mg kg ⁻¹)	113.65	125.14	144.68	126.45
Iron (mg kg ⁻¹)	10.17	13.42	17.44	12.64
Manganese (mg kg ⁻¹)	12.43	9.68	6.12	13.46
Copper (mg kg ⁻¹)	21.64	17.80	7.80	19.57
Cadmium (mg kg ⁻¹)	0.07	0.08	0.09	0.08
Nickel (mg kg ⁻¹)	0.09	0.13	0.10	0.07
Lead (mg kg ⁻¹)	0.07	0.08	0.09	0.07
Chromium (mg kg ⁻¹)	0.02	0.03	0.04	0.02

Table 2: Physiological characteristics of wheat grown with the application of micronutrients, manures, compost and PGPR

Treatment	Chlorophyll contents (mg g ⁻¹ FW)		Photosynthetic rate (μmol CO ₂ m ⁻² s ⁻¹)		Stomatal conductance (mmol H ₂ O m ⁻² s ⁻¹)	
	NPs	BS	NPs	BS	NPs	BS
	Control	0.82cd	0.80d	11.80e	11.92de	0.22d
SA	1.01bc	0.98bc	15.67ab	13.70cd	0.35b	0.29bc
FS	0.93c	0.87cd	14.24c	13.25cd	0.33b	0.28c
SA+FS	1.16a	1.07b	16.10ab	14.27c	0.38ab	0.34b
SA+FS+FYM	1.19a	1.17a	16.84a	14.56bc	0.40a	0.35b
SA+FS+PM	1.18a	1.12ab	16.22ab	14.68bc	0.40a	0.37ab
SA+FS+PrM	1.17a	1.16a	16.26a	14.22c	0.39a	0.35b
SA+FS+Comp	1.20a	1.10ab	16.49a	14.90bc	0.40a	0.36b
SA+FS+PGPR	1.19a	1.13ab	16.86a	14.83bc	0.42a	0.37ab
Integrated Application	1.23a	1.18a	16.73a	14.97b	0.41a	0.37ab

Values are means of five replicates (n = 5). Means in a column with the similar letter(s) do not differ at 5% probability level

Measurement of yield and yield characteristics

At maturity, yield and yield attributes including average number of tillers per plant, spike length, and number of grains per spike were recorded. Ten spikes were collected from each plot to record spike length and number of grains per spike. In the last week of April 2023, wheat plants were harvested. After threshing, impurities were removed, and cleaned grains were weighed, and converted to grain yield ha⁻¹.

Plant available ion concentration

After harvesting wheat, plant available concentration of Zn, Fe and B in soil were determined by shaking the soil samples with DTPA extraction solution as described by Lindsay and Norvell (1978).

2.6. Statistical analysis

The obtained data were statistically analyzed using statistical computer software package “Statistix 8.1” following the split plot design under factorial arrangement. ANOVA was performed to assess the main effects of various sources of variation and their interactions. The significant differences among the treatment means were calculated by Least Significant Difference test at 5% probability level following Steel *et al.* (1997).

Results

Physiological characteristics

The physiological characteristics of wheat in terms of chlorophyll contents, photosynthetic rate and stomatal



conductance were significantly ($p \leq 0.05$) affected by the application of Zn+Fe+B in the form of NPs and BS by SA, FS, and SA+FS in combination with FYM, PM, PrM, compost and PGPR (Table 2). NPs performed better than BS, and application methods were ranked in order of SA+FS followed by SA and FS to improve physiological characteristics. The highest improvement in physiological characteristics was observed with Integrated Application which maximally improved chlorophyll contents by 50.0% and 47.50%, photosynthetic rate 41.77% and 25.58%, and stomatal conductance 86.36% and 68.0% with NPs and BS, respectively compared to the control.

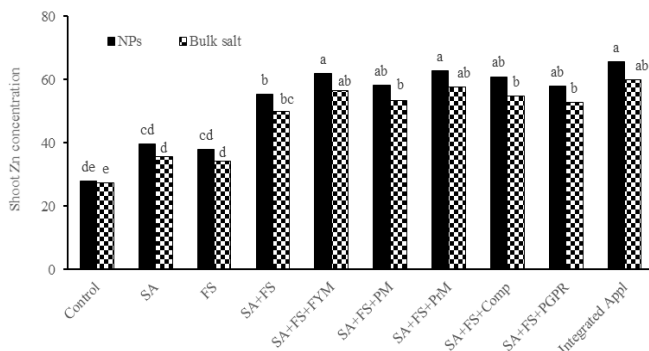


Figure 1: Shoot Zn concentration (mg kg⁻¹) of wheat grown with the application of micronutrients, manures, compost and PGPR

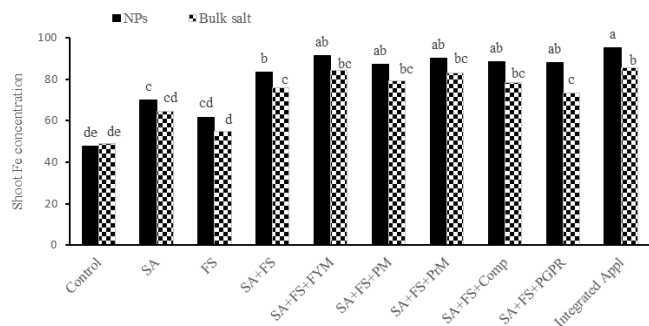


Figure 2: Shoot Fe concentration (mg kg⁻¹) of wheat grown with the application of micronutrients, manures, compost and PGPR

Shoot Zn, Fe and B concentration

Shoot Zn, Fe and B concentration of wheat was significantly ($p \leq 0.05$) affected with the application of micronutrients, manures, compost and PGPR. Zn concentration was improved 42.12% and 29.44% with SA, 35.80% and 27.25% with FS, 98.70% and 81.77% with SA+FS, 122% and 106% with SA+FS+FYM, 109% and 94%

with SA+FS+PM, 125% and 110% with SA+FS+PrM, 116% and 99.38% with SA+FS+Compost, 108% and 92.56% with SA+FS+PGPR, and 136% and 119% with Integrated Application in case of NPs and BS salt, respectively compared to the control (Figure 1). Fe concentration was markedly improved by all treatments, highest improvement of 99.32% and 75.36% with Integrated Application in case of NPs and BS, respectively compared to the control (Figure 2). Likewise, B concentration was maximally improved by 255% and 221% with Integrated Application in case of NPs and BS, respectively compared to the control (Figure 3). Almost similar trend was found for shoot Zn, Fe and B uptake (data not presented).

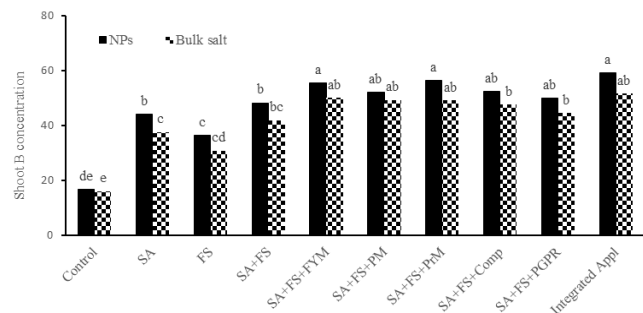


Figure 3: Shoot B concentration (mg kg⁻¹) of wheat grown with the application of micronutrients, manures, compost and PGPR

Yield and yield attributes

The grain yield and yield attributes of wheat in terms of number of tillers plant⁻¹, spike length and number grains spike⁻¹ were significantly ($p \leq 0.05$) affected with the use of micronutrients, manures, compost and PGPR (Table 3). Average number of tillers plant⁻¹ was maximally increased by 35.89% and 22.53% with the Integrated Application in case of NPs and BS, respectively compared to the control. The highest improvement in spike length was 25.14% and 20.89% with Integrated Application in case of NPs and BS, respectively compared to the control. Number of grains spike⁻¹ were maximally increased by 28.91% and 18% with Integrated Application in case of NPs and BS, respectively compared to the control. The grain yield was increased by 16.50% and 17.25% with SA, 6.69% and 10.63% with FS, 24.40% and 19.14% with SA+FS, 22.96% and 20.56% with SA+FS+FYM, 23.68% and 20.09% with SA+FS+PM, 25.83% and 21.51% with SA+FS+PrM, 23.92% and 20% with SA+FS +Compost, 22.48% and 16.54% with SA+FS+PGPR, and 26% and 21.51% with Integrated Application in case for NPs and BS, respectively compared to the control.



Table 3: Yield attributes of wheat grown with the application of micronutrients, manures, compost and PGPR

Treatment	Number of tillers plant ⁻¹		Spike length (cm)		Number of grains spike ⁻¹		Grain yield (ton ha ⁻¹)	
	NPs	BS	NPs	BS	NPs	BS	NPs	BS
Control	5.21d	5.28cd	8.63cd	8.47d	35.10e	35.19de	4.18e	4.23de
SA	6.29b	5.98bc	9.96b	9.32bc	42.24b	38.56cd	4.87b	4.69c
FS	5.68c	5.70c	9.42bc	9.17c	39.54c	37.08d	4.46d	4.68c
SA+FS	6.56ab	6.17b	10.23ab	9.86b	43.06ab	39.78c	5.20a	5.04ab
SA+FS+FYM	6.74ab	6.29b	10.67a	10.01b	43.76ab	40.82bc	5.14a	5.10ab
SA+FS+PM	6.82a	6.24b	10.36ab	9.93b	43.52ab	40.20c	5.17a	5.08ab
SA+FS+PrM	6.78a	6.11bc	10.53a	9.96b	42.86ab	40.80bc	5.26a	5.14a
SA+FS+Comp	6.90a	6.17b	10.64a	9.90b	43.13ab	39.76c	5.18a	5.08ab
SA+FS+PGPR	6.80a	6.23b	10.29ab	10.12ab	43.28ab	40.52bc	5.12ab	4.93b
Integrated Application	7.08a	6.47ab	10.80a	10.24ab	45.25a	41.53b	5.27a	5.14a

Values are means of five replicates (n = 5). Means in a column with the similar letter(s) do not differ at 5% probability level.

Table 4: Grain Zn, Fe and B concentration (mg kg⁻¹) in wheat grown with the application of micronutrients, manures, compost and PGPR

Treatment	Grain Zn		Grain Fe		Grain B	
	NPs	BS	NPs	BS	NPs	BS
Control	18.65ef	18.24f	26.78g	27.18fg	10.31f	11.04ef
SA	34.63cd	29.64d	43.64d	38.80e	29.67c	25.48cd
FS	28.18de	26.14de	36.97e	33.93ef	19.82de	18.23de
SA+FS	41.61bc	35.49c	54.72bc	46.82cd	38.10b	30.86c
SA+FS+FYM	47.86ab	41.76b	61.36ab	53.24bc	41.25ab	34.96bc
SA+FS+PM	45.28ab	40.80bc	57.21b	50.17c	40.74ab	34.12bc
SA+FS+PrM	49.10a	42.18b	59.52ab	51.86c	43.68a	35.62b
SA+FS+Comp	45.94ab	39.27bc	56.07b	50.10c	40.38ab	33.73bc
SA+FS+PGPR	44.56b	38.90bc	56.62b	52.54c	39.70ab	32.29bc
Integrated Application	51.68a	44.53b	65.87a	57.29b	45.67a	37.18b

Values are means of five replicates (n = 5). Means in a column with the similar letter(s) do not differ at 5% probability level.

Table 5: Grain quality characteristics of wheat grown with the application of micronutrients, manures, compost and PGPR

Treatment	Protein (%)		Carbohydrate (%)		Fibers (%)	
	NPs	BS	NPs	BS	NPs	BS
Control	11.18de	11.0b8e	58.24f	58.47ef	9.65de	9.46e
SA	13.21b	12.77bc	67.29bc	66.72c	10.26c	9.98cd
FS	12.66bc	12.24c	64.93cd	65.18cd	9.94cd	9.72d
SA+FS	13.69ab	12.90bc	70.56ab	68.26bc	10.75ab	10.14c
SA+FS+FYM	13.86a	13.01b	72.54a	69.87b	10.90a	10.22c
SA+FS+PM	13.78a	12.95bc	72.18a	69.42b	10.86a	10.29bc
SA+FS+PrM	13.70ab	12.82bc	71.02ab	68.77b	10.80ab	10.18c
SA+FS+Comp	13.80a	13.10b	71.36ab	69.29b	10.93a	10.21c
SA+FS+PGPR	13.94a	12.88bc	71.64a	70.10ab	10.88a	10.29bc
Integrated Application	14.10a	13.34b	72.86a	70.54ab	11.04a	10.45b

Values are means of five replicates (n = 5). Means in a column with the similar letter(s) do not differ at 5% probability level.



Grain Zn, Fe and B concentration

Grain Zn, Fe and B concentrations were also significantly ($p \leq 0.05$) affected with the application of micronutrients, manures, compost and PGPR (Table 4). Zn concentration was improved by 85.68% and 62.5% with SA, 51% and 43.31% with FS, 124% and 94.57% with SA+FS, 157% and 129% with SA+FS+FYM, 143% and 124% with SA+FS+PM, 163% and 131% with SA+FS+PrM, 146% and 115% with SA+FS+Compost, 139% and 113% with SA+FS+PGPR, and 177% and 144% with Integrated Application in case of NPs and BS, respectively compared to the control. Fe concentration was maximally increased by 146% and 111% with Integrated Application in case for NPs and BS, respectively compared to the control. B concentration was maximally increased with by 343% and 237% with Integrated Application in case NPs and BS, respectively compared to the control. Grain Zn, Fe and B uptake were also affected in the same way (data not shown).

Grain quality characteristics

There was a significant effect of micronutrients, manures, compost and PGPR on grain protein, carbohydrate and fiber contents of wheat (Table 5). Grain protein was increased by 14.94% and 14.10% with SA, 11.42% and 11.47% with FS, 21.15% and 16.74% with SA+FS, 24.55% and 19.49% with SA+FS+FYM, 23.93% and 18.72% with SA+FS+PM, 21.94% and 17.61% with SA+FS+PrM, 22.52% and 18.50% with SA+FS+Compost, 23% and 19.89% with SA+FS+PGPR, and 25.1% and 20.64% with Integrated Application in case of NPs and BS, respectively compared to the control. Grain carbohydrates were also increased with micronutrients, manures, compost and PGPR, highest increase of 26.11% and 21.27% with Integrated Application in case of NPs and BS, respectively compared to the control. The highest improvement in grain fibers of 14.40% and 10.46% was found with Integrated Application in case of NPs and BS, respectively compared to the control.

Plant available Zn, Fe and B in soil

There was a significant ($p \leq 0.05$) effect of micronutrients, manures, compost and PGPR in improving plant available Zn, Fe and B concentration in soil after wheat harvesting. Plant available Zn in soil was maximally increased by 269% and 183% with Integrated Application in case of NPs and the BS, respectively compared to the control (Figure 4). Plant available Fe in soil was maximally increased by 372% and 325% with Integrated Application in case of NPs and BS, respectively compared to the control (Figure 5). The highest improvement in plant available B was 213% and

115% with Integrated Application in case of NPs and BS, respectively compared to the control (Figure 6).

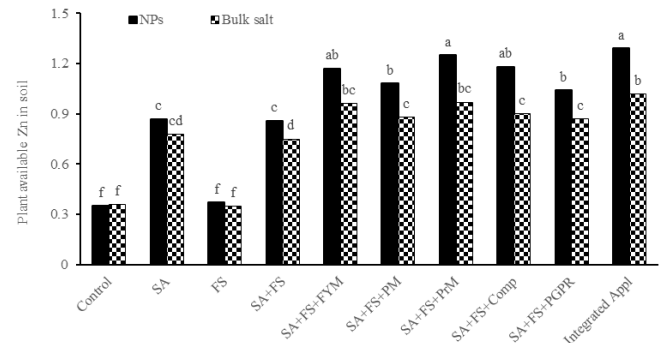


Figure 4: Plant available Zn concentration (mg kg⁻¹) in soil after harvesting wheat grown with the application of micronutrients, manures, compost and PGPR

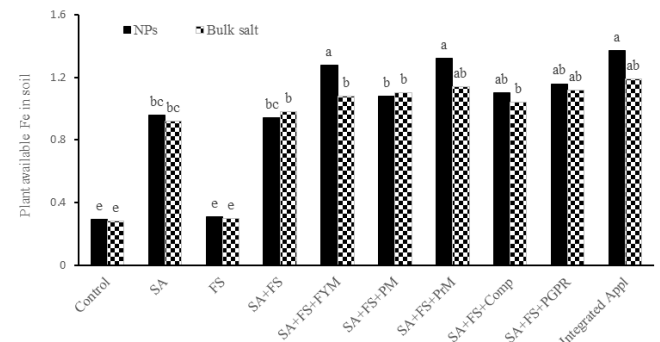


Figure 5: Plant available Fe concentration (mg kg⁻¹) in soil after harvesting wheat grown with the application of micronutrients, manures, compost and PGPR

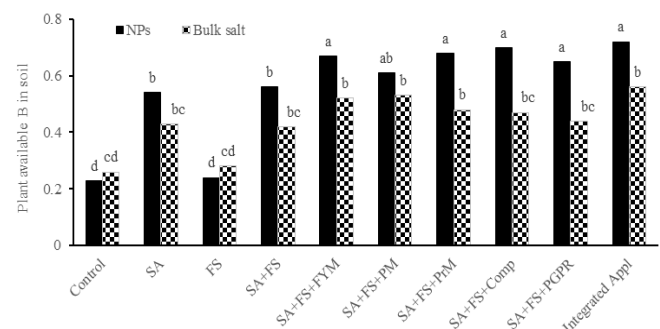


Figure 6: Plant available B concentration (mg kg⁻¹) in soil after harvesting wheat grown with the application of micronutrients, manures, compost and PGPR



Table 6: Benefit: cost ratio of wheat grown with the application of micronutrients, manures, compost and PGPR

Treatment	NPs			BS		
	Benefit (Rs. ha ⁻¹)	Cost (Rs. ha ⁻¹)	B: C ratio	Benefit (Rs. ha ⁻¹)	Cost (Rs. ha ⁻¹)	B: C ratio
Control	509525	276536	1.843	515575	276536	1.864
SA	593225	312654	1.897	571725	297190	1.924
FS	544350	283170	1.922	571075	280518	2.036
SA+FS	634625	322288	1.969	615650	302844	2.033
SA+FS+FYM	627225	326415	1.922	622175	306971	2.027
SA+FS+PM	632150	327966	1.927	621050	308492	2.013
SA+FS+PrM	642200	324968	1.976	628275	305524	2.056
SA+FS+Comp	632100	325448	1.942	620350	306004	2.027
SA+FS+PGPR	624525	323178	1.932	601150	303734	1.979
Integrated Appl	644600	338823	1.902	628800	319379	1.969

Benefit cost ratio

In case of NPs, minimum benefit: cost ratio was 1.843 in control treatment which increased to 1.897 with SA, 1.922 with FS, 1.969 with SA+FS, 1.922 with SA+FS+FYM, 1.927 with SA+FS+PM, 1.976 with SA+FS+PrM, 1.942 with SA+FS+Compost, 1.932 with SA+FS+PGPR, and 1.902 with Integrated Application. In case BS, minimum benefit: cost ratio was 1.864 in control treatment which increased to 1.924 with SA, 2.036 with FS, 2.033 with SA+FS, 2.027 with SA+FS+FYM, 2.013 with SA+FS+PM, 2.056 with SA+FS+PrM, 2.027 with SA+FS+Compost, 1.979 with SA+FS+PGPR, and 1.969 with Integrated Application (Table 6).

Discussion

The highest improvement in physiological characteristics with Integrated Application was associated with higher availability of micronutrient elements in soil and improved soil properties. Previous studies reported by Hafez *et al.* (2019), Ding *et al.* (2021) and Hafez *et al.* (2021) demonstrated that PGPR inoculation improved plant physiological processes by promoting carbohydrate metabolism and transport of photosynthates from source to sink which promoted photosynthesis. The significant improvement in chlorophyll contents and stomatal conductance with the co-application of chemical fertilizers, compost and PGPR could be related to improved nutrients and water uptake by growing plants. Yaseen *et al.* (2020) reported that increase in chlorophyll synthesis and photosynthetic rate by the integrated application of organic manures and inorganic fertilizers might be attributed to high N concentration in manures. Adekiya *et al.* (2020) reported that organic amendments favored the process of solubilizing

nutrients from native soil, delivering nutrients to plants, and subsequently improved the plant physiological processes and characteristics.

Higher concentration and uptake of Zn, Fe and B in wheat plants and grains were associated with application of organic manures and synthetic fertilizers because manures promoted soil properties, solubilized micronutrients and facilitated their absorption by plants. Furthermore, breakdown of organic manures themselves released nutrients which also became available to plants. Dhaliwal *et al.* (2019) reported that manures application regulated the soil pH, and facilitating the availability of nutrients in soil, and subsequently absorption by plants. Manuring improved soil conditions, favoring root growth and thus nutrient absorption by plants (Saha *et al.*, 2019). Bioavailability of micronutrients was greatly influenced by their interaction with other elements and soil constituents through the processes of precipitation and fixation. Integrated application of chemical fertilizers and manures inhibited precipitation and fixation of micronutrients, and subsequently improved the nutrients availability in soil, and absorption by plants (Kundu *et al.*, 2016). Better performance of PrM to improve micronutrients concentration and uptake in plants could be attributed to its fast decomposition, high nutrient contents, and strong effect on nutrient solubility by regulating soil pH. Bolinder *et al.* (2020) demonstrated that PM significantly improved total carbon, N, P and micronutrients in soil which subsequently improved nutrient concentration and uptake in plant tissues.

Higher yield and yield attributes with the integrated application of micronutrients, manures along with compost and PGPR were attributed to higher availability of



micronutrients in soil, increased nutrient uptake, higher stomatal conductance, and photosynthetic rate. Manik *et al.* (2019) reported that integrated application of synthetic fertilizers and manures caused a marked improvement in soil properties which facilitated the nutrient solubilization in soil, absorption by plants, and resulting in higher growth and yield. Improvement in soil properties by the addition of manures, compost and PGPR could promote root growth enabling them to explore greater soil volume for nutrients and water, resulting in higher yield and yield attributes. Kavinder *et al.* (2019) found that combined application of FYM with recommended N improved plant height, number of tillers, and subsequently crop yield. Applying compost and PGPR together improved plant growth due to enhanced nutrient availability in soil (Osman *et al.*, 2021). Application of compost in soil improved physiochemical properties, microbial activities, organic carbon content and reduced exchangeable sodium percentage in soil with the subsequent improvement in plant growth and yield (Ismail *et al.*, 2013). The PGPR inoculation improved the root growth by secreting organic acids in rhizosphere which increased the nutrient uptake, and crop yield (Hafez *et al.*, 2019).

Improvement in grain quality characteristics with the integrated application of micronutrients, manures, compost and PGPR was attributed to the fact that balanced nutrient supply was necessary for metabolic activities, leading to higher protein and carbohydrate synthesis. Manures were rich in nutrients and released micronutrients, particularly Zn, Fe and B in plant available form on decomposition which promoted grain nutrient contents, and other quality traits (Dhiman *et al.*, 2019). Combining manures with chemical fertilizers, compost and PGPR greatly improved soil properties, nutrient availability, plant growth, and plant metabolism. Improved soil properties and nutrient availability led to higher grain protein, starch and carbohydrates in wheat (Liu *et al.*, 2016; Chauhan *et al.*, 2020).

The increase in plant available concentration of Zn, Fe and B in soil with the integrated application of chemical fertilizer, manures, compost and PGPR was due to the replenishment of depleted nutrients with chemical fertilizers. Manures, compost and PGPR application along with chemical fertilizers reduced nutrient precipitation and fixation in soil, and resulting in higher nutrient availability in soil. Choudhary *et al.* (2018) reported that manures improved nutrients availability in soil by releasing nutrients on decomposition, and reducing nutrients precipitation and fixation in soil. Furthermore, manures improved soil conditions, and contributing to greater nutrient availability in

soil (Dhaliwal *et al.*, 2022). Mandal *et al.* (2018) also reported that nutrients were also released from manures and compost after the process of mineralization, and contributed significantly to available nutrient pool in soil. Increase in plant available micronutrients in soil could also be due to the fact that increasing soil microbial activities made elements more accessible owing to lower precipitation and fixation (Sarwar *et al.*, 2021). Shahid *et al.* (2016) reported an enhancement in available micronutrients with the combined use of chemical fertilizers and manures by promoting metal organic complexes which reduced precipitation and fixation of micronutrients. Highest benefit cost ratio was found 1.976 and 2.056 with SA+FS+PrM in case of NPs and BS, respectively, irrespective of grain nutrients accumulation which was higher in case of Integrated Application.

Conclusion

The use of micronutrient fertilizers in the form of NPs and BS applied as SA, FS, and/or SA+FS could significantly improve physiological, yield and grain quality characteristics of wheat as well as plant available concentration of Zn, Fe and B in soil. The efficiency of micronutrient fertilizers to improve wheat productivity and Zn, Fe and B concentration in soil could greatly be enhanced when applied in combination with manures, compost and PGPR. When comparing the individual effect of manures, PrM performed best to improve the grain yield of wheat in combination with both NPs and BS. The highest improvement in wheat physiological, yield and quality characteristics was found with Integrated Application. Among NPs and BS, higher improvement in wheat growth and soil concentration of Zn, Fe and B were recorded with NPs compared to BS. However, higher benefit: cost ratio was found in case of BS. Integrated use of micronutrient fertilizers and manures could be recommended for optimum wheat productivity under alkaline calcareous conditions.

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