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Integrated Effects of DAP Fertiliser, Soil Amendments, and Nano-Biostimulant Foliar Application on Growth and Yield of Wheat

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ABSTRACT

This study evaluated the effects of DAP fertiliser rates, soil amendments, and foliar applications of biostimulants and chelated micronutrient nano-fertiliser on the growth and yield of wheat. A field trial was conducted over a single growing season in a randomised complete block design with a split-split plot arrangement and three replications. Treatments comprised three DAP rates (0, 150, and 300 kg ha^{-1}), three soil amendment levels (none, agricultural gypsum at 800 kg ha^{-1}, and EM Bokashi bio-organic fertiliser at 5 t ha^{-1}), and four foliar treatments (water, EM liquid biofertiliser, the biostimulant Fertigrain, and chelated nano-fertiliser). DAP at 300 kg ha^{-1} increased biological yield (BIY) by 24.8% (from 16.347 to 20.403 Mg ha^{-1}) and grain yield (GRY) by 17.1% (from 4.857 to 5.690 Mg ha^{-1}) compared with the control. Bokashi had a greater effect, increasing GRY by 26.6% and BIY by 30.2%, whereas chelated nano-fertiliser increased GRY by 17.0% compared with water spray. Two- and three-way combinations were clearly superior: 300 kg ha^{-1} DAP + Bokashi + nano-fertiliser produced the highest GRY (7.287 Mg ha^{-1}; 72.7% above the control, 4.220 Mg ha^{-1}) and BIY (26.260 Mg ha^{-1}; 94.9% increase). The harvest index was highest without DAP (29.73%) and declined to 27.94% at 300 kg ha^{-1}. Post-harvest soil properties were not assessed, which is the main limitation of this study. Combining mineral, organic, and nano-based inputs is a practical strategy for improving wheat productivity on nutrient-poor, salt-affected soils in dryland and semi-arid regions.

Keywords: Bokashi, DAP Fertiliser, Fertigrain, grain yield, nano-fertiliser

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INTRODUCTION

Wheat can be said to be the most consumed cereal crop in the world based on its

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nutritional value, its usage in bread, and its products. Wheat and barley are the oldest domesticated cereal crops by humans. The domestication of wheat is said to have begun more than ten thousand years ago. The earliest domesticated wheat species was Emmer. Emmer crops originated in the Fertile Crescent in the Middle East, comprising countries such as Iraq, Syria, Jordan, Palestine, and Turkey (Erenstein et al., 2022; Gąsiorowski, 2004). Wheat is important for food security; thus, grain production and quality depend on the physical characteristics of the soils in which wheat is grown. The nutrient content in soils favours the development of plants and grains, whereas the presence of heavy metals such as Cd and Pb reduces the accumulation of metals in grains (Rizwan et al., 2016; Shahad et al., 2026). The accumulation negatively impacts grain quality and poses health hazards for humans and animals. Therefore, there is a need to enhance soil quality and use the best fertilisers, including bio-fertilisers and nano-fertilisers, to promote sustainable production and safe grain for human consumption (Al-Juthery et al., 2025; Bhardwaj et al., 2014).

Genaidy (2011), Qadir et al. (2014), and Zoca and Penn (2017) indicated that agricultural gypsum, $CaSO_4 \cdot H_2O$, is one of the most important reclamation materials for saline and alkaline soils. It improves the soil's physical, chemical, and biological properties. It also helps reduce the harmful accumulation of sodium in the soil. It improves soil permeability and helps leach salts. It also improves the availability of essential nutrients in the soil, which are important for wheat growth, thereby increasing its productivity. Apart from gypsum applications, the use of nano-fertilisers is beneficial for efficiently increasing nutrient uptake by the plant. This is due to the small size of the particles, which enables efficient nutrient absorption by minimising nutrient loss and increasing the reactive sites of the roots. Moreover, it is advantageous for reducing heavy metal levels in grains, improving crop quality, and protecting the environment by reducing chemical residues in water and soil (Al-Juthery et al., 2026; Parra-Torrejón et al., 2023; Zulfiqar et al., 2019). The application of nano-fertilisers is also beneficial in increasing plant nutrient uptake due to their small particle size, which enables the plant to absorb nutrients more efficiently by increasing the number of reaction sites in the roots and reducing nutrient loss (Alzreejawi & Al-Juthery, 2020). Furthermore, nano-fertilisers help reduce heavy metals in grains and improve crop quality and the environment by reducing chemical residues in water and soil (Al-Juthery et al., 2018; Dimkpa & Bindraban, 2018; Parra-Torrejón et al., 2023).

In addition to the above factors that play a vital role in increasing soil fertility and promoting plant growth, the use of biofertiliser s such as EM (Effective Microorganisms) provides specific nutrients, including nitrogen, phosphorus, potassium, and micronutrients. The microorganisms also increase plants' resistance to environmental stresses such as drought and heavy-metal contamination in soil, as well as improve crop quality (Adesemoye & Kloepper, 2009; Al-Silmawy et al., 2025; Bhardwaj et al., 2014; Itelima et al., 2018). Liquid biofertiliser also plays an important role in reducing cultivation costs, as it does not require processing or sterilisation, which are often required for other products.

Liquid biofertiliser s also requires less labour, materials, and storage space, unlike other biofertilisers that use a carrier medium to maintain bacteria (Velineni & Brahmaprakash, 2011). Based on the above, this research aims to investigate the effect of various rates of DAP Fertiliser, soil conditioners such as gypsum and organic biofertiliser Bokashi, foliar spray of chelated nano-fertilisers such as Zn, Cu, Fe, and Mn, liquid biofertiliser AM, and biostimulant Fertigrain on some of the key growth and yield-contributing characters of wheat. While the individual effects of mineral fertilisers, organic amendments, and nano-based biostimulants on wheat have each been documented separately, few field studies have evaluated their combined, three-way interaction within a single factorial trial. Salinity and nutrient-poor soils constrain wheat productivity across many dryland and semi-arid regions worldwide, not only in Mesopotamia, so evidence on integrated mineral-organic-nano fertilisation strategies of this kind is relevant to wheat production systems facing similar constraints internationally.

MATERIALS AND METHODS

Experiment Site

The field experiment was conducted in District 7, Umm Al-Hatr area, Al-Nasr District, Dhi Qar Governorate, Nasiriyah City, Iraq, at the geographical coordinates of latitude (31°55′28.7″ N) and longitude (46°12′57.4″ E). The experimental field at establishment and at the flowering stage is shown in Figure 1 and Figure 2, respectively.

Experiment Design

The experiment was conducted according to a factorial arrangement within a Randomised Complete Block Design (RCBD) with three replications using a split-split plot system.



Figure 1. Field experiment layout at establishment, showing randomised treatment plots marked with numbered flags



Figure 2. Wheat plots at the flowering stage, showing the same treatment plot layout under crop cover

The main plots consisted of three levels of DAP Fertiliser application (0, 150, and 300 kg ha^{-1}). The sub-plots included soil amendments represented by agricultural gypsum (800 kg ha^{-1}) and EM Bokashi bio-organic Fertiliser (5 t ha^{-1}). Sodicity indicators for the experimental soil were measured and are reported in Table 1: SAR = 6.35, exchangeable Na^+ = 2.00 cmolc kg^{-1}, and ESP = 7.38%, which is below the classic sodic-soil threshold (ESP > 15%; Richards, 1954). The 800 kg ha^{-1} gypsum rate was therefore not calculated from a sodicity-reclamation equation, since the soil was not classified as sodic; rather, it was selected as a moderate, practical rate intended primarily to supply soluble Ca^{2+} and improve the soil's chemical and physical conditions, while avoiding an excessive addition that could unnecessarily raise the soluble salt concentration of the soil. This rate is consistent with its use as a general conditioning amendment in previous studies conducted under similar agricultural conditions in Iraq. The sub-sub plots involved foliar applications, including water spray (control), liquid biofertiliser EM at 5 ml L^{-1}, Fertigrain biostimulant at 2.5 ml L^{-1}, and nano-chelated fertiliser at 2.5 g L^{-1}. All foliar treatments were applied sequentially in three sprays during the growing season.

Preparation of the Experimental Field

The field was ploughed twice crosswise, then leveled and smoothed to ensure uniform soil conditions. Soil samples were randomly collected from representative locations at a depth of 0-30 cm before planting for physical and chemical analyses as presented in Table 1. The total experimental area was 450 m^2 and was divided into three replications, each containing 36 experimental units. The area of each experimental unit was 3 m^2 (1.5 m × 2 m). Irrigation channels were established between the experimental units to facilitate irrigation.

Fertilisation

After ploughing, levelling, and dividing the experimental field, the experimental units were fertilised according to the treatments: DAP Fertiliser (Nippon Jordan Fertiliser Company, NJFC, Jordan) at three levels (0, 150, and 300 kg ha^{-1}), agricultural gypsum (Advanced Village Co., Iraq) at a level of (800 kg ha^{-1}), and the organic biofertiliser EM Bokashi (EM Research Organisation, EMRO, Japan) (5 tons ha^{-1}) mixed with the soil. Foliar spray treatments included a chelated nano-Fertiliser compound of micronutrients (Zn, Cu, Fe, and Mn) (Nano Chelated Complete Micro Fertiliser; Khazra Nanochelating Technology, Sodour Ahrar Shargh Co., Tehran, Iran) at a concentration of (2.5 g L^{-1}), liquid biofertiliser EM (EMRO / EM-1 system, Japan) at a concentration of (5 ml L^{-1}), and the biostimulant Fertigrain (Fertigrain Foliar; AgriTecno Fertilizantes, S.L., Valencia, Spain) at a concentration of (2.5 ml L^{-1}), as per Table 2. Three sprays were applied at the branching, budding, and 50% flowering stages, starting on February 17, 2025.

Table 1
Physical and chemical properties of the field soil before planting

Property		Value	Unit
Soil reaction (pH)		7.6	---
Electrical conductivity (EC)		3.0	dS m^{-1}
Cation exchange capacity (CEC)		27.1	cmolc kg^{-1} soil
Soil organic matter		1.4	%
Carbonate minerals		219	g kg^{-1} soil
Bulk density		1.3	Mg m^{-3}
Available nitrogen		21.1	mg N kg^{-1} soil
Available phosphorus		11.3	mg P kg^{-1} soil
Available potassium		260.2	mg K kg^{-1} soil
Available sulfur		20.4	mg S kg^{-1} soil
Soluble calcium (Ca^{2+})		10.2	mmolc L^{-1}
Soluble magnesium (Mg^{2+})		6.8	mmolc L^{-1}
Soluble sodium (Na^{+})		18.5	mmolc L^{-1}
Sodium adsorption ratio (SAR)		6.4	(mmolc L^{-1})½
Exchangeable sodium (Na^{+} exch)		2.0	cmolc kg^{-1} soil
Exchangeable sodium percentage (ESP)		7.4	%
Soil separates	Sand	132	132 g kg^{-1} soil
	Silt	560	560 g kg^{-1} soil
	Clay	308	308 g kg^{-1} soil
Soil texture		Silty clay loam	

Note. Sodicity indicators were calculated as: $SAR = Na^{+} / \sqrt{[(Ca^{2+} + Mg^{2+}) / 2]}$, using soluble cation concentrations (mmolc L^{-1}) in the saturation extract; and ESP (%) = (exchangeable Na / CEC) × 100, using exchangeable sodium and CEC (cmolc kg^{-1} soil) (Richards, 1954)

Plantation and Crop Management

The Wafiya wheat variety, of Italian origin and approved by the Iraqi Ministry of Agriculture, was used. The seeds were planted on November 18, 2024, at a rate of 90 kg ha-1 using a tractor-mounted seeder.

Harvest

The wheat crop was harvested on May 9, 2025, when all treated plants were fully mature. Each experimental unit was packed in a plastic bag and transported to its designated location for laboratory analysis.

Table 2
Fertilisers used in the experiment and their components

Fertiliser Name	Fertiliser Type	Components
DAP	Granular	Nitrogen (N) 18-21%, Phosphorus (P_2O_5) 46-48%
Agricultural gypsum	Granular	Calcium (Ca) 23-24%, Sulfur (S) 18-19%
EM.Bokashi	Bio-organic Fertiliser	Nocardia [45.45%], Streptomyces [36.36%], Terrabacter [9.1%], Micromonospora [4.54%], Mycobacterium [4.54%], Lactobacillus spp. [30-50%], Aspergillus spp., Dactylium spp., Rhizopus spp.; $CaCO_3$ [2-3%], $Ca_3(PO_4)_2$ [1-2%], (Mn, Fe, Zn) [0.5-1%], OM [82.5%], pH [4.9], NaCl [0.25%], Na [0.10%], EC [7.30 mhos/cm], Moisture [7.74%], CFU [1.45×10^6]
Nano-chelated micronutrient Fertiliser	Granular nanomaterial	Fe 8%, Mg 2%, Zn 1.5%, Cu 0.5%, Mn 1.5%, B 0.5%, Mo 0.5%
Fertigrain (biostimulant)	Liquid Fertiliser	Plant-derived organic matter 40%, Free amino acids 10%, Total N 5.50% + Zn 0.75% + Mn 0.50% + B 0.10% + Fe 0.10% + Cu 0.10% + Mo 0.02% + Co 0.01%
Liquid biofertiliser EM	Liquid biofertiliser	Photosynthetic bacteria (Rhodospirillum, Rhodopseudomonas palustris, Rhodobacter sphaeroides), lactic acid bacteria (Lactobacillus casei, Lactobacillus delbrueckii, Lactobacillus fermentum), actinomycetes (Streptococcus spp.), yeasts (Saccharomyces cerevisiae), phosphate-solubilizers (Aerobacter, Candida, Penicillium, Xanthomonas), N-fixing bacteria (Azotobacter, Azospirillum, Pseudomonas), fungi (Aspergillus, Penicillium)

Studied Indicators before Harvest

Chlorophyll Index (SPAD)

The chlorophyll index in leaves was measured at 50% flowering using a portable SPAD-502 device. Readings were taken randomly from ten plants in each experimental unit, and the average was calculated by dividing the sum of the readings by the number of leaves (Markwell et al., 1995)

Plant Height

When plants reached full maturity (100%), plant height was measured from the soil surface to the top of the plant using a measuring tape. Ten plants were randomly selected from each experimental unit, and the average height was calculated by dividing the sum of the measurements by the number of plants (Singh & Stoskopf, 1971)

Post-Harvest Indices

Biological Yield

The total dry weight of aboveground plant material per square meter of the experimental unit was calculated after 10 days of air drying and then converted to (Mg ha^{-1}) (Sharma & Smith, 1986).

Grain Yield

The grain yield for each experimental unit was determined after drying the plants. The grains were separated from the biomass and weighed in kilograms per square meter, then converted to Mg ha-1 after confirming that the moisture content was approximately 14% using a moisture meter (Sharma & Smith, 1986).

Harvest Index

The harvest index for wheat was calculated using Equation 1 (Sharma & Smith, 1986).

$$Harvest\ Index = \frac{Grain\ yield\ Mg\ ha^{-1}}{Biological\ yield\ Mg\ ha^{-1}} \times 100 \text{ for each treatment} \quad [1]$$

Thousand Grain Weight

The weight of 1,000 grains was estimated. 1,000 grains were counted per treatment with a grain counter, then weighed on a sensitive electronic scale (Dhi Qar Agriculture Directorate Research Station).

Percentage Yield Increase over Control (PYI) for Production

Percentage Yield Increase over Control (PYI) for production was calculated as: Grain yield in the fertilised treatment (Mg ha-1) - Grain yield in the control treatment (Mg ha-1) / Grain yield in the control treatment (Mg ha-1) × 100 (Fixen et al., 2014). This index expresses the relative yield gain over the control and is therefore distinct from conventional fertiliser-use efficiency metrics, which normalise the yield gain by the quantity of nutrient applied (e.g., agronomic efficiency, kg yield per kg nutrient)

Statistical Analysis

The data obtained were statistically analysed using GenStat software according to the Randomised Complete Block Design (RCBD) with a split-split-plot arrangement. Analysis of variance (ANOVA) was performed to evaluate the effects of the experimental treatments on the studied traits. Mean comparisons were conducted using the Least Significant

Difference (LSD) test at the 0.05 probability level to determine significant differences among treatment means.

RESULTS

Plant Height (PLH): The results in Table 3 indicated that the average height of wheat plants with no application of DAP Fertiliser was 68.065 cm, which increased to 69.778 cm at 150 kg ha^{-1} of DAP Fertiliser, and then reached the highest average of 72.833 cm at 300 kg ha^{-1}.It also showed that the application of soil amendments significantly affected PLH. The highest average PLH of 72.306 cm was recorded when Bokashi Fertiliser was applied, followed by agricultural gypsum with an average PLH of 69.833 cm, and the lowest average PLH of 68.528 cm when no amendment was applied. As shown in Table 3, spraying with

Table 3
Effect of DAP fertiliser levels, soil amendments, foliar applications of biostimulants and chelated nano-fertiliser, and their interactions on wheat height (cm)

DAP Level	Soil Amendment	Spraying Transactions				DAP Levels × Amendments
		Water	Fertigrain	Nano-Fertiliser	Biofertiliser	
No addition	No treatment	65.333	66.333	67.667	67.000	66.583
	gypsum	67.667	68.333	68.667	68.667	68.334
	Bokashi	68.000	69.000	70.333	69.667	69.250
150 kg ha^{-1}	No treatment	68.333	68.667	69.333	69.000	68.833
	gypsum	69.000	69.333	70.333	69.333	69.500
	Bokashi	69.000	70.667	73.000	71.333	71.000
300 kg ha^{-1}	No treatment	67.333	70.667	71.667	71.000	70.167
	gypsum	71.000	71.333	72.333	72.000	71.667
	Bokashi	72.667	74.667	83.333	76.000	76.667
LSD 0.05			1.348			0.775
Effect of DAP Levels						
DAP Fertiliser × Spraying	No addition	67.000	67.889	68.889	68.445	68.065
	150 kg ha^{-1}	68.778	69.556	70.889	69.889	69.778
	300 kg ha^{-1}	70.333	72.222	75.778	73.000	72.833
LSD 0.05			0.844			0.678
Effect of Enhancers						
Enhancers × sprays	No treatment	67.000	68.556	69.556	69.000	68.528
	gypsum	69.222	69.666	70.444	70.000	69.833
	Bokashi	69.889	71.445	75.555	72.333	72.306
LSD (0.05)			0.756			0.404
Effect of spraying		68.704	69.889	71.852	70.444	
LSD (0.05)				0.441		

water alone resulted in the lowest average height of 68.704 cm, which increased to 69.889 cm with the biostimulant Fertigrain and to 70.444 cm with the liquid biofertiliser EM. The chelated nano-Fertiliser for micronutrients achieved the highest average height of 71.852 cm. The interaction effect of DAP Fertiliser and soil amendments was significant, with wheat PLH increasing as DAP Fertiliser increased. The highest PLH of 76.667 cm was recorded with 300 kg ha^{-1} of DAP Fertiliser and Bokashi Fertiliser, compared with the lowest PLH of 66.583 cm recorded without DAP Fertiliser and amendments. Similarly, the interaction between DAP Fertiliser and foliar treatments indicated a progressive response. The average height increased from 67.000 cm without DAP and water spray only to 75.778 cm with 300 kg/ha DAP and chelated nano-Fertiliser.

The interaction of soil amendments and foliar treatments showed the lowest average height of 67.000 cm with no amendment and water spray, and the highest value of 75.555 cm was obtained with Bokashi Fertiliser combined with nano-fertiliser spray. Finally, the three-way interaction between DAP levels, soil amendments, and foliar treatments produced the highest response. PLH ranged from 65.333 cm without any treatments applied to a maximum of 83.333 cm when 300 kg ha^{-1} DAP was applied in combination with Bokashi Fertiliser and chelated nano-Fertiliser spray for micronutrient supply.

Chlorophyll Index (SPAD)

The results in Table 4 indicate that the SPAD increased with increasing rates of DAP Fertiliser. On average, it rose from 47.353 SPAD in the no-fertiliser treatment to 49.764 SPAD in the 150 kg ha^{-1} treatment, and it reached its peak in the 300 kg ha^{-1} treatment, which recorded 50.097 SPAD. In terms of soil amendment, Bokashi Fertiliser had the highest SPAD among the treatments. Its average was 52.803 SPAD, compared to 48.336 SPAD in the gypsum treatment and 46.075 SPAD in the control.

Foliar treatments also resulted in a significant increase in SPAD compared with the control (water spray). The average SPAD for nano-chelate Fertiliser spraying was 51.711 SPAD units, whereas for water spray, it was only 46.955 SPAD units. The SPAD for all foliar treatments increased gradually with increasing DAP concentration, and the highest SPAD of 52.389 units was recorded for the 300 kg ha^{-1} DAP and nano-chelate Fertiliser spray. Moreover, the interaction between DAP levels and soil amendments contributed to bokashi, with 55.109 SPAD units at all DAP levels. Furthermore, the interaction between soil amendments and foliar application showed that bokashi with nano-chelated Fertiliser spray had the highest SPAD value of 58.145. The triple interaction effect of DAP levels, soil amendment, and foliar spray was significant for SPAD, with the highest value of 62.867 SPAD recorded at 150 kg ha^{-1} DAP with bokashi + nano-chelated fertiliser spray, whereas the lowest value was 46.004 SPAD in the control treatment.

Table 4
Effect of DAP fertiliser levels, soil amendments, and foliar applications of bio-stimulants, chelated nano-fertilisers, and their interactions on chlorophyll index SPAD

DAP Level	Soil Amendment	Spraying Transactions				DAP Levels × Amendments
		Water	Fertigrain	Nano-Fertiliser	Biofertiliser	
No addition	No treatment	41.600	45.033	46.267	45.267	44.542
	Gypsum	46.400	47.467	47.733	47.700	47.325
	Bokashi	47.733	48.467	54.667	49.900	50.192
150 kg ha^{-1}	No treatment	43.133	46.633	48.000	47.000	46.192
	Gypsum	47.100	47.467	48.700	48.700	47.992
	Bokashi	51.533	51.867	62.867	54.167	55.109
300 kg ha^{-1}	No treatment	46.000	46.767	48.933	48.267	47.492
	Gypsum	49.067	49.167	51.333	49.200	49.692
	Bokashi	50.033	51.333	56.900	54.167	53.108
LSD 0.05		0.945				0.661
Effect of DAP Levels						
DAP Fertiliser × spraying	No addition	45.244	46.989	49.556	47.622	47.353
	150 kg ha^{-1}	47.255	48.656	53.189	49.956	49.764
	300 kg ha^{-1}	48.367	49.089	52.389	50.545	50.097
LSD (0.05)		0.450				0.248
Effect of Enhancers						
Enhancers × sprays	No treatment	43.578	46.144	47.733	46.845	46.075
	Gypsum	47.522	48.034	49.255	48.533	48.336
	Bokashi	49.766	50.556	58.145	52.745	52.803
LSD 0.05		0.756				0.404
Effect of Spraying		46.955	48.245	51.711	49.374	
LSD 0.05		0.275				

Biological Yield (BIY)

From the results presented in Table 5, it is clear that as DAP Fertiliser levels increased, BIY increased significantly. The average yield was 16.347 Mg ha^{-1} without Fertiliser application, increasing to 18.360 Mg ha^{-1} at 150 kg ha^{-1} and then to 20.403 Mg ha^{-1} at 300 kg ha^{-1}. However, it is observed that as levels increased from 150 kg ha^{-1} to 300 kg ha^{-1}, the increase in BIY is not as significant as that from 0 to 150 kg ha^{-1}. This is due to the fact that the plant had almost reached sufficiency. Regarding the effect of the soil amendments on BIY, Bokashi Fertiliser recorded the highest mean value of 20.988 Mg ha^{-1}, whereas agricultural gypsum recorded the second-highest value of 18.000 Mg ha^{-1}. The lowest value of 16.122 Mg ha^{-1} was recorded without the application of any amendment. It is noticed that chelated nano-Fertiliser ranked first in foliar treatments with the highest mean of BIY (19.394 Mg ha^{-1}), followed by liquid biofertiliser EM and biostimulant Fertigrain, while water spray only ranked last with the lowest mean (17.360 Mg ha^{-1}). The two-way

interaction between DAP Fertiliser and soil amendments revealed that the interaction of 300 kg ha^{-1} of DAP Fertiliser with Bokashi Fertiliser produced the highest BIY of 24.043 Mg ha^{-1}, compared to 14.875 Mg ha^{-1} when both factors were absent.

In addition, the interaction of 300 kg ha^{-1} DAP with chelated nano-Fertiliser recorded the highest BIY of 21.409 Mg ha^{-1}, while Bokashi with nano-Fertiliser spray recorded a high BIY of 22.911 Mg ha^{-1}. The highest value of BIY (26.260 Mg ha^{-1}) was recorded when 300 kg ha^{-1} of DAP, Bokashi Fertiliser, and chelated nano-Fertiliser spray were used, while the lowest value (13.477 Mg ha^{-1}) was recorded when all factors were absent.

Table 5
Effect of DAP fertiliser levels, soil amendments, foliar applications of biostimulants, chelated nano-fertiliser, and their interactions on biological yield (Mg ha^{-1})

DAP Level	Soil Amendment	Spraying Transactions				DAP Levels × Amendments
		Water	Fertigrain	Nano-Fertiliser	Biofertiliser	
No addition	No treatment	13.477	14.057	16.033	15.933	14.875
	Gypsum	16.050	16.117	16.147	16.310	16.156
	Bokashi	16.590	16.607	20.907	17.933	18.009
150 kg ha^{-1}	No treatment	14.697	16.227	16.873	16.253	16.013
	Gypsum	16.883	18.253	18.797	18.693	18.157
	Bokashi	20.123	20.770	21.567	21.180	20.910
300 kg ha^{-1}	No treatment	17.120	17.183	17.933	17.673	17.477
	Gypsum	19.053	19.820	20.033	19.847	19.688
	Bokashi	22.243	22.507	26.260	25.163	24.043
LSD 0.05			0.953			0.486
Effect of DAP Levels						
DAP Fertiliser × Spraying	No addition	15.372	15.594	17.696	16.725	16.347
	150 kg ha^{-1}	17.234	18.417	19.079	18.709	18.360
	300 kg ha^{-1}	19.472	19.837	21.409	20.894	20.403
LSD 0.05			0.550			0.340
Effect of Enhancers						
Enhancers × sprays	No treatment	15.098	15.822	16.946	16.620	16.122
	Gypsum	17.329	18.063	18.326	18.283	18.000
	Bokashi	19.652	19.961	22.911	21.425	20.988
LSD 0.05			0.550			0.281
Effect of Spraying		17.360	17.949	19.394	18.776	
LSD 0.05			0.318			

Grain Yield (GRY)

The results in Table 6 show that the average GRY improved from 4.857 Mg ha^{-1} without Fertiliser application to 5.410 Mg ha^{-1} when DAP Fertiliser level was 150 kg ha^{-1}, and

Table 6
Effect of DAP fertiliser levels, soil amendments, foliar applications of biostimulants, chelated nano-fertiliser, and their interactions on grain yield (Mg ha⁻¹)

DAP Level	Soil Amendment	Spraying Transactions				DAP Levels × Amendments
		Water	Fertigrain	Nano-Fertiliser	Biofertiliser	
No addition	No treatment	4.220	4.387	4.670	4.357	4.409
	Gypsum	4.473	4.903	5.033	4.930	4.835
	Bokashi	4.457	5.263	5.933	5.660	5.328
150 kg ha⁻¹	No treatment	4.423	4.943	4.977	4.830	4.793
	Gypsum	4.943	5.577	5.627	5.237	5.346
	Bokashi	5.713	6.317	6.460	5.867	6.089
300 kg ha⁻¹	No treatment	4.457	4.930	5.340	5.137	4.966
	Gypsum	5.273	5.523	5.963	5.597	5.589
	Bokashi	5.867	6.460	7.287	6.450	6.516
LSD (0.05)		0.227				0.244
Effect of DAP Levels						
DAP Fertiliser × Spraying	No addition	4.383	4.851	5.212	4.982	4.857
	150 kg ha⁻¹	5.026	5.612	5.688	5.311	5.410
	300 kg ha⁻¹	5.199	5.638	6.197	5.728	5.690
LSD (0.05)		0.131				0.119
Effect of Enhancers						
Enhancers × sprays	No treatment	4.367	4.753	4.996	4.775	4.723
	Gypsum	4.896	5.334	5.541	5.255	5.257
	Bokashi	5.346	6.013	6.560	5.992	5.978
LSD 0.05		0.131				0.141
Effect of Spraying		4.870	5.367	5.699	5.341	
LSD 0.05		0.076				

finally to 5.690 Mg ha⁻¹ when DAP Fertiliser level was 300 kg ha⁻¹. Bokashi Fertiliser produced the highest average GRY (5.978 Mg ha⁻¹), while agricultural gypsum produced the second highest average GRY (5.257 Mg ha⁻¹), and the lowest average GRY (4.723 Mg ha⁻¹) was recorded without applying any Fertiliser to the soil. Among the foliar treatments, chelated nano-Fertiliser for micronutrients was found to be superior, with a value of 5.699 Mg ha⁻¹ compared to other treatments, while water spraying alone gave the lowest value. The two-way interaction of DAP Fertiliser and soil amendments showed that the highest GRY was obtained by using 300 kg ha⁻¹ of DAP Fertiliser with Bokashi Fertiliser, giving 6.516 Mg ha⁻¹, compared to the lowest value of 4.409 Mg ha⁻¹ when both factors were absent. Among the interactions of DAP Fertiliser and foliar application, the highest mean value was recorded from the combination of 300 kg ha⁻¹ DAP and nano-Fertiliser spray, i.e., 6.197 Mg ha⁻¹, and the lowest value, i.e., 4.383 Mg ha⁻¹, was recorded from no DAP

and water spray only. Likewise, the blend of Bokashi Fertiliser with nano-fertiliser spray produced the highest GRY of 6.560 Mg ha^{-1}, whereas the control treatment, which received no amendment and used water spray, produced only 4.367 Mg ha^{-1}. Finally, the three-way interaction revealed that the highest GRY of 7.287 Mg ha^{-1} was obtained by using 300 kg ha^{-1} of DAP Fertiliser in combination with Bokashi Fertiliser and chelated nano-Fertiliser, whereas the lowest GRY of 4.220 Mg ha^{-1} was obtained in the absence of all three factors.

Harvest Index (HI)

The results in Table 7 indicated that the average HI was highest without DAP Fertiliser application (29.73%), decreased slightly to 29.47% at 150 kg ha^{-1}, and declined further to 27.94% at 300 kg ha^{-1}. The decrease in the HI was around 6%. The results also indicated that

Table 7
Effect of DAP fertiliser levels, soil amendments, foliar applications of biostimulants, chelated nano-fertiliser, and their interactions on HI (%)

DAP Level	Soil Amendment	Spraying Transactions				DAP Levels × Amendments
		Water	Fertigrain	Nano-Fertiliser	Biofertiliser	
No addition	No treatment	31.260	31.161	29.089	27.306	29.704
	Gypsum	27.831	30.384	31.134	30.191	29.885
	Bokashi	26.829	31.657	28.356	31.533	29.594
150 kg ha^{-1}	No treatment	30.050	30.425	29.463	29.681	29.905
	Gypsum	29.244	30.525	29.908	27.988	29.416
	Bokashi	28.366	30.392	29.933	27.679	29.092
300 kg ha^{-1}	No treatment	25.999	28.658	29.747	29.036	28.360
	Gypsum	27.648	27.841	29.742	28.176	28.352
	Bokashi	26.356	28.683	27.735	25.617	27.098
LSD 0.05		0.466				0.446
Effect of DAP Levels						
DAP Fertiliser × Spraying	No addition	28.640	31.067	29.526	29.677	29.728
	150 kg ha^{-1}	29.220	30.447	29.768	28.449	29.471
	300 kg ha^{-1}	26.668	28.394	29.075	27.609	27.936
LSD (0.05)		0.388				0.396
Effect of Enhancers						
Enhancers × Sprays	No treatment	29.103	30.081	29.433	28.674	29.323
	Gypsum	28.241	29.583	30.261	28.785	29.218
	Bokashi	27.184	30.244	28.674	28.276	28.595
LSD 0.05		0.241				0.228
Effect of Spraying		28.176	29.970	29.456	28.578	
LSD 0.05		0.060				

the soil amendments affected the HI. The average HI was around 29.218% for agricultural gypsum and 28.595% for Bokashi Fertiliser, whereas it was around 29.323% without any amendment. Foliar applications of biostimulants and nano-fertilisers clearly outperformed water spray only, as the HI increased from 28.176% to 29.97% with Fertigrain spray, achieving an increase of approximately 6.3%. The two-way interaction of DAP Fertiliser with soil amendment revealed that 150 kg ha^{-1} DAP + water spray only recorded the highest value of HI (29.905%), whereas 300 kg ha^{-1} DAP + Bokashi recorded only 27.098%. Likewise, 150 kg ha^{-1} DAP + Fertigrain spray recorded the highest value of HI (30.447%), whereas 300 kg ha^{-1} DAP + Fertigrain recorded only 28.394%. The interaction of soil amendment with foliar spray revealed that Bokashi Fertiliser + Fertigrain spray recorded the highest value of HI (30.244%), whereas Bokashi + EM liquid biofertiliser recorded only 28.276%. The three-way interaction showed that the highest HI value (31.657%) was obtained when no DAP Fertiliser was applied and Bokashi Fertiliser and Fertigrain spray were used, whereas the lowest value was recorded when 300 kg ha^{-1} DAP Fertiliser was applied without any soil amendments and foliar spray.

Weight of 1,000 grains (g)

It is clearly shown in Table 8 that the average thousand-grain weight increases from 34.389 g without DAP to 37.018 g with 150 kg ha^{-1} of DAP and then decreases to 35.611 g with 300 kg ha^{-1} of DAP. Therefore, it can be concluded that the average thousand-grain weight is best promoted with the medium level of DAP Fertiliser. On the other hand, Table 8 also shows that the highest average thousand-grain weight is with Bokashi Fertiliser, at 38.083 g, compared to 34.991 g with agricultural gypsum and 33.945 g without any amendment. In addition, Table 8 shows that the highest average thousand-grain weight was with the chelated nano-fertiliser, at 36.954 g, compared to other foliar treatments. The interaction of DAP Fertiliser and soil amendments showed that the highest thousand-grain weight was obtained when the plants were subjected to the application of 150 kg ha^{-1} of DAP Fertiliser and Bokashi, at 41.083 g. The interaction between DAP Fertiliser and foliar application showed that the highest average was obtained when the plants were subjected to 150 kg ha^{-1} of DAP Fertiliser and chelated nano-fertiliser, with the highest weight of 38 g. As for the interaction between the soil amendments and the foliar, the addition of Bokashi along with EM bio-fertiliser resulted in the highest average thousand-grain weight of 40g, whereas the lowest average of 32.889 g was recorded in the absence of all factors, where only water was sprayed. Finally, the three-way interaction resulted in the highest thousand-grain weight of 45g for the combination of 150 kg ha^{-1} DAP, Bokashi, and chelated nano-Fertiliser, whereas the lowest value of 33.000 g was recorded in the absence of all factors.

Table 8
Effect of DAP fertiliser levels, soil amendments, and foliar applications of bio-stimulants, chelated nano-fertilisers, and their interactions on thousand-grain weight (g)

DAP Level	Soil Amendment	Spraying Transactions				DAP × Amendments
		Water	Fertigrain	Nano-Fertiliser	Biofertiliser	
No addition	No treatment	33.000	33.667	33.667	33.667	33.500
	Gypsum	33.667	34.000	35.000	34.333	34.250
	Bokashi	35.333	35.333	35.667	35.333	35.417
150 kg ha^{-1}	No treatment	34.000	35.000	35.000	35.000	34.750
	Gypsum	34.667	35.333	35.555	35.333	35.222
	Bokashi	34.667	40.333	45.000	44.333	41.083
300 kg ha^{-1}	No treatment	31.667	33.667	34.667	34.333	33.584
	Gypsum	35.000	35.333	36.000	35.667	35.500
	Bokashi	35.667	37.000	39.333	39.000	37.750
LSD 0.05	1.959					0.498
Effect of DAP Levels						
DAP × Spraying	No addition	34.000	34.333	34.778	34.444	34.389
	150 kg ha^{-1}	34.445	36.889	38.518	38.222	37.018
	300 kg ha^{-1}	34.111	35.333	36.667	36.333	35.611
LSD 0.05	1.131					0.629
Effect of Enhancers						
Enhancers × Sprays	No	32.889	34.111	34.445	34.333	33.945
	Gypsum	34.445	34.889	35.518	35.111	34.991
	Bokashi	35.222	37.555	40.000	39.555	38.083
LSD 0.05		1.131				0.288
Spraying Nano-Bio		34.185	35.518	36.954	36.333	
LSD 0.05		0.653				

Percentage Yield Increase over Control (PYI)

As depicted in Table 9, significant differences were exhibited in the results obtained for PYI (%). The PYI value ranged from 0.00% in the control treatment (with no addition + no treatment + water spray), up to the value of 72.68% in the treatment involving addition of 300kg ha^{-1} of DAP Fertiliser + Bokashi + spraying with chelated nano-Fertiliser (Zn, Cu, Fe, Mn). The results demonstrated that Bokashi soil amendment treatments attained high PYI values across different DAP Fertiliser and spraying treatments, ranging from 5.62% to 72.68%. The highest PYI value was observed when the Bokashi treatment was applied in combination with high quantities of DAP Fertiliser and nanoelement spraying. It was further found that increasing the DAP Fertiliser rate led to a gradual increase in PYI. Treatment with 300kg ha^{-1} DAP Fertiliser attained higher PYI than those with 150 kg ha^{-1} or with no treatment at all, in conjunction with soil amendment and spray treatments.

Table 9
Effect of DAP fertiliser levels, soil amendments, foliar spray treatments with biostimulants, chelated nano-fertiliser, and their interactions on PYI for production (%)

No.	DAP Level	Soil Amendment	Foliar Treatment	GRY (Mg ha^{-1})	PYI (%)
1	No addition	None	Water spray only	4.220	0.00
2	No addition	None	Fertigrain	4.387	3.96
3	No addition	None	Nano-chelated	4.670	10.66
4	No addition	None	EM	4.357	3.25
5	No addition	Gypsum	Water spray only	4.473	6.00
6	No addition	Gypsum	Fertigrain	4.903	16.18
7	No addition	Gypsum	Nano-chelated	5.033	19.27
8	No addition	Gypsum	EM	4.930	16.82
9	No addition	Bokashi	Water spray only	4.457	5.62
10	No addition	Bokashi	Fertigrain	5.263	24.72
11	No addition	Bokashi	Nano-chelated	5.933	40.59
12	No addition	Bokashi	EM	5.660	34.12
13	150 kg ha^{-1}	None	Water spray only	4.423	4.81
14	150 kg ha^{-1}	None	Fertigrain	4.943	17.13
15	150 kg ha^{-1}	None	Nano-chelated	4.977	17.94
16	150 kg ha^{-1}	None	EM	4.830	14.45
17	150 kg ha^{-1}	Gypsum	Water spray only	4.943	17.13
18	150 kg ha^{-1}	Gypsum	Fertigrain	5.577	32.16
19	150 kg ha^{-1}	Gypsum	Nano-chelated	5.627	33.34
20	150 kg ha^{-1}	Gypsum	EM	5.237	24.10
21	150 kg ha^{-1}	Bokashi	Water spray only	5.713	35.38
22	150 kg ha^{-1}	Bokashi	Fertigrain	6.317	49.69
23	150 kg ha^{-1}	Bokashi	Nano-chelated	6.460	53.08
24	150 kg ha^{-1}	Bokashi	EM	5.867	39.03
25	300 kg ha^{-1}	None	Water spray only	4.457	5.62
26	300 kg ha^{-1}	None	Fertigrain	4.930	16.82
27	300 kg ha^{-1}	None	Nano-chelated	5.340	26.54
28	300 kg ha^{-1}	None	EM	5.137	21.73
29	300 kg ha^{-1}	Gypsum	Water spray only	5.273	24.95
30	300 kg ha^{-1}	Gypsum	Fertigrain	5.523	30.88
31	300 kg ha^{-1}	Gypsum	Nano-chelated	5.963	41.30
32	300 kg ha^{-1}	Gypsum	EM	5.597	32.63
33	300 kg ha^{-1}	Bokashi	Water spray only	5.867	39.03
34	300 kg ha^{-1}	Bokashi	Fertigrain	6.460	53.08
35	300 kg ha^{-1}	Bokashi	Nano-chelated	7.287	72.68
36	300 kg ha^{-1}	Bokashi	EM	6.450	52.84

The results further illustrated that treatments with chelated nano-Fertiliser produced the highest PYI values in comparison with other treatments, ranging from 10.66% to 72.68% according to the different interactions, while treatment with water spray recorded low PYI values.

DISCUSSION

The results show that the three-dip treatment (DAP × soil amendments × spraying) is superior to both the individual and dual treatments, as these interactions yielded the highest PYI values for production under experimental conditions. This increase in SPAD levels in response to DAP Fertilisers resulted from the fertilisers' ability to act as sources of both nitrogen and phosphorus. The former is an element that constitutes chlorophyll and Rubisco proteins involved in carbon fixation, whereas the latter is a key element involved in energy transport processes in chloroplasts through ATP, hence increasing photosynthetic efficiency and chlorophyll content in leaves (Arzu et al., 2024; Marschner, 2012). However, the superiority of Bokashi treatment was attributed to its role in enhancing soil conditions and stimulating microbial growth around plant roots. The influence of agricultural gypsum on crops is related to improved soil characteristics due to soluble calcium and reduced exchangeable sodium. Thus, such factors can positively influence soil structure and water permeability, increase nutrient uptake efficiency, and stabilise chlorophyll levels in leaves (Qadir et al., 2014; Zoca & Penn, 2017). Treatment with a nano-formula of micronutrients and biostimulants increases chlorophyll levels by activating the enzymatic system responsible for photosynthesis. For instance, iron contributes to electron transport in plants, manganese to the second photosynthetic system, and zinc helps to regulate the process of chlorophyll synthesis. Moreover, the application of nano-formulations positively influences the efficiency of absorption and transport in plants (Ali et al., 2023; Raliya et al., 2018; Zulfiqar et al., 2019).

The notable increase in height of wheat plants with the application of DAP Fertiliser is associated with its contribution to increasing soil fertilisation with nitrogen and phosphorus. The role of nitrogen includes protein synthesis, chlorophyll synthesis, and enzyme production for growth purposes, whereas the role of phosphorus lies in energy exchange reactions and stimulation of root growth. As a consequence, cell division, photosynthesis, and internode elongation occur, resulting in increased plant height (Arzu et al., 2024; Marschner, 2012). An explanation of improved productivity with the use of Bokashi Fertiliser can be provided by its contribution to improved rhizosphere conditions. Organic materials improve soil structure and increase porosity, and stimulate phosphate-solubilising microbes that produce growth hormones (Almashhadani et al., 2026; Diacono & Montemurro, 2010; Quiroz & Céspedes, 2019). Agricultural gypsum influences the effect via the enhancement of cationic balance within the soil due to the

replacement of exchangeable sodium with soluble calcium, enhancing the soil structure and water permeability and minimising osmotic pressure in the root zone (Alsalami et al., 2025a; Qadir et al., 2014; Zoca & Penn, 2017). This results in improved uptake capacity of plants, in addition to promoting cell and vegetation growth (Qadir et al., 2014; Zoca & Penn, 2017). The leaf spraying of nano-fertilisers containing both micronutrients and biostimulants triggers physiological activities related to growth. These include the control of auxin synthesis through zinc and copper, resulting in cell elongation. Manganese is involved in enzyme activation for metabolic processes (Ali et al., 2023; Raliya et al., 2018; Zulfiqar et al., 2019). The use of nano-fertilisers increases the absorption efficiency by the plants, resulting in vegetative growth (Al-Juthery et al., 2018; Raliya et al., 2018; Zulfiqar et al., 2019). The advantage in the interaction of the three is evident from the combination of mineral fertilisation, soil improvement, and physiological activation of plants, leading to meristem and internode elongation (Khalaf & Al-Juthery, 2025; Wu & Ma, 2015).

An impressive increase in the number of wheat grains is associated with higher efficiency of photosynthesis-driven conversion of source tissues into grains during the flowering and grain-filling stages. DAP Fertiliser is an easily obtainable source of nitrogen and phosphorus. The former stimulates cell division and protein production and increases the effectiveness of carbohydrate-producing surfaces, whereas phosphorus plays an important role in energy transfer and regulation of carbohydrate flow to the grains, thus contributing to effective grain formation and filling (Arzu et al., 2024; Marschner, 2012). Better performance of the Bokashi treatment is caused by better conditions in terms of soil fertility and nutrient availability. Organic matter helps increase the capacity for ketones exchange and activate phosphorus solubilisers and growth regulators, thus ensuring nutrient supply at the crucial grain formation stage (Diacono & Montemurro, 2010; Quiroz & Céspedes, 2019). The effect of agricultural gypsum is due to several reasons, such as improving the root environment through balancing ions, repairing soil structure and improving its ability to transport water. Such changes reduce osmotic pressure and facilitate water and nutrient absorption, as well as the transport of carbohydrates to grains, thereby increasing production levels (Alsalami et al., 2025b; Qadir et al., 2014; Zoca & Penn, 2017). As for the impact of micro- and nano-fertilisers used as sprays, their effect on yield components is mainly related to activating enzymes involved in photosynthesis and the synthesis of carbohydrates and proteins. Furthermore, using nano-fertilisers increases plant nutrient and carbohydrate absorption and transport, thereby enhancing grain filling (Ali et al., 2023; Raliya et al., 2018; Zulfiqar et al., 2019).

The two-way and three-way interactions indicate a combination of mineral fertilisation, increased soil fertility, and physiological activation of plants, thereby making efficient use of nutrients and improving dry matter conversion into grain. It is therefore understandable why the three-way interaction outperforms other treatments in the context of integrated plant nutrition management (Khalaf & Al-Juthery, 2025; Wu & Ma, 2015).

The considerable increase in wheat biomass yield is due to enhanced photosynthetic efficiency and increased dry mass accumulation during the growth period. The DAP Fertiliser is an easily accessible source of nitrogen and phosphorus, which leads to greater leaf area and enzyme activation for carbon assimilation and energy transmission processes, thereby contributing to biomass formation (Arzu et al., 2024; Marschner, 2012). The better performance of bokashi composting lies in its contributions to soil fertility and food security. Organic matter increases the capacity for ketone exchange and stimulates the activity of phosphate solubilising microbes and growth regulators, hence leading to higher nutrient uptake and dry matter accumulation (Diacono & Montemurro, 2010; Quiroz & Céspedes, 2019). Gypsum used in agriculture increases biomass by improving soil quality, ketone metabolism, and water permeability, thereby decreasing salt stress and promoting plant development (Qadir et al., 2014; Zoca & Penn, 2017). On the other hand, micronutrient and nanonutrient sprays stimulate enzymes involved in photosynthesis and respiration. Such nutrients include iron, zinc, manganese, and copper. The metabolism of micronutrients affects biological processes in plants. In addition, nanonutrients enhance nutrient uptake and transport within the plant, thereby increasing biomass productivity (Ali et al., 2023; Dimkpa & Bindraban, 2018; Zulfiqar et al., 2019). The binary and tertiary use cases involve a combination of mineral and organic Fertilisers with foliar sprays. The effect is enhanced nutrient availability, absorption, and physiological functions in plants, which increases dry weight production and yield (Khalaf & Al-Juthery, 2025; Wu & Ma, 2015).

Regarding the harvest index, it is more concerned with the efficiency of dry matter partitioning between vegetative biomass and grain than with the total yield produced. The heavy application of DAP results in a higher biological yield than grain yield, leading to a lower amount of dry matter partitioned into grains due to excessive vegetative growth (Marschner, 2012; Sharma & Smith, 1986). Conversely, the moderate amount of DAP ensures better balance between vegetative and reproductive growth, leading to efficient dry matter partitioning into grains (Wu & Ma, 2015). Amendments such as bokashi encourage biomass production rather than economic yield by improving root conditions and microbial metabolism, whereas gypsum helps maintain harvest index stability by altering cation composition and alleviating salt stress (Quiroz & Céspedes, 2019; Zoca & Penn, 2017). In addition, the application of biostimulants enhances carbohydrate transport into seeds and promotes efficient distribution, and micronutrients may enhance vegetative development in certain instances, thereby minimising their influence on harvest index (Ali et al., 2023; Dimkpa & Bindraban, 2018; Zulfiqar et al., 2019).

The interaction between fertilisation and biostimulation at two and three levels is related to the harvest index's sensitivity to nutrition balance. Balanced fertilisation and biostimulation improve dry matter allocation and the conversion of energy into grain (Khalaf & Al-Juthery, 2025; Wu & Ma, 2015). Additionally, the findings also showed that

the effects of wheat depend on the combination of mineral Fertilisers, soil management, and physiological stimulation. The DAP Fertiliser stimulates vegetative growth and photosynthetic activity, soil management improves nutrient supply, and foliar sprays boost metabolism (Ali et al., 2023; Marschner, 2012). Therefore, the harvest index reflects the balance between vegetative and reproductive growth stages and highlights the importance of integrating plant nutrition to ensure high productivity and effective dry matter distribution (Khalaf & Al-Juthery, 2025; Wu & Ma, 2015).

The predominance of the 150 kg ha-1 DAP Fertiliser dose for increasing grain weight is due to balanced phosphorus nutrition, which promotes grain development and filling and makes nutrient transfer more effective. A relative reduction in this trait may be due to reduced physiological efficiency from over-fertilisation or a relative nutritional imbalance. The predominance of Bokashi Fertiliser is due to improved root conditions, enhanced microbial activity, and more efficient nutrient use. The predominance of secondary material spraying indicates increased enzyme activity and grain filling efficiency during the late development stage (Rossini et al., 2025; Tan et al., 2026). The reason behind the superiority of two-way and three-way interactions is that using 150 kg ha^{-1} DAP, bokashi fertilisation, and secondary sources resulted in an optimal balance between soil nutrition, soil management, and leaf nutrition. This optimal balance enhanced grain filling, increased dry matter content, and gave the best thousand-grain weight among combined treatments, single treatments, and the control group (Rossini et al., 2025; Tan et al., 2026).

Furthermore, the findings from the percentage yield increase (PYI) evaluation indicate a definite increase in yield across all experimental treatments. Treatments involving mineral fertilisation, soil amendment, and nano-spraying had the highest success rate. This was because of the combined effects of these factors in improving nutrient utilisation efficiency and yielding higher crop yields. The soil amendment Bokashi appears to have contributed to this higher percentage yield increase (PYI). Soil physical, chemical, and biological properties were not directly measured in this study (see Limitations); however, Bokashi application has been reported in the literature to increase soil organic matter and microbial activity, thereby enhancing nutrient availability and reducing nutrient losses (Diacono & Montemurro, 2010; Quiroz & Céspedes, 2019). Moreover, the findings indicated that applying higher doses of mineral fertiliser (DAP) enhances the fertilisation process, particularly when applied together with organic amendments. Mineral Fertilisers deliver nutrients rapidly, whereas organic Fertilisers ensure high nutrient retention in the soil and minimise nutrient losses, hence increasing nutrient use efficiency. According to research, the practice of integrated fertilisation (application of mineral and organic Fertilisers) enhances nutrient use efficiency and productivity compared to single Fertiliser application (Ali et al., 2023; Khalaf & Al-Juthery, 2025). In spray applications, the use of chelated nano-fertilisers was more effective at enhancing the percentage yield increase (PYI). This was due to certain features of nanoparticles, including small size, large surface

area, and enhanced ability to penetrate plant tissues (Al-Shahmani & Al-Juthery, 2021). Nano-fertilisers also help minimise nutrient losses and improve utilisation efficiency. According to recent findings, agricultural nanotechnology helps in improving nutrient utilisation efficiency and productivity (Dimkpa & Bindraban, 2018; Shoukat et al., 2025).

Another reason for the effectiveness of the three-dip technique (DAP×Bokashi×nano-spray) may be attributed to the synergy among these variables. Specifically, Bokashi enhances soil conditions and boosts microbial activity; the mineral Fertiliser supplies plant nutrients, whereas the nano-spray facilitates their absorption (Al-Juthery & Al-Shami, 2019; Al-Shahmani & Al-Juthery, 2021). Research findings have confirmed that the use of organic and mineral fertilisers, alongside nanotechnology, is a promising approach to optimising fertilisation techniques and maintaining agricultural sustainability (Khalaf & Al-Juthery, 2025; Quiroz & Céspedes, 2019).

CONCLUSION

Results revealed a positive effect of increased DAP Fertiliser application on growth and productivity parameters. The highest fertiliser amount applied (300 kg ha^{-1}) yielded the highest values for plant height, biomass production, and grain production compared with no Fertiliser application. This indicates the essential contributions of nitrogen and phosphorus to plant photosynthesis and the formation of dry matter, due to their physiological roles. Moreover, Bokashi organic biofertiliser proved more effective than agricultural gypsum fertiliser and the control group in promoting biomass and grain yields, likely through improved nutrient supply (soil properties were not directly measured in this study). Spraying treatments were also significantly better than the rest, with the chelated nano-fertiliser having the best values for all studied parameters. It is also evident from the findings that two-way and three-way interactions among DAP Fertilisers, soil amendments, and sprays resulted in maximum productivity. The three-way treatment (300 kg ha-1 DAP Fertiliser + Bokashi + spraying nano-fertiliser) produced the best grain yield (7.287 Mg ha-1), bioyield (26.260 Mg ha-1), and percentage yield increase over the control (72.68%). This underscores the need for integrated application of mineral and organic Fertilisers with nanotechnology to boost nutrient utilisation efficiency. On the other hand, medium doses of DAP (150 kg ha-1) exhibited the maximum thousand-grain weight, while the harvest index was highest without DAP Fertiliser application and declined progressively with increasing DAP rate, emphasising the need for nutrient balance in optimising quality parameters. Thus, integrated fertilisation management that combines mineral, organic, and nano-based inputs may be recommended to achieve high productivity and sustainability in agriculture. Because nutrient-poor and salt-affected soils constrain wheat production well beyond Iraq, these findings offer a transferable framework for improving wheat productivity in other dryland and semi-arid wheat-growing regions internationally.

IMPLICATIONS OF THE STUDY

It draws out the practical takeaway: the three-way DAP × Bokashi × nano-fertiliser interaction supports shifting Fertiliser recommendations toward integrated mineral-organic-nano strategies, with direct relevance to sustainable wheat intensification on salt-affected Mesopotamian soils and national food security, and broader relevance to wheat production on nutrient-poor and salt-affected soils in other dryland and semi-arid regions internationally.

LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study was conducted over a single growing season at a single experimental location under the environmental conditions of southern Iraq. Therefore, the results may vary under different climatic conditions, soil types, and management practices (Hassan et al., 2021). In addition, the experiment focused primarily on growth and yield parameters without evaluating changes in soil biological activity, nutrient use efficiency, root characteristics, or grain quality traits. The long-term residual effects of DAP Fertiliser, Bokashi, agricultural gypsum, and nano-biostimulant applications on soil health and sustainability were also beyond the scope of this study.

Future studies should evaluate these integrated fertilisation strategies across multiple growing seasons and diverse agroecological regions to validate their stability and applicability (Arshad et al., 2025; Al-Salihi et al., 2026). Long-term experiments are recommended to assess their effects on soil fertility, microbial diversity, carbon sequestration, and nutrient cycling. Further research should also investigate the physiological and molecular mechanisms responsible for the observed improvements in wheat performance, including nutrient uptake efficiency, antioxidant responses, and photosynthetic activity. In addition, economic feasibility analyses and environmental impact assessments should be incorporated to determine the practicality and sustainability of integrated applications of DAP Fertiliser, soil amendments, and nano-biostimulants for large-scale wheat production.

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