Integrated Use of Biofertilizers, Compost, and Mineral Fertilizers to Improve Wheat Productivity and Soil Fertility in Calcareous Soils

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ABSTRACT

Wheat (*Triticum aestivum* L.) is an essential crop with considerable economic and nutritional significance. However, its productivity is often hindered in calcareous soils due to limited nutrient availability, low organic matter content, and high soil pH, all of which reduce nutrient uptake efficiency. This study examines the effect of arbuscular mycorrhizal fungi (AMF) and yeast inoculation, in conjunction with compost application, on wheat yield, nutrient content, and soil properties under calcareous soil conditions. A field experiment was conducted over two consecutive growing seasons at the El-Nubaria Agricultural Research Station in Egypt, utilizing a split-plot design. The main treatments consisted of three rates of compost (0, 15, and 30 m³ fed^{-1}), while the sub-main treatments included varying levels of mineral fertilizers (100, 75, and 50% NPK) and biofertilizers (AMF, yeast, and combination of both). The results showed that the integration of compost with biofertilizers significantly enhanced plant height and grain yield. The highest grain yield recorded was 2.73 tons fed^{-1}, with a biological yield of 11.76 ton fed^{-1}, achieved through the application of 30 m³ fed^{-1} of compost combined with both AMF and yeast. Additionally, the nutrient content in wheat grains and straw, including nitrogen, phosphorus, and potassium, showed notable increases with biofertilizer treatments. Soil quality parameters, such as organic matter content, mineral nitrogen (135.33 ppm), available phosphorus (13.99 ppm), and exchangeable potassium (212.68 ppm), were significantly improved in plots treated with compost. Furthermore, microbial activity, indicated by soil respiration and mycorrhizal spore count, increased with the combined application of compost and biofertilizers. These findings illustrate the potential of utilizing compost in combination with microbial inoculants as a sustainable agricultural practice to enhance wheat productivity and improve soil fertility in calcareous soils.

Keywords: Wheat, Mycorrhiza, Yeast, Compost, Mineral fertilizers.

INTRODUCTION

Calcareous soils in Egypt cover approximately 0.273 million hectares, accounting for 25–30% of the country's total land area. These soils are characterized by pH levels ranging from 7.6 to 8.4 and calcium carbonate content varying from 1% to over 25% (Taalab *et al.,* 2019 and Abou Hussien *et al.,* 2020). Such soils present significant agricultural challenges, including high infiltration rates, low water-holding capacity, poor soil structure, nutrient leaching, elevated pH levels, low organic matter content, and micronutrient deficiencies particularly phosphorus (Aboukila *et al.,* 2018). Additionally, imbalances in potassium, magnesium, and calcium further exacerbate these issues. The high $CaCO_3$ content in these soils also reduces the availability of essential nutrients such as nitrogen, phosphorus, and potassium (Wahba *et al.,* 2019).

The application of organic amendments (e.g., compost), biofertilizers, and arbuscular mycorrhizal fungi has been recommended to mitigate these challenges. These practices enhance nutrient availability, reduce $CaCO_3$ levels, and improve soil health (Al-Enazy *et al.,* 2017; Das *et al.,* 2021; Vahedi *et al.,* 2021 and Mohamed & Ibrahim, 2023).

Wheat (*Triticum aestivum* L.) is Egypt's most vital grain crop, yet its yields often remain suboptimal due to unfavorable climatic conditions (El-Sabagh, 2021). With approximately 1.425 million hectares under cultivation, annual production reaches 9.279 million tons, yielding an average of 6.511 tons per hectare (FAO, 2016). Wheat grains are a rich source of essential nutrients, including protein (6–21%), fats (1.5–2.0%), cellulose (2.0–2.5%), minerals (1.8%), and vitamins (Malav *et al.,* 2017). However, the long-term use of NPK fertilizers in calcareous soils has led to significant alterations in soil physicochemical properties and wheat cropping systems (Das *et al.,* 2021). Despite these challenges, chemical fertilizers remain widely used due to their high nutrient content, availability, and ease of transportation and application (Shen *et al.,* 2010).

The addition of compost to soil has been shown to reduce pH and phosphorus fixation while increasing organic matter content and readily available phosphorus, which correlates with improved wheat grain production (El-Ngar *et al.,* 2022). In calcareous soils, compost application enhances water retention and water-holding capacity (Jashothan, 2021), while organic amendments significantly boost crop productivity and improve plant growth components (Sary and Hamed,

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2021). Soil organic matter plays a critical role in maintaining soil fertility, improving soil texture, and enhancing microbial activity (Ahmed and Al-Mutairi, 2022). Compost is formed through the microbial decomposition of organic materials under hot, humid, and aerobic conditions (Ayilara *et al.*, 2020), and its long-term application has been proven to enhance soil nutrition and sustainability (Deakin, 2021).

Biofertilizers, which consist of cultured soil microorganisms, play a vital role in enhancing crop yield and soil fertility. They achieve this by fixing nitrogen, solubilizing phosphorus, and supplying essential nutrients, thereby promoting plant growth (Mahdi & Ismail, 2015 and Zaeim *et al.,* 2017). These microbial inoculants improve soil organic matter content and nutrient cycling, fostering sustainable plant health (Medani and Taha, 2015). Additionally, biofertilizers are critical for reducing environmental pollution while simultaneously enhancing wheat productivity and grain quality (Malusà *et al.,* 2016 and Taha *et al.*, 2016).

Organic manure and microbial inoculation contribute to lowering soil pH through the release of CO_2 and organic acids during decomposition. This process solubilizes calcium carbonate ($CaCO_3$) and neutralizes soil alkalinity. Furthermore, the microbial mineralization of organic amendments generates ammonium (NH_4^+), carbon dioxide (CO_2), and organic acids, which further reduce soil pH (Roy and Kashem, 2014). The application of yeast also accelerates the uptake of soil-soluble nutrients by plants. This is facilitated by the formation of carbonic acid, which results from the reaction of carbon dioxide with soil water (Abdou, 2015).

Arbuscular mycorrhizae (AM), which form symbiotic associations between fungi and plant roots, play a crucial role in enhancing nutrient uptake and micronutrient solubility, particularly when combined with organic substrates (Khan *et al.,* 2022). Inoculating wheat with arbuscular mycorrhizal fungi (AMF) spores has been shown to improve root density and phosphorus absorption (Hazzoumi *et al.,* 2022). Furthermore, long-term fertilization practices significantly influence AMF community dynamics in agricultural ecosystems (Ma *et al.,* 2021). AMF are particularly effective in mobilizing immobile phosphorus in calcareous soils, thereby boosting cereal productivity (Wahid *et al.,* 2020). They also improve soil properties by releasing organic acids and glomalin, which reduce soil erosion, chelate metals, and stabilize soil aggregates. Additionally, AMF enhances microbial diversity and alkaline phosphatase activity, increasing the availability of organic phosphorus (Fall *et al.,* 2022).

The benefits of AMF are significantly amplified when combined with compost application (Xin *et al.,* 2022), making AMF inoculation an eco-friendly strategy to improve soil fertility and crop productivity (Dal Cortivo *et al.,* 2018). Given these advantages, the present study aimed to investigate the influence of arbuscular mycorrhizal fungi and yeast as bio-fertilizers, compost as an organic fertilizer, and mineral fertilizers on the growth, yield, and nutrient content of wheat under calcareous soil conditions.

MATERIAL AND METHODS

A field experiment was conducted at the El-Nubaria Agricultural Research Station in Behaira Governorate, Egypt, Agricultural Research Center, Ministry of Agriculture and Land Reclamation. The study took place during the winter growing seasons of 2022–2023 and 2023–2024, focusing on how arbuscular mycorrhizal fungi inoculation and yeast application with compost influenced the yield and nutritional content of wheat (*Triticum aestivum* L. cv. Gimmaza 12) under calcareous soil conditions. The research farm is located at coordinates 30° 90' N and 29° 96' E, at an elevation of 25 meters above sea level. Soil samples (0–30 cm) and compost were collected and analyzed for their chemical and physical properties (Table 1 and Table 2), following the procedures described by Dewis & Freitas (1970) and Page (1982). The total nitrogen in the soil was determined using the micro-Kjeldahl distillation method, as explained by Bremner and Mulvaney (1982). The available phosphorus content was measured according to the methods outlined by Olsen (1954) and Watanabe & Olsen (1965), with phosphorus concentrations assessed using the colorimetric method employing ascorbic acid. The concentration of potassium (K) was measured using a flame photometer (Page, 1982). Additionally, concentrations of iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) were determined by extracting the soil with a DTPA solution, based on the method of Lindsay and Norvell (1978).

Table 1. The main physical and chemical analysis of the experimental soil for the two growing seasons (average values)

Particle size distribution			pH	EC	OC		O.M	CO_2	$CaCO_3$	Elements (mg/kg)			
Sand %	Silt %	Clay %		dS/m	%		%	mg /100 g equivalent soil /day	%	NH_4^- N	NO_3^- N	P	K
67	9	24	8.2	3.01	0.37		0.64	0.067	22.9	61.5	16	3.96	87.5
Soil texture			Na^+	K^+	Ca^{++}	Mg^{++}	SO_4^{--}	CO_3^{--}	HCO_3^-	Cl^-			
Sandy clay loam			9.6	1.05	8.35	11.1	17.25	-	2.4	10.45			

Table 2. Chemical analysis of compost

EC	pH	O.C	O.M	C/N	T. N	T. P	T. K	Fe	Zn	Mn	Cu
dS/m		%				%				mg kg $^{-1}$	
2.03	8.15	8.69	14.9	10.16	0.855	0.325	1.545	1.08	0.03	0.135	0.04

Experimental design and treatments:

All trials were conducted using a split-plot design within a complete randomized block arrangement, featuring three replications. The main plot treatments consisted of three rates of compost, made from agricultural residual by authors in the treatment location, (0, 15, and 30 m^3/fed). The sub-main treatments included three rates of mineral fertilizers (100, 75, and 50% of NPK) and biofertilizers, which comprised Mycorrhiza, Yeast, and a combination of both (Mycorrhiza + Yeast). The mycorrhizal strain used was Glomus sp., and the yeast strain was Candida. The Gimmaza variety was obtained from the El-Nubaria Research Station, Field Crops Institute, and Agricultural Research Station in Giza, Egypt, and was sown on November 15 at a rate of 60 kg fed^{-1}. Fertilizers included ammonium sulfate (20.5% N), superphosphate (15.5% P_2O_5), and potassium sulfate (48% K_2O), applied at rates of 480 kg fed^{-1}, 150 kg fed^{-1}, and 50 kg fed^{-1}, respectively. These additions, along with all other cultivation practices such as irrigation, weed control, and disease management were implemented for the wheat crop, by the recommendations of the Ministry of Agriculture and Land Reclamation.

Measurements and Analysis:

Yield components:

Parameters for yield components included plant height (cm), weight of 1000 grains (g), harvest index (%), biological yield, and grain yield (ton fed^{-1}). The Harvest Index was calculated using the Donald (1962) equation as following:

$$Harvest\ Index\ (HI) = \frac{Grain\ Yield\ (ton/fed)}{Biological\ Yield\ (ton/fed)} x\ 100$$

Nutrient Analysis in Straw and Grain:

Harvested plant samples (straw and grains) were analyzed to determine nutrient content using established methods (Estefan *et al.,* 2013). Nitrogen content (%) was measured using the Micro-Kjeldahl method, and a conversion factor of 5.75 was applied to calculate protein content (%). Potassium levels were determined using a flame photometer, while phosphorus was measured colorimetrically (Page, 1982).

Soil Analysis:

Available Nitrogen: The Kjeldahl method was used to determine the amount of available nitrogen in the soil. Available Phosphorus: Ascorbic acid was used for the colorimetric determination of available phosphorus. Available Potassium: A flame photometer was used to estimate available potassium, which was extracted using neutral normal ammonium acetate (NH_4OAc). Organic Carbon and Organic Matter: Organic carbon (%) was determined using the Walkley-Black method (Page, 1982), and organic matter (%) was calculated as follows: Organic Matter (%) =Organic Carbon (%) ×1.72. Soil pH: The pH of a 1:2.5 soil-to-water suspension was measured using a pH meter (Jenway, model 3310) (Jackson, 1973).

Plant Analysis:

Plant samples were wet-digested using a sulfuric acid-hydrogen peroxide (H_2SO_4-H_2O_2) digest (Chapman and Pratt, 1971) for the determination of total nitrogen, phosphorus, and potassium. Total nitrogen was determined using the modified micro-Kjeldahl method. Phosphorus was measured using the vanado-molybdate phosphoric yellow color method. Potassium was quantified using a flame photometer (Page, 1982).

Biological measurements:

Soil respiration was measured using the elevation of CO_2 method (Kaloosh, 1978). Arbuscular Mycorrhizal (AM) spore numbers were determined in rhizosphere soil samples collected at depths of 0–30 cm and 30–60 cm during plant harvest. AMF spores were isolated using the wet-sieving and decantation method (Gerdeman and Nicolson, 1963). Mycorrhizal infection was assessed in composite root samples from three plants per plot using the staining method described by Phillips and Hayman (1970). The percentage of mycorrhizal infection was calculated using the gridline intersect method (Giovannetti and Mosse, 1980).

$$Mycorrhizal\ Infiction\ (\%) = \frac{No.of\ infected\ segments}{Total\ No.of\ segments\ studied} * 100$$

Statistical Analysis and Heatmap:

Data were statistically analyzed, and Duncan's test was used to compare the means at the significant level ($p \leq 0.05$) according to Snedecor and Cochran (1990) using XLSTAT software version 2019 (Addinsoft, 2019). XLSTAT software version 2019 was used to perform a Heat Map and classify the data into different clusters having a common trait and was executed to define soil and plant properties versus treatment groups.

RESULTS AND DISCUSSION

Yield components:

The data presented in Table (3) provides a thorough analysis of how various combinations of compost, bio-fertilizers (such as mycorrhiza and yeast), and chemical fertilizers (NPK) impact several yield components. These components include plant height, weight of 1,000 seeds, biological yield, grain yield, and harvest index. The results demonstrate significant differences in these crop components across the different treatment combinations.

Plant height:

Plant height (Table 3) is a crucial indicator of vegetative growth and overall plant health. The data show that the application of 30 m³ of compost per fed combined with the Mix (M+Y) led to the highest plant height at 130.00 cm, followed by 30 m³ of compost with yeast at 125.00 cm, and 30 m³ fed^{-1} of compost with mycorrhiza at 121.67 cm. This suggests that higher levels of compost, when paired with bio-fertilizers, significantly enhance plant height. In contrast, treatments without compost and those with lower NPK levels (e.g., NPK 50 without compost) produced the shortest plants at 91.67 cm. Compost enhances soil fertility, promoting plant growth, with mycorrhiza enhancing nutrient uptake, while yeast stimulates hormonal growth, while mineral fertilization alone is insufficient for sustainable long-term growth. These findings are in line with Taha *et al.* (2016), who demonstrated that plant height improved with mineral fertilizers in a 75% NPK combination with biofertilizers, likely due to nitrogen-stimulating amino acids and potassium-stimulating metabolism. Additionally, Attia & Abd El Salam (2016) and Waheed & Muhammad (2021) observed that the inclusion of 100% NPK and 20 m³ of organic manure per fed increased plant height compared to just 50% NPK. Furthermore, yeast extract at a concentration of 1000 mg/L has been identified as the most effective treatment for increasing plant height in the Gemiza 7 variety of wheat (Nabila *et al.*, 2007; El-Hosary *et al.,* 2013 and Abdelaziz, 2022).

Weight of 1000 grains:

The weight of 1000 grains is an important parameter for assessing grain quality and yield potential. The highest 1000-grain weight was observed in the treatment with 30 m³ of compost per fed with a mix of mycorrhiza and yeast (83.33 g). This was followed by treatments with 30 m³ fed^{-1} of compost with mycorrhiza (76.67 g) and 15 m³ fed^{-1} of compost with mycorrhiza (76.67 g). These findings indicate that the combination of compost and biofertilizers significantly improves the weight of 1000 grains. The 30 m³/fed compost with Mix (M+Y) treatment promotes grain filling, resulting in the highest 1000-grain weight with well-developed, heavier grains. In contrast, treatments without compost, such as NPK 50 without compost, resulted in the lowest grain weight (53.33 g). These results align with findings published by Taha *et al.* (2016), which showed that potassine N plus 75% NPK application improved 1000 grain weight. Biofertilizers play a crucial role in managing the decomposition of organic matter, enhancing the availability of plant nutrients, and increasing nitrogen fixation rates. Additionally, the application of organic manure fertilizer at 20 m³ fed^{-1}, along with mineral fertilizer at the recommended dose of 100% NPK, also increased the 1000-grain weight of wheat, as found by Kandil *et al.* (2011) and Attia & Abd El Salam (2016).

Biological fertilizers, especially mycorrhizae, notably increased the weight of 1000 grains compared to unfertilized controls (Farnia & Hassanpour, 2015; Hussain *et al.*, 2016 and Abdelaziz, 2022). These outcomes are consistent with research demonstrating that organic and biofertilizers enhance nutrient uptake and promote seed filling, leading to heavier grains (Fageria *et al.,* 2010).

Biological yield:

Data presented in Table (3) indicate that the highest biological yield, representing the total biomass produced, was observed with the treatment of 30 m³ of compost per fed with the Mix (M+Y) combination, achieving 11.76 tons per fed. This was followed by 30 m³ of compost per fed with mycorrhiza at 10.99 tons per fed, and 30 m³ of compost per fed with yeast at 10.36 tons per fed. These results demonstrate that higher levels of compost, particularly when combined with biofertilizers, significantly enhance biomass production. Mycorrhiza enhances nutrient absorption, especially phosphorus, promoting plant growth. Yeast stimulates (auxins and gibberellins) and increases biomass. In contrast, low NPK levels (e.g., NPK 50) and zero compost resulted in the lowest biological yield of 4.70 tons per fed because mineral fertilization alone is not as effective as organic and microbial amendments in improving biological yield. These findings support the notion that organic amendments and biofertilizers improve soil fertility and promote plant growth, leading to increased biomass formation (Ma *et al.,* 2021). Additionally, research by Jan *et al.* (2014); Hussain *et al.* (2016); Mohamed A. *et al.* (2019) and Ewis (2020) how to show that mycorrhizal inoculation combined with vermicompost significantly enhances yield. Most yield parameters were markedly improved through biofertilizer inoculation, particularly as yeast treatments outperformed others (Ahmed *et al.*, 2011 and El-Aal *et al.,* 2012).

Grains yield:

Data in Table (3) and Fig (1) illustrate that grain yield is a crucial factor in agricultural productivity. The treatment involving 30 m³ of compost per fed, combined with the Mix (M+Y), produced the highest grain yield at 2.73 tons per fed. This was closely followed by the same amount of compost combined with mycorrhiza, which yielded 2.65 tons per fed, and the compost with yeast, which resulted in 2.54 tons per fed. These illustrations that the synergistic effects of compost and biofertilizers enhance grain production. Higher compost levels improve soil health, leading to better grain yield. Conversely, the lowest grain yields were observed in the treatment without compost and with lower NPK levels, such as NPK 50, resulting in only 1.22 tons per fed. Because organic and microbial treatments ensure long-term soil fertility and reduce nutrient loss compared to mineral fertilization. These results align with previous studies that show organic and biofertilizers improve nutrient availability, photosynthesis, and grain filling, ultimately leading to higher yields (Kumar *et al.*, 2011). Similarly, research by Farnia & Hassanpour (2015); Taha *et al.* (2016) and Abouhussien *et al.* (2019), indicates that applying 100% of NPK along with 20 m³ of organic manure per fed resulted in a remarkable grain yield. Wheat grain yield was further enhanced by mycorrhizal root colonization (Castillo *et al.*, 2016; Hussain *et al.*, 2016; Abdelaziz, 2022 and Hafez *et al.*, 2022). Additionally, wheat treated with mycorrhizal fungi produced the highest grain yield, as noted by Wahid *et al.* (2020) and Muchhadiya *et al.* (2021).

Table 3. Effect of biofertilizers and mineral fertilizer in presence of compost on yield components of the wheat plant (Combined analysis of two successive seasons)

Treatment		Plant Height (cm)	wt. of 1000 seeds (g)	Biological yield (ton/fed)	grain yield (ton/fed)	Harvest index (%)
Compost	**Bio & Chemical**					
without	NPK 100	105.00 f	63.33 bcd	6.09 h	1.52 l	24.96 bc
	NPK 75	103.33 f	60.00 cd	5.53 h	1.33 m	24.05 bc
	NPK 50	91.67 g	53.33 d	4.70 i	1.22 n	25.96 abc
	Mycorrhiza	106.67 ef	63.33 bcd	6.79 g	1.80 j	26.50 ab
	Yeast	111.67 def	66.67 bcd	5.88 h	1.67 k	28.40 a
	Mix (M+Y)	115.00 cde	66.67 bcd	6.87 g	1.80 j	26.20 abc
15 m^3/fed	NPK 100	116.67 bcd	70.00 abc	7.91 ef	2.03 gh	25.66 abc
	NPK 75	111.67 def	63.33 bcd	7.35 fg	1.95 hi	26.53 ab
	NPK 50	103.33 f	63.33 bcd	7.00 g	1.89 ij	27.00 ab
	Mycorrhiza	115.00 cde	76.67 ab	8.05 ef	2.15 f	26.70 ab
	Yeast	118.33 bcd	70.00 abc	7.91 ef	2.11 fg	26.67ab
	Mix (M+Y)	121.67 abc	76.67 ab	8.96 d	2.19 ef	24.44 bc
30 m^3/fed	NPK 100	120.00 bcd	70.00 abc	9.80 c	2.43 c	24.79 bc
	NPK 75	116.67 bcd	66.67 bcd	9.800 c	2.34 cd	23.87 bc
	NPK 50	115.00 cde	63.33 bcd	8.61 de	2.27 de	26.36 ab
	Mycorrhiza	121.67 abc	73.33 abc	10.99 b	2.65 a	24.11 bc
	Yeast	125.00 ab	70.00 abc	10.36 bc	2.54 b	24.51 bc
	Mix (M+Y)	130.00 a	83.33 a	11.76 a	2.73 a	23.21c

Values followed by the same letter (s) within each column did not significantly differ according to the Duncan multiple comparison test at the 5% level.

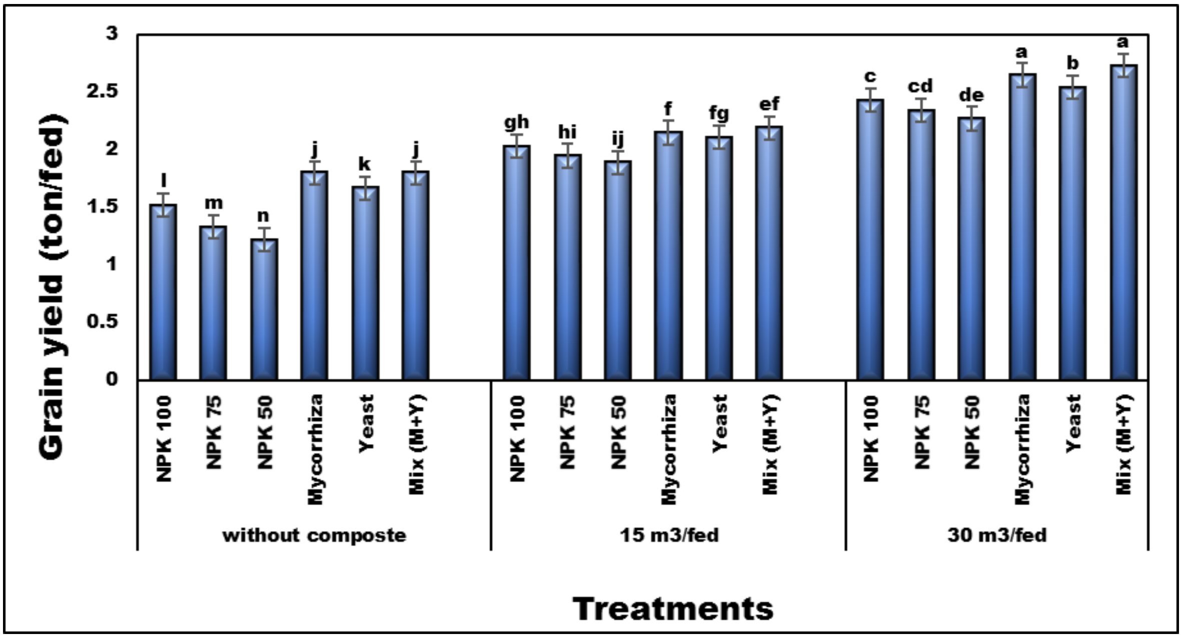

Fig. 1. Effect of biofertilizers and mineral fertilizer in presence of compost on grain yield of wheat plant

Harvest index:

Table (3) shows that the harvest index had the lowest value (23.21 %) with 30 m³/fed compost and Mix (M+Y) due to adding compost, rich in nitrogen, promotes leaf and stem growth more than grain production, increasing total biomass. The addition of yeast without compost recorded the highest value (28.4 %) of the harvest index due to yeast contains growth promoting substances that improve nutrient uptake and translocation from vegetative parts to grains, this ensures that more assimilates (photosynthetic products) are directed toward grain filling and increasing HI. Using 15 tons of compost-controlled fertilization led to better grain production and a higher HI. Biological fertilizers greatly enhanced HI when applied compared to controls, confirming the findings of Farnia and Hassanpour (2015). The harvest index significantly increased (40.66%) following the application of compost at a rate of 15 m^3 fed^{-1}. With an increase in biofertilizer rate, the harvest index gradually increased by a significant amount. In comparison to the control treatment, it rises by around 57% with 30 kg P fed^{-1} plus 15 m^3 of compost fed^{-1} and 2 L of biofertilizer fed^{-1} (Ewis, 2020).

Elements in straw and grain:

Nitrogen:

Nitrogen is a plant growth-critical macronutrient, playing a key role in chlorophyll synthesis, protein formation, and overall biomass production. The data in Table (4) demonstrated that nitrogen content in both straw and grain increased significantly with the application of compost, biofertilizers, and chemical fertilizers, particularly at higher rates (30 m^3 fed^{-1}). The highest straw-N content (1.29%) was observed in the Mix (M+Y) treatment at 30 m^3 fed^{-1}, followed by the yeast treatment (1.16%). This indicates that biofertilizers, especially when combined with compost, enhance nitrogen uptake by improving root efficiency and nutrient availability (Adesemoye *et al.*, 2009 and El-Habashy *et al.,* 2017). Mycorrhizal fungi, in particular, are known to facilitate nitrogen absorption by extending the root system and forming symbiotic relationships with plants (Smith *et al.*, 2011). Similarly, grain-N content was highest in the Mix (M+Y) treatment at 30 m³/feddan (2.26%), demonstrating the synergistic effect of combining biofertilizers with compost. This aligns with studies showing that biofertilizers improve nitrogen use efficiency by reducing losses through leaching and volatilization (Meena *et al.,* 2014). Comparison with Chemical Fertilizers: NPK treatments also increased N content, the biofertilizer treatments outperformed them, particularly at higher compost rates. For example, NPK 100 at 30 m³/feddan resulted in 2.26% grain N content, also the Mix (M+Y) treatment achieved 2.26%. This suggests that biofertilizers enhance the availability of nitrogen in the soil, making it more accessible to plants. 30-ton compost + (M+Y) is the most effective treatment for maximizing nitrogen content. Mycorrhiza enhances nitrogen absorption, while yeast boosts microbial activity for better nitrogen availability. Also, mineral fertilization provides nitrogen quickly, while compost improves its absorption efficiency and sustainability.

Phosphorus:

Phosphorus is necessary to transfer energy, root development, and reproductive growth. Data in Table (4) reveals that the phosphorous content in straw and grains was greatly affected by treatments, as biological fertilizers play an important role in improving P-uptake. The highest straw content (664.2 ppm) was recorded for treating the mix (M+Y) at 30 m³/fed. Mycorrhizal fungi are particularly effective in solubilizing fixed phosphorus in the soil, making it available for plant uptake (Sharma *et al.,* 2013). This explains the excellent performance of mycorrhiza-based treatments. Also, grain-P content was highest in the Mix (M+Y) treatment at 30 m³/fed (0.36%). This is consistent with the results that biological creatures enhance the availability of phosphorus by secreting organic acids and phosphates, which release the insoluble P (Richardson *et al.,* 2009). In comparison with chemical Fertilizers, the NPK treatments also improved P content, and the biofertilizer treatments were more effective. For instance, NPK 100 at 30 m³/feddan resulted in 0.29% grain-P content, while the Mix (M+Y) treatment achieved 0.36%. This highlights the role of biofertilizers in improving the efficiency of phosphorous.

Potassium:

Potassium is important for enzyme activation, water regulation, and stress tolerance. The data in Table (4) illustrated that potassium content in straw and grain increased with the application of compost and biofertilizers, particularly at higher rates. The highest straw-K content (3.6%) was noticed in the Mix (M+Y) treatment at 30 m³/fed. Potassium uptake is influenced by root growth and soil microbial activity, both of which are enhanced by biofertilizers (Meena *et al.,* 2014). Also, grain-K content was highest in the Mix (M+Y) treatment at 30 m³/feddan (0.44%). This is consistent with studies showing that biofertilizers improve potassium availability by promoting root growth and enhancing soil microbial activity (Römheld and Kirkby, 2010). Whereas NPK treatments also increased K content, the biofertilizer treatments were more effective. For example, NPK 100 at 30 m³/fed resulted in 0.37% grain-K content, whereas the Mix (M+Y) treatment reached 0.44%. This proposes that biofertilizers improve potassium use efficiency by enhancing root access to soil K reserves. These results agree with those found that treating wheat with farmyard manure with acid-producing bacteria, yeast, and molasses improves calcareous soil and nutrient uptake (El-Aal *et al.,* 2012; Hanna *et al.,* 2012; Farrag & Bakr, 2021 and Hamed *et al.,* 2022). Besides, plants' N, P, and K contents were increased by humic acid treatment and PGPR inoculation. When applied to dry leaves, 75% NPK+ potassine enhanced the percentages of N, P, and K (Taha *et al.,* 2016 and Hafez *et al.,* 2022). These results support those presented by Donn *et al.* (2014) and Abouhussien *et al.* (2019) who noted that composting tomato waste at a rate of 20-ton fed^{-1} under calcareous soil conditions was the optimum treatment for enhancing nutrient uptake. This increased N, P, and K content are found in wheat plants' grains. Moreover, applying compost with yeast has a better performance than chemical fertilizers at promoting the nutrient content of the grains (Mohamed M. *et al.,* 2019).

Protein:

Grain protein content is a critical quality parameter, influenced primarily by nitrogen availability and uptake. The data in Table (4) illustrated that grain protein content increased significantly with the application of compost and biofertilizers, particularly at higher rates. The highest grain protein content (12.99%) was recorded in the Mix (M+Y) treatment at 30 m³/fed. This treatment of compost enhances nutrient availability, mycorrhiza improves phosphorus, enhancing amino acid synthesis and yeast provides vitamins and plant hormones stimulating protein synthesis. This highlights the role of biofertilizers in improving nitrogen use efficiency and protein synthesis. This is consistent with studies showing that biofertilizers enhance nitrogen uptake and assimilation, leading to higher protein synthesis in grains (Kumar *et al.,* 2011; Smith *et al.,* 2011 and Ewis, 2020). NPK treatment also improved grain protein content at 30 m³/fed resulting in 12.99% grain protein content. Mineral fertilization ensures sufficient nitrogen, a key element in protein formation. These findings are in agreement with those revealed by Taha *et al.* (2016) who discovered that wheat protein levels were higher with 100% NPK than with 50% NPK treatments. Also, wheat treated with 75% NPK plus 5 t/ha of city compost had significantly higher protein content (Muchhadiya *et al.,* 2021). Protein was improved by the addition of yeast and 50% or 75% nitrogen fertilization, which also improved soil fertility (Hamed *et al.,* 2022).

Table 4. Effect of biofertilizers and mineral fertilizer in presence of compost on macronutrient content in straw, grain, and protein of wheat plant (Combined analysis of two successive seasons)

Treatment		Straw			Grain			Grain Protein (%)
Compost	Bio & Chemical	N (%)	P (ppm)	K (%)	N (%)	P (%)	K (%)	
without	NPK 100	0.50 k	41.44 jk	2.01 kl	1.85g	0.18 m	0.31 gh	10.64 g
	NPK 75	0.45 l	29.87 k	1.92 l	1.73h	0.15 n	0.31 gh	9.95 h
	NPK 50	0.38 m	28.60 k	1.62 m	1.62i	0.13 o	0.30 h	9.32 i
	Mycorrhiza	0.53 k	60.05 ijk	2.23 ij	1.87g	0.21 kl	0.31 gh	10.75g
	Yeast	0.59 j	48.20 jk	2.12 jk	1.89g	0.20 l	0.32 fg	10.86 g
	Mix (M+Y)	0.63 ij	69.97 ijk	2.29 ij	1.89g	0.22 k	0.32 fg	10.86 g
15 m^3 /fed	NPK 100	0.69 gh	119.82 h	2.540 gh	1.98e	0.25 hi	0.34 ef	11.39 e
	NPK 75	0.68 h	99.39 hi	2.41 hi	1.98ef	0.24 ij	0.33 ef	11.39ef
	NPK 50	0.65 hi	84.04 hij	2.35 hi	1.94f	0.23 jk	0.33 ef	11.16 f
	Mycorrhiza	0.73 g	222.23 f	2.68 fg	2.04d	0.26 fg	0.35 e	11.73 d
	Yeast	0.80 f	170.85 g	2.62 g	2.11c	0.25 gh	0.35 e	12.13 c
	Mix (M+Y)	0.83 f	271.21 e	2.75 efg	2.12c	0.27 ef	0.35 de	12.19 c
30 m^3 /fed	NPK 100	1.03 cd	402.96 cd	3.02 cd	2.26a	0.29 cd	0.37 cd	12.99 a
	NPK 75	1.00 d	366.78 d	2.93 de	2.17b	0.29 cd	0.37 cd	12.48 b
	NPK 50	0.93 e	303.90 e	2.87 def	2.14bc	0.28 de	0.37 cd	12.31bc
	Mycorrhiza	1.06 c	471.03 b	3.29 b	2.23a	0.31 b	0.38 bc	12.82 a
	Yeast	1.16 b	435.57 bc	3.17 bc	2.24a	0.30 c	0.39 b	12.88 a
	Mix (M+Y)	1.29 a	664.20 a	3.60 a	2.26a	0.36 a	0.44 a	12.99 a

Values followed by the same letter (s) within each column did not significantly differ according to the Duncan multiple comparison test at the 5% level.

Soil analysis:

Available N:

The data of soil-N in Table (5) showed that soil available-N increased significantly with the application of compost and biofertilizers, particularly at higher rates. The highest soil available-N (135.33 ppm) was observed in the Mix (M+Y) treatment at 30 m³/fed. This is consistent with studies showing that biofertilizers, particularly mycorrhiza, enhance nitrogen fixation and mineralization, making N more available to plants (Adesemoye *et al.*, 2009). Whereas NPK treatments also increased soil-available N, the biofertilizer treatments were more effective. For example, NPK 100 at 30 m³/feddan resulted in 129.71 ppm, whereas the Mix (M+Y) treatment achieved 135.33 ppm. This suggests that biofertilizers improve nitrogen use efficiency by enhancing microbial activity and nutrient cycling. The results are in agreement with those given by Jan *et al.* (2014) AMF inoculation with compost-enhanced N in soil. AMF affects soil nutrients and the cycling of nitrogen, carbon, and phosphorus (Parihar *et al.*, 2020 and Farrag & Bakr, 2021). The crop could efficiently use absorbed nutrients due to improved nitrogen status from chemical fertilizers and city compost (Muchhadiya *et al.*, 2021).

Available P:

Phosphorus availability is often limited in alkaline soils, but it can be improved through the application of organic amendments and biofertilizers. The data in Table (5) showed that soil-available P increased significantly with the application of compost and biofertilizers, particularly at higher rates. The highest soil-available P (13.99 ppm) was observed in the Mix (M+Y) treatment at 30 m³/fed. This is consistent with studies showing that mycorrhizal fungi and other biofertilizers enhance phosphorus availability by solubilizing fixed P through the secretion of organic acids and phosphatases (Sharma *et al.*, 2013). Also, NPK treatments increased soil-available P, the biofertilizer treatments were more effective. For example, NPK 100 at 30 m³/fed., resulted in 10.81 ppm, whereas the Mix (M+Y) treatment achieved 13.99 ppm. This highlights the role of biofertilizers in improving phosphorus use efficiency. The same obtained results are in good agreement with those obtained by Zhu *et al.* (2018) who observed that mycorrhizal fungi are P activators that can accelerate the process of transforming P into bioavailable forms through chemical processes and biological interactions. Similar to this, organic matter encourages microbial activity, increasing the solubility of P (Brucker *et al.,* 2020 and Waheed & Muhammad, 2021).

Available K:

The data in Table (5) showed that soil-available K increased significantly with the application of compost and biofertilizers, particularly at higher rates. The highest soil-available K (212.68 ppm) was observed in the Mix (M+Y) treatment at 30 m^3 fed^{-1}. It enhances potassium availability by improving soil organic matter, microbial activity, and root interaction with soil minerals. Mycorrhiza helps in potassium uptake by expanding root surface area and improving nutrient absorption, while yeast stimulates microbial activity, promoting the release of K from organic matter and mineral sources. This is consistent with studies showing that biofertilizers improve potassium availability by promoting root growth and enhancing microbial activity (Meena *et al.*, 2014). Also, NPK treatments increased soil-available K, the biofertilizer treatments were more effective. For example, NPK 100 at 30 m^3/feddan resulted in 169.77 ppm, whereas the Mix (M+Y) treatment achieved 212.68 ppm. This suggests that biofertilizers enhance potassium use efficiency by improving root access to soil K reserves. Similar results were obtained by Abo-Baker (2017) who found that organic amendments to the soil increased the available K. Higher application rates of composts resulted in more commonly available macronutrients (Abouhussien *et al.,* 2019).

Organic matter:

Organic matter is essential for soil health, as it improves soil structure, water retention, and nutrient availability. The data in Table (5) showed that OM content increased significantly with the application of compost and biofertilizers, particularly at higher rates. The highest OM content (0.99%) was observed in the Mix (M+Y), mycorrhiza, and yeast treatments at 30 m^3/fed. This is consistent with studies showing that compost application increases soil organic matter by adding carbon-rich materials and stimulating microbial activity (Diacono and Montemurro, 2011). Biofertilizers further enhance this effect by promoting root growth and organic matter decomposition. On the other side, the biofertilizer treatments were more effective, where NPK 100 at 30 m^3/fed resulted in 0.97% OM, and the Mix (M+Y) treatment achieved 0.99%. This highlights the role of biofertilizers in improving soil organic matter dynamics. Similar results were obtained by Das *et al.* (2021), who noted that the highest levels of soil organic carbon were found in treated plots with 150% NPK (7.33) and with the addition of compost and crop waste (7.58), whereas the lowest levels were found in plots treated just with inorganic (5.49) and no-organic (5.56) treatments. Abo-Baker (2017); Abouhussien *et al.* (2019) and Farrag & Bakr (2021) showed that the application of filter mud cake or farmyard manure significantly increased the soil's organic matter content. The AMF inoculation and compost addition treatments had the highest soil organic matter content (Vahedi *et al.,* 2021).

pH:

Soil pH is a critical factor influencing nutrient availability, microbial activity, and plant growth. The data in Table (5) showed that soil pH was slightly reduced with the application of compost and biofertilizers, particularly at higher rates (30 m^3/fed.). The lowest pH (8.18) was observed in the Mix (M+Y) treatment at 30 m^3/fed., followed by the yeast treatment (8.19). This slight reduction in pH can be attributed to the organic acids produced during the decomposition of compost and the metabolic activities of biofertilizers (Weil and Brady, 2016). A lower pH can enhance the availability of certain nutrients, such as phosphorus and micronutrients, which are less soluble in alkaline soils. In contrast, NPK treatments resulted in slightly higher pH values (e.g., 8.34 for NPK 100 without compost). These results are in agreement with those reported by Fageria *et al. (*2010) and Das *et al.* (2021) which revealed that at 50, 100, and 150% NPK levels, the pH decreased by 0.6, 1.1, an d 1.7 percent compared to control (8.21).

The reduced pH range might be due to organic acids released during the organi c material's decomposition. Compost treatment decreases the pH of calcareous soil leads to increased nutrient availability, lowering the pH from 7.44 to 7.15 (Al-Enazy *et al.,* 2017 and Jashothan, 2021). Besides, co-inoculation of microorganisms with farmyard manure was used in the first and third seasons, the soil pH decreased more significantly than the control (Abo-Baker, 2017; Abouhussien *et al.,* 2019; Wahid *et al.,* 2020 and Farrag & Bakr, 2021).

Table 5. Effect of bio, mineral fertilizer in presence of compost on pH, OM and available N, P and K in soil (combined analysis of two successive seasons)

Treatment		pH	OM (%)	Soil Av. N (ppm)	Soil-Av. P (ppm)	Soil-Av. K (ppm)
Compost	Bio & Chemical					
without	NPK 100	8.34 ab	0.66 f	94.21 l	8.46 hij	111.66 m
	NPK 75	8.35 ab	0.61 g	90.72 m	7.80 ij	103.30 n
	NPK 50	8.39 a	0.51 h	79.93 n	6.16 k	96.47 o
	Mycorrhiza	8.32 abcd	0.67 f	104.91 j	9.62 fg	118.11 l
	Yeast	8.30 abcd	0.65 fg	98.01 k	9.01 gh	121.91 kl
	Mix (M+Y)	8.28 bcd	0.73 e	107.82 ij	10.72 de	126.85 jk
15 m^3 /fed	NPK 100	8.33 abc	0.84 d	113.86 fg	10.13 ef	142.42 h
	NPK 75	8.34 ab	0.74 e	112.11 gh	8.58 hi	136.72 i
	NPK 50	8.36 ab	0.68 f	109.88 hi	7.55 j	131.41 j
	Mycorrhiza	8.28 bcd	0.89 c	117.80 e	11.26 cd	149.26 g
	Yeast	8.31 abcd	0.79 d	115.92 ef	10.98 cde	153.82 g
	Mix (M+Y)	8.27 bcde	0.89 c	119.48 de	12.25 b	159.13 f
30 m^3 /fed	NPK 100	8.23 def	0.97 a	129.71 bc	10.81 de	169.77 d
	NPK 75	8.29 bcd	0.96 ab	127.01 c	9.31 fgh	166.73 de
	NPK 50	8.34 ab	0.92 bc	122.77 d	7.88 ij	161.79 ef
	Mycorrhiza	8.24 cdef	0.99 a	132.99 ab	13.17 a	176.60 c
	Yeast	8.19 ef	0.98 a	130.73 b	11.80 bc	190.65 b
	Mix (M+Y)	8.18 f	0.99 a	135.33 a	13.99 a	212.68 a

Values followed by the same letter (s) within each column did not significantly differ according to the Duncan multiple comparison test at the 5% level.

Biological performance:

Soil respiration:

The evolution of CO_2 is a key indicator of soil microbial activity, reflecting the decomposition of organic matter and the overall health of the soil ecosystem. The data in Table (6) showed that CO_2 evolution increased significantly with the application of compost and biofertilizers, particularly at higher rates (30 m³/fed). The highest CO_2 evolution (0.175 mg/100 g soil/day) was observed in the Mix (M+Y) treatment at 30 m³/fed., followed by the mycorrhiza treatment (0.147 mg/100 g soil/day). This is consistent with studies showing that compost application increases microbial activity by providing a carbon-rich substrate for microorganisms (Diacono & Montemurro, 2011 and Jashothan, 2021). Biofertilizers additionally enhance this effect by promoting microbial diversity and activity (Adesemoye *et al.*, 2009 and Vahedi *et al.*, 2021). Also, NPK treatments increased CO_2 evolution, and the biofertilizer treatments were more effective. For example, NPK 100 at 30 m³/fed. This resulted in 0.134 mg/100 g soil/day, while the Mix (M+Y) treatment achieved 0.175 mg/100 g soil/day. Compost 15 ton/fed is beneficial but less effective than 30 ton while without compost, CO_2 levels decrease, negatively impacting microbial activity and carbon cycling in the soil. This highlights the role of biofertilizers in enhancing soil microbial activity and organic matter decomposition (Hanna *et al.*, 2012). Carbon dioxide is produced by yeast as a result of its respiration, which increases the amount of carbon dioxide in the air around plants (Aly *et al.*, 2014; Abdou, 2015 and Aileni, 2022).

Number of Arbuscular mycorrhizal spores:

Mycorrhizal spore count is an indicator of the abundance of mycorrhizal fungi in the soil, which play a crucial role in nutrient uptake, particularly phosphorus. Data in Table (6) showed that mycorrhizal spore count increased significantly with the application of compost and biofertilizers, particularly at higher rates. The highest mycorrhizal spore count (16.70 spores/g soil) was observed in the Mix (M+Y) treatment at 30 m³/fed., followed by the mycorrhiza treatment (16.20 spores/g soil). This is consistent with studies showing that compost application provides a favorable environment for mycorrhizal fungi by improving soil structure and organic matter content (Smith *et al.*, 2011; Jan *et al.*, 2014 and Bi *et al.*, 2022). Biofertilizers, particularly mycorrhiza, greater enhance spore production by promoting fungal colonization and reproduction. In the same way, NPK 100 at 30 m³/fed resulted in 15.10 spores/g soil, whereas the Mix (M+Y) treatment reached 16.70 spores/g soil. This suggests that biofertilizers improve the abundance and activity of mycorrhizal fungi in the soil (Wahid *et al.*, 2020). Such observations were also noted that *Glomus Mosseae* produces more spores due to its relationship with soil yeast species

(Mohamed, 2015). Arbuscular mycorrhizal and soil yeast treatments increased the number of mycorrhizal spores in the soil root zone (Boby *et al.,* 2008 and Abdelaziz, 2022).

Mycorrhizal infection:

Mycorrhizal infection rate reflects the extent of root colonization by mycorrhizal fungi, which is critical for nutrient uptake and plant growth. Data in Table (6) also showed that mycorrhizal infection rates increased significantly with the application of compost and biofertilizers, particularly at higher rates. The highest mycorrhizal infection rate (43.60%) was observed in the Mix (M+Y) treatment at 30 m^3/fed., followed by the mycorrhiza treatment (43.40%). This is consistent with studies showing that compost application enhances mycorrhizal colonization (Sharma *et al.,* 2013). Biofertilizers, particularly mycorrhiza, further enhance infection rates by promoting fungal symbiosis with plant roots. Also, NPK treatments increased mycorrhizal infection rates where NPK 100 at 30 m^3/fed resulted in 41.00% infection, while the Mix (M+Y) treatment achieved 43.60%. For maximizing mycorrhizal infection, compost application (especially 30 tons combined with mycorrhiza and yeast is the best approach, while mineral fertilization alone is the least effective. These results agree with Mohamed (2015) and Hussain *et al.* (2016) who found that *Glomus Mosseae* infection significantly increased when it was associated with soil yeast species. Inoculating AMF with compost gave lower root infection intensity compared to using AMF and phosphate-solubilizing bacteria with rock phosphate (Jan *et al.,* 2014 and Wahid *et al.,* 2020). Also, organic amendment with AMF significantly increased root mycorrhizal infection compared to biochar treatment (Vahedi *et al.,* 2021).

Table 6. Effect of biofertilizers and mineral fertilizer in presence of compost on biological performance in soil (Combined analysis of two successive seasons)

Treatment		CO_2 (mg /100 g equivalent soil /day)	number spore/g soil	myco-infection (%)
Compost	**Bio & Chemical**			
without	NPK 100	0.070 lm	9.80 ij	25.30 gh
	NPK 75	0.062 mn	9.50 ij	22.80 h
	NPK 50	0.056 n	8.90 j	12.30 i
	Mycorrhiza	0.078 jkl	10.90 hi	29.90 ef
	Yeast	0.074 kl	10.80 hi	28.30 fg
	Mix (M+Y)	0.080 jk	11.80 gh	31.70 ef
15 m^3 /fed	NPK 100	0.093 ghi	12.50 defgh	37.70 bc
	NPK 75	0.090 hi	12.30 efgh	35.20 cd
	NPK 50	0.085 ij	12.20 fgh	32.70 de
	Mycorrhiza	0.100 fg	13.70 bcdef	37.80 bc
	Yeast	0.097 gh	13.40 cdefg	37.80 bc
	Mix (M+Y)	0.108 ef	14.10 bcde	37.90 bc
30 m^3 /fed	NPK 100	0.134 c	15.10 abc	41.00 ab
	NPK 75	0.120 d	15.00 abc	40.10 ab
	NPK 50	0.111 e	14.20 bcd	40.00 ab
	Mycorrhiza	0.147 b	16.20 a	43.40 a
	Yeast	0.142 bc	15.50 ab	41.10 ab
	Mix (M+Y)	0.175 a	16.70 a	43.60 a

Values followed by the same letter (s) within each column did not significantly differ according to the Duncan multiple comparison test at the 5% level.

Interrelationship among Traits:

To explore the relationships between quantified traits and the applied treatments of chemical, organic, and biofertilizers, heat map analysis was employed to visualize these interactions (Figure 2). The treatments were categorized into three groups based on their effects:

Group One: This group included treatments without organic fertilizer, specifically NPK 100, NPK 75, and NPK 50. These treatments exhibited a significant negative correlation with plant growth parameters and yield properties, except for soil pH and harvest index, which showed no significant correlation.

Group Two: This group included treatments with 30 m³ fed^{-1} of organic fertilizer combined with NPK 100, NPK 75, mycorrhiza, yeast, and the mix of mycorrhiza and yeast (M+Y). These treatments exhibited a significant positive correlation with plant growth parameters and yield properties.

Group Three: This group included the remaining treatments, which showed a mixed pattern of correlations. Some traits had a negative correlation, others had a positive correlation, and some showed no significant correlation.

Key Findings:

The application of 30 m³ fed^{-1} of organic fertilizer combined with the mix of mycorrhiza and yeast (M+Y) exhibited a strong positive and significant correlation with growth traits, including plant height, weight of 1000 seeds, biological yield, grain yield, soil available nitrogen (Av. N), available phosphorus (Av. P), available potassium (Av. K), straw nitrogen (N), phosphorus (P), potassium (K), grain nitrogen (N), phosphorus (P), potassium (K), organic matter (OM%), CO_2 evolution, number of mycorrhizal spores, root mycorrhizal infection, and grain protein content.

The treatment of 30 m³ fed^{-1} organic fertilizer with mycorrhiza, followed by 30 m³ fed^{-1} organic fertilizer with yeast, also displayed a positive correlation with most of the aforementioned traits, except for soil pH, which showed a negative correlation. These results align with findings by Rehan *et al.* (2023), highlighting the synergistic effects of combining organic fertilizers with biofertilizers to enhance plant growth, yield, and soil health.

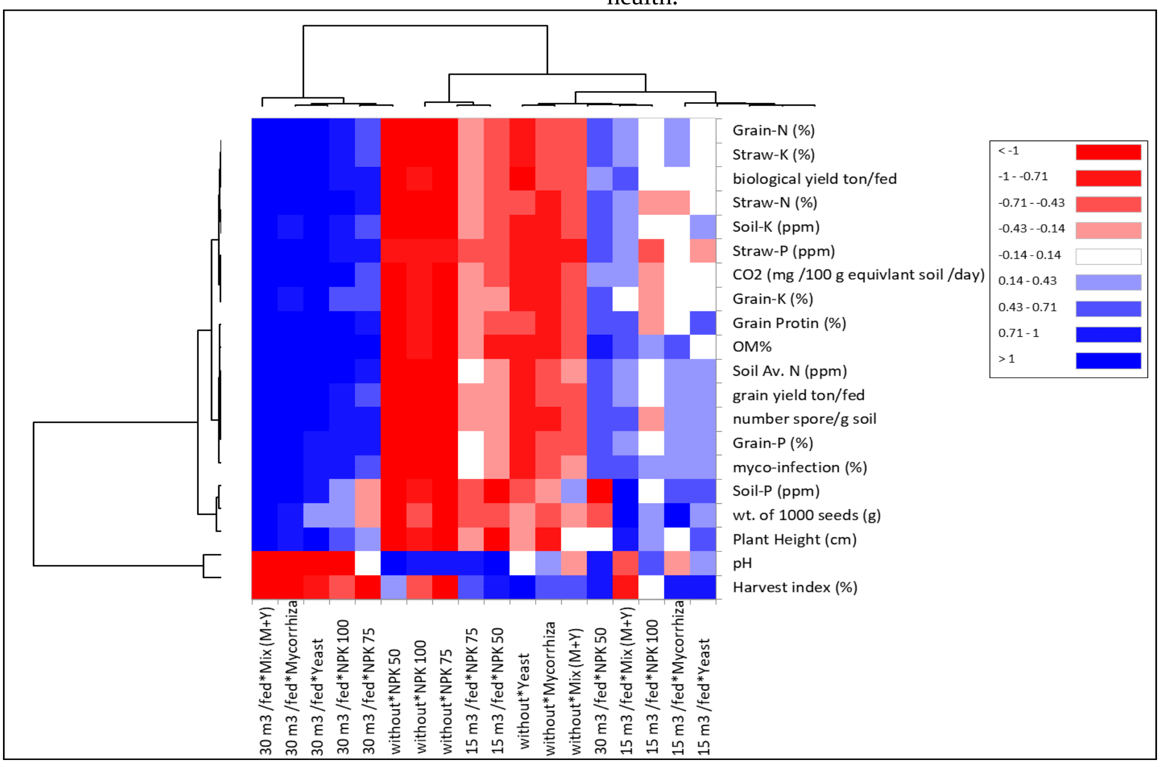

Figure 2. Correlation heatmap of the evaluated yield, elements, and soil parameters under compost, Bio, and chemical fertilizer treatments

CONCLUSION

This study indicates that integrating 30 m³ compost fed^{-1} with arbuscular mycorrhizal fungi and yeast significantly enhances wheat (Gimmiza 12) productivity and soil health in calcareous soils of Nubaria, Egypt, outperforming conventional mineral fertilization. This synergy can be qualified to improved soil microbial activity, nutrient solubilization, and root colonization, which collectively enhance plant growth and reduce stress effects. The combined treatment produced the highest grain (2.73 ton fed^{-1}) and biological (11.76 ton fed^{-1}) yields, beside improved nutrient uptake (N, P, K), soil microbial activity (CO_2 evolution: 0.175 mg/100g soil d^{-1}), mycorrhizal spore density (16.7 spores g^{-1} soil) and mycorrhizal colonization (43.6% root infection). Especially, this approach allowed reducing NPK use by 25–50% without affecting yield, offering a sustainable alternative for resource-efficient agriculture. Farmers in similar arid regions should adopt this compost-biofertilizer synergy to optimize productivity while preserving soil health, though long-term studies on crop rotations is recommended to validate enduring benefits.

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الملخص العربي

الاستخدام المتكامل للأسمدة الحيوية والعضوية والمعدنية لتحسين إنتاجية القمح وخصوبة التربة في الأراضى الجيرية

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القمح (*Triticum aestivum* L.) هو محصول أساسي ذو أهمية اقتصادية وتغذوية كبيرة. ومع ذلك، غالبًا ما ينخفض إنتاجه في التربة الجيرية بسبب محدودية توافر العناصر الغذائية، وانخفاض محتوى المادة العضوية، وارتفاع درجة حموضة التربة، مما يقلل كفاءة امتصاص المغذيات. أجريت هذه الدراسة لتوضيح تأثير التلقيح بفطريات الميكوريزا (AMF) والخميرة، بالتزامن مع إضافة السماد العضوي، على إنتاجية القمح ومحتواه الغذائي وخصائص التربة تحت ظروف التربة الجيرية. أُجريَت تجربة حقلية على مدار موسمين زراعيين متتاليين في محطة البحوث الزراعية بالنوبارية بمصر، باستخدام تصميم القطع المنشقة. شملت المعاملات الرئيسية ثلاث مستويات من السماد العضوي (٠، ١٥، ٣٠ م³/فدان)، بينما شملت المعاملات الفرعية مستويات مختلفة من الأسمدة المعدنية (100%، ٧٥%، ٥٠% من NPK) والأسمدة الحيوية (AMF، الخميرة، ومزيج منهما).

أظهرت النتائج أن اضافة السماد العضوي مع الأسمدة الحيوية عزز بشكل ملحوظ طول النبات ومحصول الحبوب. سُجِل أعلى محصول حبوب عند ٢,٧٣ طن/فدان، مع محصول حيوى بلغ ١١,٧٦ طن/فدان، وذلك عند تطبيق ٣٠ م³/فدان من السماد العضوي مع كلٍ من AMF والخميرة. كما زاد محتوى العناصر الغذائية (النتروجين، الفوسفور، البوتاسيوم) في حبوب القمح والقش بشكل ملحوظ مع المعاملات الحيوية.

تحسنت معايير جودة التربة، مثل محتوى المادة العضوية، النتروجين المعدني (١٣٥,٣٣ جزء في المليون)، الفوسفور المتاح (١٣,٩٩ جزء في المليون)، والبوتاسيوم المتاح (٢١٢,٦٨ جزء في المليون)، بشكل كبير في القطع المُعالجة بالسماد العضوي. علاوةً على ذلك، زاد النشاط الميكروبي (مُقاسًا بتنفس التربة وعدد جراثيم فطريات الميكوريزا) مع الجمع بين السماد العضوي والأسمدة الحيوية. توضح هذه النتائج إمكانية استخدام السماد العضوي مع الملقحات الميكروبية كَممارسة زراعية مستدامة لتعزيز إنتاجية القمح وتحسين خصوبة التربة في الأراضي الجيرية.

الكلمات المفتاحية: القمح، فطريات الميكوريزا، الخميرة، السماد العضوي، الأسمدة المعدنية.