Research Article

Enhancing Nutrient Use Efficiency and Wheat Productivity through Application of Humic Acid and Farmyard Manure with Synthetic Fertilizers

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Abstract | The excessive use of chemical fertilizers for enhancing crop yields has led to negative effects on soil properties and plant growth, necessitating the exploration of integrated nutrient management approaches. A field experiment was carried out at the Research Farm of the University of Agriculture, Peshawar to assess the combined impacts of humic acid (HA) and farmyard manure (FYM) with synthetic fertilizers on nutrient use efficiency and wheat productivity. The study employed a randomized complete block design (RCBD) with three replications, incorporating HA (10 kg ha^{-1}) and FYM (10 tons ha^{-1}) along with different levels of NPK fertilizers (90-120, 60-90, and 45-60 kg ha^{-1} respectively). The results confirmed that the integrated application of HA and FYM with synthetic fertilizers significantly improved plant height, biological yield, and 1000- grain weight compared to the control treatment. While synthetic fertilizers alone enhanced grain yield and nutrient uptake, the combined application of FYM and HA with 75% NPK (N:90: P:60: K:45 kg ha^{-1}) resulted in superior yield performance compared to 100% NPK application. Additionally, maximum nutrient use efficiency was observed in plots treated with the combination of FYM, HA, and 75% NPK fertilizer. These findings suggest that integrated nutrient management practices, particularly the combination of organic amendments with reduced synthetic fertilizer rates, can effectively improve wheat productivity while promoting sustainable soil fertility management.

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Introduction

Fertilizers are necessary to increase crop growth (USMAN, 2013). According to (Kalsoom *et al*., 2020) essential plant nutrients play a vital role in the development and growth of plants. Nitrogen is an essential element of plant cellular material, amino acids, nucleic acid, and chlorophyll. It is a major macronutrient that significantly increases yield (Sher *et al*., 2019). Its availability at early growth stages is very essential for the fulfillment of crop requirements (Slafer and Savin, 2018; Ur Rahman *et al*., 2019). The application of N improves the 1000-grain weight, N use efficiency, protein content and production (Liu *et al*., 2022). Phosphorus is also an important macronutrient required by plants and it improves the development of roots (Wang *et al*., 2021). Higher application of P fertilizer, up to a certain level, significantly increases P availability, improves P use efficiency, and enhances crop yield (Swaney and Howarth, 2019). Potassium is required by plants in large amounts and plays a role in biochemical and physiological processes (Khan *et al*., 2013). It enhances plant resistance to stresses such as temperature, drought, and diseases (Jat *et al*., 2013). Although chemical fertilizers have tremendous potential to increase yield significantly, they also have serious hazardous effects on human health, the environment, and soil health. To reduce the harmful impact of chemical fertilizers, we should focus on organic farming and use organic manures as an alternative source of plant nutrients.

In agriculture, organic amendments have been used to improve nutrient availability, including green manures and farmyard manures. Farmyard manures are a significant source of nutrient supply, also on smallholding farm areas. It is considered a valuable amendment and has a positive impact on the soil (Fageria, 2012). According to (Ramborun *et al*., 2021), it provides nutrients and plays a vital role in enhancing water-holding capacity and improving soil conditions for crop growth. It develops root strength, increases mineral uptake, improves chlorophyll synthesis, favorable seed germination, and enhances fertilizer maintenance. Organic manures improve soil condition physically, chemically, and biologically. They provide essential micro-nutrients, reduces the toxic effect of acidity, salinity, and alkalinity on crop growth. The application of farmyard manure enhances the concentration of N in soil (Ramborun *et al*., 2021). Humic substances are the constituents of organic materials that are commonly available in soils, rivers, oceans, and coal sites and derived from the natural sources of peat, lignite and Leonardite (Bibi *et al*., 2024). Humic acid is formed due to the chemical and biological humification process of animal and plant residues with the help of soil microorganisms. Humic acid improves plant growth, soil properties, enhances soil fertility and CEC (Dawood *et al*., 2019). It has an effective impact on the enhancement of cytokinin and auxin content and it also improves plant metabolic activity (El-Sayed *et al*., 2024). The application of humic acid contributes to biotic and abiotic processes that significantly improve microbial respiration, xenobiotic transformation, enhance soil fertility and reduces the concentration of heavy metals (Kulikova and Perminova, 2021). The availability of P to plant becomes more convenient due to the presence of P containing substances at acidic soil environment (Chojnacka *et al*., 2020). The foliar application of humic acid stimulates the plant parameters like spike length and number, number of grains and 1000 grain weight (Kandil *et al*., 2016). Humic acid plays a significant role in improving wheat yield and is used to meliorate or decrease the negative impact of stress (Azarpour *et al*., 2012). According to (Burhan and AL-Taey, 2018), the amendment of humic acid is a pollution-free technique of agriculture. It is formed due to the decomposition of animal and plant materials that improves soil physically, chemically, increases plant metabolism and physiological parameters (Aziz *et al*., 2014).

Wheat is a major crop that is cultivated worldwide on a total area of 220 million hectares with an estimated yield of 750 million tons (Tadesse *et al*., 2018). Globally, the demand for wheat is expected to exceed 950 Mha^{-1} by the year 2020. The demand of wheat can be attained by increasing the worldwide production at the rate of 2.5 % per year (Bairwa *et al*., 2018). Wheat is one of the necessary foods containing almost 20 % of the protein and calories content and is an essential source of energy (Sheehy *et al*., 2019). After rice, it is the most cultivated crop in many developing countries and about 80 million farmers depend on wheat for their livelihood (Curtis and Quarnstrom, 2019). In Pakistan, wheat is cultivated over an area of 9.63 Mha^{-1} with a production of 31.4 million tons with an estimated yield of 3261 kg ha^{-1} and in KPK, it is cultivated on an area of 0.7325 million hectares with a total production of 1.26 million tons and a yield of 1721 kg ha^{-1} (USDA, 2014). Since a large global population depends on wheat for their food and livelihood, it is essential to increase production. Therefore, it is necessary to maximize wheat yield to bring prosperity and positive change in the socioeconomic life of the masses belonging to agriculture. Therefore, this study was conducted to sustainably increase wheat yield and enhance nutrient use efficiency to reduce production costs and improve the socioeconomic conditions of the farming community.

Materials and Methods

Experimental site and treatments

A field experiment was conducted from 28th October, 2020 to 21st March 2021 the Agriculture Research Farm, University of Agriculture, Peshawar, Pakistan, located at 34.1°21″ N, 71°28′5″ E (Figure 1) to study the role of organic amendments (Farmyard manure and Humic acid) and different levels of synthetic fertilizers (NPK) for soil physico-chemical properties, wheat yield, total nutrient uptake and use efficiency in alkaline calcareous soil of the semiarid region of Khyber Pakhtunkhwa, Pakistan. The experimental soil had a pH of 7.63, with a texture class of silt loam comprising 21.3% sand, 68.2% silt, and 10.5% clay. The soil electrical conductivity was 0.18 dS m^{-1}, and the organic matter content was 0.63%. The total N content was 0.053%, while the available P and K levels were 4.39 mg kg^{-1} and 88.42 mg kg^{-1}, respectively. During the period of the field experiment, Peshawar city had a soil temperature of 10.09–33.12 °C with an average temperature of 22.64 °C, while the air temperature was within the range of 9.47–31.11 ^{0}C with an average temperature of 21.50 ^{0}C. The monthly mean relative humidity and rainfall were 53.08% and 12.66 mm (Figure 2).

The experiment was designed with a two-factor factorial arrangement, incorporating organic amendments (Factor A) and NPK fertilizer levels (Factor B). Factor A included four levels of organic amendments: (1) no amendment (control), (2) farmyard manure (FYM) applied at 10 t ha^{-1}, (3) humic acid applied at 10 kg ha^{-1}, and (4) a combination of FYM and humic acid at the same rates. The FYM used in the experiment had the following physico-chemical properties: pH of 6.85 (1:5), electrical conductivity (EC) of 3.65 dS m^{-1} (1:5), nitrogen (N) content of 1.07%, phosphorus (P_2O_5) content of 0.33%, potassium (K_2O) content of 0.77%, moisture content of 26.45%, organic matter content of 48.30%, and a carbon-to-nitrogen (C/N) ratio of 18:1. Factor B consisted of three levels of NPK fertilizer, expressed as a percentage of the recommended dose: (1) 0% NPK (no fertilizer), (2) 75% NPK (90:60:45 kg ha^{-1} of $N:P_2O_5:K_2O$), and (3) 100% NPK (120:90:60 kg ha^{-1} of $N:P_2O_5:K_2O$). The combination of these two factors resulted in a total of 12 treatments, which included inorganic fertilizers applied both alone and in combination with organic amendments. Each treatment was replicated three times to ensure statistical reliability. The experiment was laid out in a Randomized Complete Block Design (RCBD) with a factorial arrangement. The plot size for each treatment was 3 m × 3 m (9 m^2), providing sufficient space for accurate measurement and observation of treatment effects.

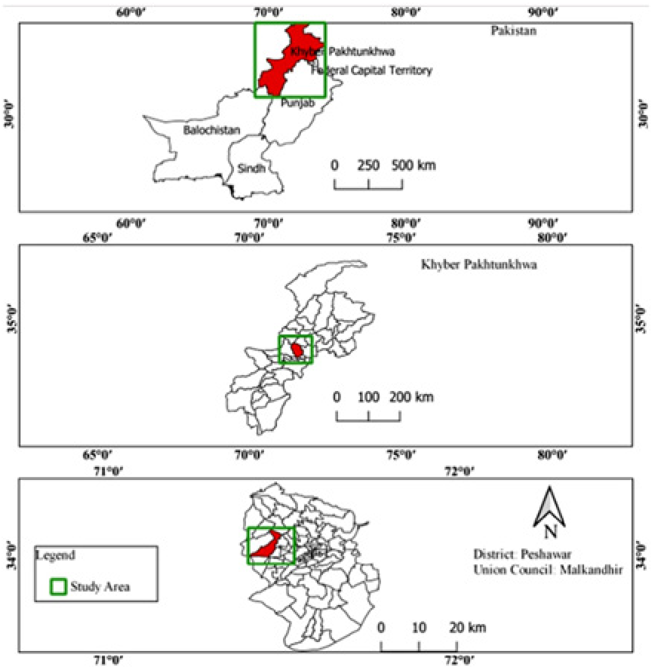

Figure 1: *Geographical location of the study area (agricultural research farm, the university of agriculture, peshawar, Pakistan). (Khan et al., 2022) (CC BY 4.0, http://creativecommons.org/licenses/by/4.0/)*

Crop husbandry

Wheat seeds were sown on October 28, 2020, using a single-row hand drill. The seeds were planted in rows spaced 22.5 cm apart, with a seeding rate of 125 kg ha^{-1}. Fertilizer application was tailored based on the results of the soil analysis, as outlined in the treatment section. To manage weed growth, the herbicide Atlantis (a combination of iodosulfuron and mesosulfuron) was applied at a rate of 14.4 g active ingredient per hectare on December 15, 2020, during the early post-emergence stage. The crop received a total of four irrigations during its growth period, with each irrigation delivering 3 acre-inches of water. Additionally, a pre-sowing soaking irrigation of 4 acre-inches was applied to ensure optimal soil moisture for seed germination and early crop establishment. The crop was harvested on 21st March 2021 and was threshed to record the yield and other related traits.

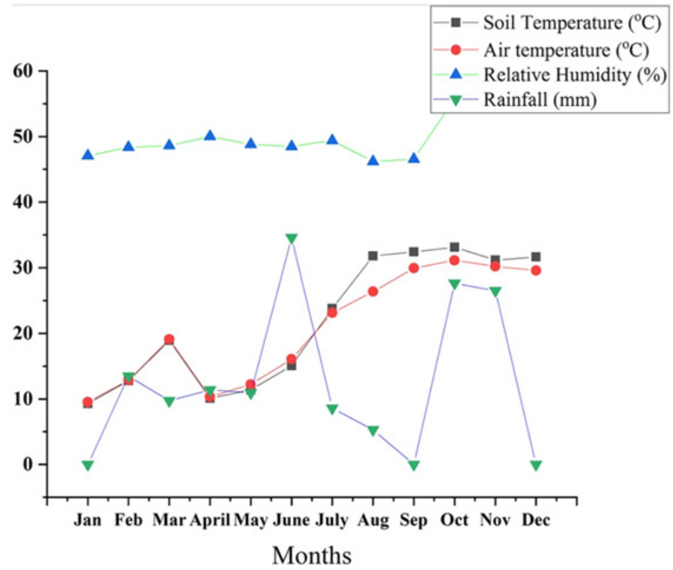

Figure 2: *Weather data during field experiment*

Data recording

Agronomic parameters

At maturity, ten plants were selected randomly from each experimental unit and their height was measured using a scale. The grains per spike of ten spikes from the same plants were harvested and threshed to count the number of grains per spike. To determine 1000 grain weight, four subsamples of 1000 grains were taken from each plot and weighed. Grain yield was determined by manually harvesting each plot (whole plot), threshing and weighing the grains. The grain and straw yields are reported in kg ha^{-1} at 12 and 20% (the approximate moisture content of stored straw used for livestock fodder) moisture content, respectively. The harvest index was calculated as the ratio of dry grain yield to dry biological yield (grain yield + straw yield) and expressed as a percentage.

Soil physiochemical and plant mineral analysis

Soil samples were collected randomly from the experimental field using an auger. Sampling was conducted at a depth range of 0-15 cm to ensure a representative analysis of the topsoil. Each sample was carefully placed in a separate plastic bag, labeled appropriately to avoid cross-contamination or misidentification, and transported to the laboratory for further processing.

In the laboratory, the soil samples were air-dried to remove moisture, followed by sieving through a 2 mm mesh to achieve a uniform particle size for analysis. All subsequent laboratory analyses were conducted using standard protocols to ensure accuracy and consistency.

The pH of the soil was determined using the method proposed by Thomas (1996), which involves a soil-water suspension and measurement with a calibrated pH meter. Electrical conductivity (EC) was measured following the procedure outlined by Rhoades (1996), which assesses the soil's salinity levels. Soil organic matter (SOM) content was analyzed using the method described by Nelson and Sommers (1996), which involves oxidation and titration to quantify organic carbon. For nutrient analysis, soil nitrogen (N) content was determined using the protocol established by Bremner and Mulvaney (1982), which involves the Kjeldahl digestion method. Phosphorus (P) and potassium (K) concentrations in both soil and plant samples were measured using the method detailed by Soltanpour and Schwab (1977), which employs spectrophotometric and flame photometric techniques, respectively. .

Nutrient uptake and nutrient use efficiencies

Nutrient uptake in plants was determined by using the following formula;

$$\text{Nutrient uptake} = \text{Dry biomass of plant} \times \text{Concentration of nutrient in plant}$$

The N, P and K use efficiencies were calculated according to Fageria (2009).

Data analysis

The experiment was designed in randomized complete block design with a factorial arrangement and the data collected was subjected to analysis of variance (ANOVA). The means were compared by using the Least Significant Difference (LSD) techniques. The ANOVA and LSD were computed by using the computer statistical software Statistics 8.1 (Analytical Software, 1985-2005).

Results

Agronomic parameter

The treatments significantly affected plant height

(Table 1). The FYM+HA treatment had the maximum plant height (87.6 cm), which was statistically equivalent to FYM (86 cm). The control treatment had the lowest plant height (80.4 cm). In contrast, 100% nutrient application (N, P and K) produced the tallest plants (89.9 cm), followed by 75% (84.7 cm) and 0% (78.7 cm). The 1000-grain weight differed significantly between treatments (Table 1). The FYM + HA treatment had the highest grain weight (45.9 g), surpassing the control (43.9 g) but being statistically similar to FYM (44.9 g). The maximum 1000-grain weight was 46.4 g at 75% nutrient application (N, P and K) and the lowest at 0% (42.5 g). All the treatments significantly affected number of grain spikes per plant (Table 1). FYM+HA had the most grain spikes (46.9), followed by FYM (46.3), HA (45.7), and the control (44.7). The highest grain spikes (46.7) were at 75% NPK level, which was equal to 100% (46.6) but much greater than 0% (44.5). The treatments significantly affected grain yield (Table 1, Figure 3a). The FYM+HA treatment yielded 3755.9 kg/ha, followed by FYM (3509.1 kg/ha) and HA (3343.7 kg/ha), whereas the control treatment had the lowest yield of 3094.7 kg/ha. Among fertilizer rates the 100% nutrient treatment (N, P and K) yielded the most grain (3774.2 kg/ha), followed by 75% (3608.5 kg/ha) and 0% (2894.8 kg/ha). The results showed that FYM+HA produced the most biological yield (9483 kg/ha) as presented in Table 1, and Figure 3b. FYM and HA yielded 8991 and 8821 kg/ha respectively, while the control yielded 8449 kg/ha. Biological yield was highest at 75% nutrient level (9477 kg/ha), followed by 100% (9127 kg/ha) and lowest at 0% (8205 kg/ha). Treatments significantly affected harvest index (Table 1). The FYM+HA treatment had the highest harvest index (39.9%), followed by FYM (38.7%) and HA (37.8%) while control had the lowest harvest index (36.5%). Harvest index was highest with 100% nutrient application of N, P and K (41.3%), followed by 75% (38.1%) and lowest at 0% (35.2%).

Table 1: *Effect of FYM, HA and different rates of NPK fertilizer on plant height (cm), 1000-grain weight (g), grain spike^{-1}, grain yield (kg ha^{-1}), biological yield (kg ha^{-1}) and harvest index (%) of wheat.*

Treatments	Plant height cm	1000-grain weight g	Grain spike^{-1}	Grain yield Kg/ha	Biological yield Kg/ha	Harvest index%
Control	80.4 c	43.9 d	44.7 d	3094.7 d	8449 d	36.5 c
FYM	86.0 a	44.9 b	46.3 b	3509.1 b	8991 b	38.7 ab
HA	83.6 b	44.4 c	45.7 c	3343.7 c	8821 c	37.8 b
FYM*HA	87.6 a	45.9 a	46.9 a	3755.9 a	9483 a	39.9 a
0	78.7 c	42.5 c	44.5 b	2894.8 c	8205 c	35.2 c
75	84.7 b	46.4 a	46.7 a	3608.5 b	9477 a	38.1 b
100	89.9 a	45.3 b	46.6 a	3774.2 a	9127 b	41.3 a

Note: Organic amendments (FYM and HA) and N, P and K fertilizers (0, 75 and 100% rates) were both applied in kgha^{-1}

Table 2: *Effect of FYM, HA and different rates of NPK fertilizer on straw N, straw P, straw K, grains N, grains P and grains K concentration of wheat*

Treatments	Straw N	Straw P	Straw K	Grains N	Grains P	Grains K
	%					
Control	0.75 d	0.15 d	2.23 d	1.6 d	0.14 c	0.71 d
FYM	0.79 b	0.18 b	2.31 b	1.8 b	0.17 b	0.78 b
HA	0.77 c	0.17 c	2.28 c	1.7 c	0.16 bc	0.75 c
FYM*HA	0.81 a	0.20 a	2.35 a	2.0 a	0.19 a	0.82 a
0	0.71 c	0.12 c	2.14 c	1.2 c	0.13 c	0.61 c
75	0.79 b	0.19 b	2.34 b	1.9 b	0.16 b	0.91 a
100	0.85 a	0.20 a	2.41 a	2.2 a	0.19 a	0.78 b

Note: *Organic amendments (FYM and HA) and N, P and K fertilizers (0, 75 and 100% rates) were both applied in kgha^{-1} Means that share distinct letters within a column are significantly (p≤0.05) different from one another NS = non-significant.*

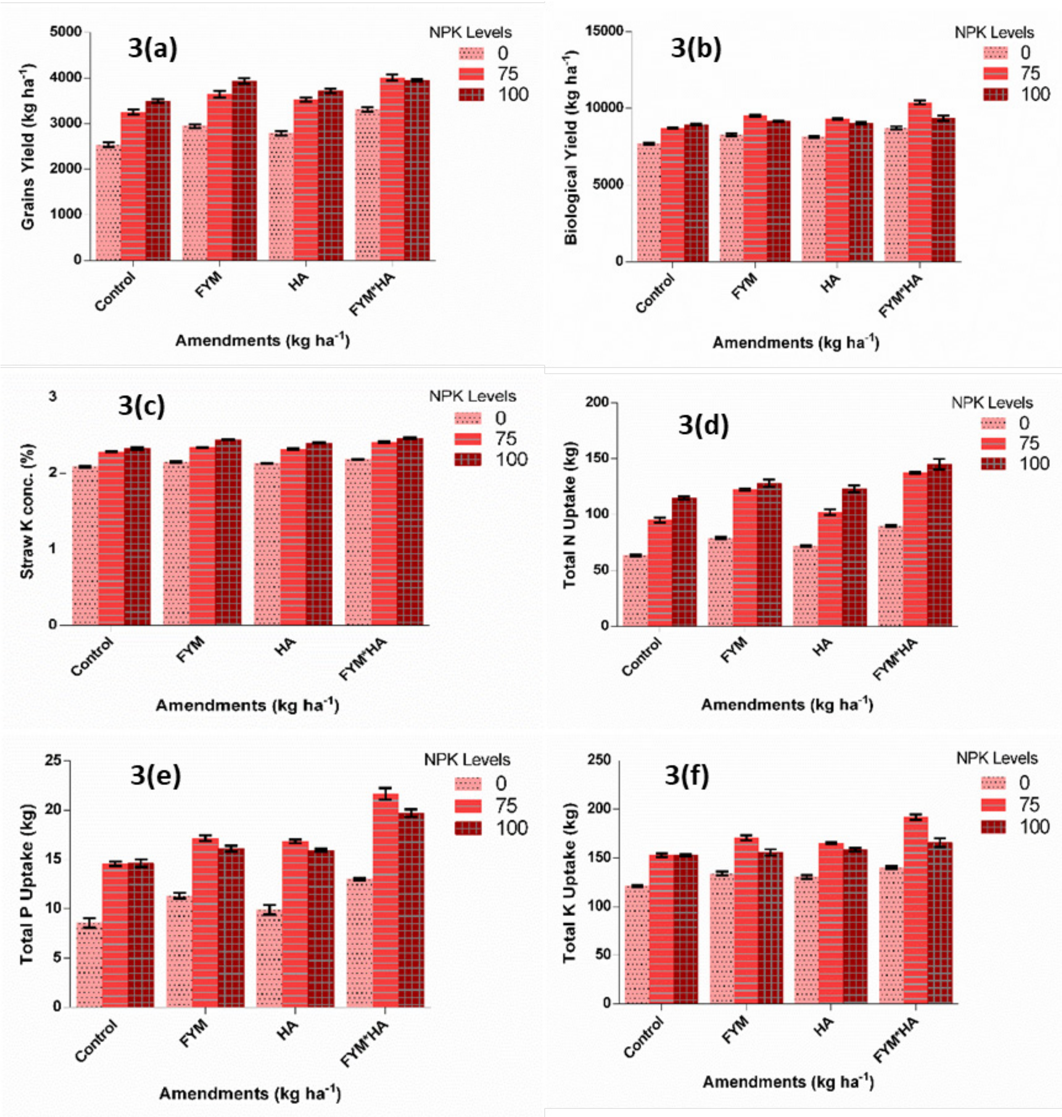

Figure. 3: *The combine effect of FYM, HA and synthetic NPK fertilizer on grain yield (kg ha^{-1}) (3a), Biological yield (kg ha^{-1}) (3b), straw K concentration (3c), total N uptake (3d), total P uptake (3e), total K-uptake (3f), N-use efficiency (3g), K-use efficiency (3h), soil total-N (3i) and soil total K (3j).*

Concentration of N, P and K in wheat straw

The 100% NPK treatment had the greatest straw N content (0.85%), followed by FYM+HA (0.81%) (Table 2). In comparison to HA (0.77%) and control (0.75%), FYM alone (0.79%) displayed higher values, suggesting that full NPK fertilization and organic additions greatly increased nitrogen uptake in straw. Both the FYM+HA treatment and the 100% NPK treatment had the highest straw P content (0.20%) (Table 2). P levels in FYM (0.18%) were marginally higher than those in HA (0.17%) and control (0.15%), indicating that the addition of organic amendments enhanced the availability of phosphorus in straw. The 100% NPK (2.41%) and FYM+HA (2.35%) treatments had the greatest straw K content (Table 2, Figure 3c), followed by FYM (2.31%), HA (2.28%), and control (2.23%). The findings show that balanced NPK application and combined treatments improved potassium buildup in straw.

Concentration of N, P and K in wheat grains

In comparison to FYM (1.8%), HA (1.7%), and control (1.6%), the grain N content was much greater under the 100% NPK treatment (2.2%) and FYM+HA (2.0%), as shown in Table 2. These results imply that FYM and HA work in concert to enhance grain nitrogen uptake. As shown in Table 2, the grain P concentration maximized with 100% NPK (0.19%) and FYM+HA (0.19%). Compared to HA (0.16%) and control (0.14%), FYM (0.17%) produced higher values, suggesting that the combination of organic and inorganic amendments greatly increased the amount of phosphorus that accumulated in grains. The grain K content (Table 2) was maximal in the 75% NPK treatment (0.91%), followed by FYM+HA (0.82%)

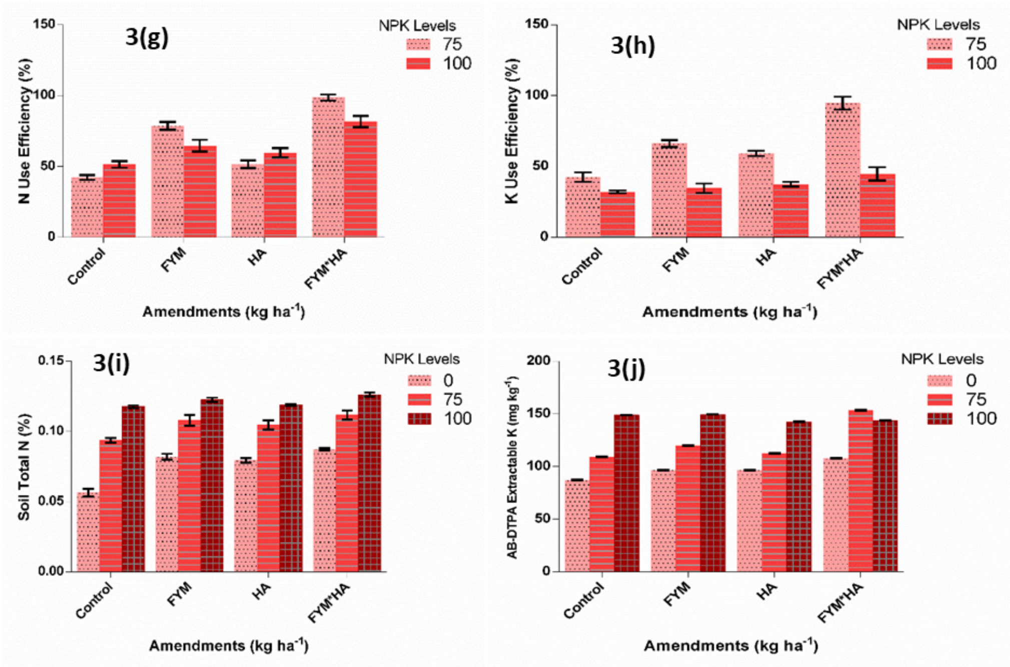

Figure 3: *The combine effect of FYM, HA and synthetic NPK fertilizer on grain yield (kg ha^{-1}) (3a), Biological yield (kg ha^{-1}) (3b), straw K concentration (3c), total N uptake (3d), total P uptake (3e), total K-uptake (3f), N-use efficiency (3g), K-use efficiency (3h), soil total-N (3i) and soil total K (3j).*

Table 3: *Effect of FYM, HA and different rates of NPK fertilizer on total N uptake, total P uptake, total K uptake, N-use efficiency, P-use efficiency and K-use efficiency of wheat*

Treatments	Uptake N	Uptake P	Uptake K	N use efficiency	P use efficiency	K use efficiency
	kg			%		
Control	91.1 d	12.6 d	142.3 d	46.77 d	7.03 c	37.16 c
FYM	109.7 b	14.9 b	153.4 b	71.57 b	9.50 b	50.31 b
HA	99.0 c	14.2 c	151.5 c	55.53 c	9.19 b	48.22 b
FYM*HA	124.0 a	18.1 a	166.0 a	90.13 a	14.30 a	69.64 a
0	75.9 c	10.7 c	131.4 c	-	-	-
75	114.2 b	17.6 a	170.2 a	67.7	11.99 a	65.53 a
100	127.7 a	16.6 b	158.2 b	64.3	8.02 b	37.13 b

Note: *Organic amendments (FYM and HA) and N, P and K fertilizers (0, 75 and 100% rates) were both applied in kgha^{-1}. Means that share distinct letters within a column are significantly ($p \leq 0.05$) different from one another.*

and FYM (0.78%). HA (0.75%) and the control (0.71%) exhibited the lowest concentrations. These findings underscore the significance of FYM and HA in augmenting potassium absorption in grains. *Total Nutrient (N, P & K) Uptake*

The combination of FYM and HA (FYM+HA) yielded the maximum nitrogen uptake at 124.0 kg, as shown in Table 3 and Figure 3d, indicating a notable improvement over the control group, which recorded 91.1 kg. FYM alone resulted in a significant rise of 109.7 kg, whereas HA exhibited moderate enhancements of 99.0 kg. The maximum nutrient uptake was seen at the 100% fertilizer treatment level, totaling 127.7 kg, demonstrating the efficacy of complete nutrient administration. Phosphorus absorption reached a maximum of 18.1 kg in the FYM+HA treatment, indicating the synergistic effect of the combined organic amendments (Table 3, Figure 3e). FYM and HA individually resulted in phosphorus uptakes of 14.9 kg and 14.2 kg, respectively, both exceeding the control's uptake of 12.6 kg. Among fertilizer treatments, the 75% level demonstrated enhanced phosphorus uptake (17.6 kg) relative to the 100% level (16.6 kg), indicating possible optimization at lower input levels. The highest potassium uptake (166.0 kg) occurred in plants treated with FYM*HA (Table 3, and Figure 3f), underscoring the significance of organic amendments in potassium mobilization. FYM alone enhanced potassium uptake to 153.4 kg, whilst HA achieved 151.5 kg. The control therapy had a markedly reduced intake of 142.3 kg. The 75% fertilizer level exhibited excellent potassium uptake at 170.2 kg, exceeding the 100% level, which recorded 158.2 kg.

Total Nutrient (N, P & K) Use Efficiency

Nitrogen consumption efficiency (Table 3 and Figure 3g) significantly increased with the FYM+HA treatment (90.13%), highlighting the improved nutrient use enabled by organic inputs. FYM alone achieved an efficiency of 71.57%, much surpassing that of HA at 55.53%. The control exhibited the lowest efficiency at 46.77%. The FYM+HA application demonstrated enhanced phosphorus usage efficiency (14.30%), signifying improved utilization of phosphorus resources under this treatment (Table 3). FYM and HA had similar efficiency (9.50% and 9.19%, respectively), both surpassing the control (7.03%). The assessment of fertilizer levels indicated that the 75% treatment (11.99%) surpassed the 100% level (8.02%). The integrated FYM+HA treatment attained the highest potassium utilization efficiency (69.64%), demonstrating the efficacy of organic amendments in improving nutrient uptake efficiency (Table 3, Figure 3h). FYM achieved an efficiency of 50.31%, whereas HA recorded 48.22%. Fertilizer treatments had an inverse relationship, with the 75% fertilizer level achieving the best efficiency (65.53%) in contrast to the 100% level (37.13%).

Table 4: *Effect of FYM, HA and different rates of NPK fertilizer on soil PH, total soil N, AB-DTPA Extractable P and AB-DTPA Extractable K.*

Treatments	Soil pH	Soil total N	AB-DTPA extractable P	AB-DTPA extractable K
		%	mg/kg	
Control	7.74 d	0.089 d	5.71 d	115.04 d
FYM	7.81 b	0.104 b	6.79 b	121.98 b
HA	7.79 c	0.101 c	6.07 c	117.23 c
FYM*HA	7.83 a	0.108 a	7.23 a	134.92 a
0	7.72 c	0.076 c	5.34 c	97.01 c
75	7.80 b	0.104 b	6.76 b	123.70 b
100	7.86 a	0.121 a	7.26 a	146.17 a

Note: *Organic amendments (FYM and HA) and N, P and K fertilizers (0, 75 and 100% rates) were both applied in kgha^{-1}. Means that share distinct letters within a column are significantly ($p \leq 0.05$) different from one another.*

Soil indicators after experiment

The incorporation of FYM, HA and NPK fertilizer significantly influence soil pH after experiment as mentioned in Table 4. The maximum pH of the soil (7.84) was recorded in the plots that received the combine dose of FYM and HA. The increase in synthetic fertilizer application raises soil pH. The highest soil PH (7.86) was recorded in the plots that received 100% NPK as compare to control and other fertilizer treatments. The application of humic acid along with farmyard manure significantly affects soil pH as compared to alone application of farmyard manure and humic acid. Soil total N content after experiment was observed to increase with incorporation of NPK fertilizers (Table 4). The highest soil total nitrogen content (0.108%) was observed in the plots that received the combine dose of FYM+HA as compare to control other amendments treatments. Among different NPK fertilizers incorporation, the maximum data for soil total nitrogen (0.121%) was recorded in the plots treated with 100% NPK, followed by 75% NPK treated plots. The interaction of amendments incorporation and NPK application also significantly increased soil N (Figure 3i). The data in Table 4, indicates that the application of synthetic fertilizer had a significant effect on the improvement of AB-DTPA P extractable content of treated soil. The amendment of FYM and HA in combination with NPK fertilizer positively increase AB-DTPA extractable P content. The maximum AB-DTPA extractable P (7.23 mg kg^{-1}) was observed in the plots that were amended with FYM along with HA. The mean data revealed that maximum AB-DTPA extractable P (7.26 mg kg^{-1}) was obtained from the plots that received 100% NPK, followed by 75% NPK level, which resulted (5.34 mg kg^{-1}) soil P content. The maximum data of AB-DTPA extractable K (134.9 mg kg^{-1}) was recorded in the plots that were treated with FYM along with HA (Table 4). The incorporation of NPK fertilizers also improved the K level of the soil. The maximum AB-DTPA extractable K (146.2 mg kg^{-1}) was noticed in the plots of 100% NPK, followed by 75% NPK, which produced (97.1 mg kg^{-1}) of soil K content. Among the amendments, the highest value of soil K (134.9 mg kg^{-1}) was noticed in the plot treated with FYM and HA that was followed by sole application of FYM that produced (115.04 mg kg^{-1}) of soil K. The combined effect of amendments and synthetic fertilizers was found significant (Figure 3j). The amendments of FYM+HA with 75% NPK application result in maximum concentration of soil extractable K.

Discussion

Impact of humic acid, farmyard manure, and synthetic fertilizers on wheat growth and yield

The utilization of humic acid (HA), farmyard manure (FYM), and synthetic fertilizers resulted in significant enhancements in wheat growth and yield metrics by improving nutrient availability and soil quality. The use of HA significantly enhanced wheat plant height, corroborating other research (Roudgarnejad *et al*., 2021), (Khan *et al*., 2013; Weissy *et al*., 2018). This enhancement is attributed to HA's function in augmenting nutrient availability and soil structure, thus promoting superior root development and plant growth (Mohammadipour *et al*., 2012). Likewise, FYM positively affected plant height by providing vital nutrients and enhancing soil conditions (Özkan *et al*., 2021), (Aksu, 2017). The simultaneous application of FYM and HA produced enhanced growth, underscoring its synergistic effect. The use of HA significantly increased the number of grains per spike by enhancing N availability during decomposition, hence supporting spike growth (Atak *et al*., 2004; Sharif *et al*., 2002; Sharma *et al*., 2014). FYM enhanced the grains per spike by augmenting soil fertility and facilitating a gradual release of nutrients (Chattha *et al*., 2019; Özkan *et al*., 2021). The amalgamation of FYM with synthetic fertilizers optimized the grains per spike, supporting evidence that such combinations improve nutrient usage efficiency (Aksu, 2017).

The integration of HA, FYM, and synthetic fertilizers significantly improved grain yield. HA enhanced nutrient absorption and photosynthetic efficiency, resulting in increased yields [42]. FYM enhanced soil organic matter and nutrient availability, whereas synthetic fertilizers supplied nutrients in a readily available form (Alizadeh Dehkordi, 2010; Li *et al*., 2012; Roudgarnejad *et al*., 2021). The synergistic application of these changes exceeded the efficacy of their individual use, as evidenced by numerous investigations (Ghanbari *et al*., 2013). HA enhanced soil nutrient availability and plant absorption, increasing thousand-grain weight (Atak *et al*., 2004; Shazma Anwar *et al*., 2016). FYM and NPK fertilizers optimized nutrient availability at critical growth stages (Antoun *et al*., 2010; Mahmood *et al*., 2017). Similar studies show that organic manures and synthetic fertilizers improve grain weight (El-Kouny, 2007). The application of HA greatly increased biological yield, presumably due to enhanced soil conditions and the availability of critical nutrients (Abril *et al*., 2007; Shazma Anwar *et al*., 2016). The FYM application enhanced biological yield by promoting soil microbial activity and nitrogen cycling (El-Sayed *et al*., 2024; Khayat, 2021). The harvest index was markedly enhanced by HA and FYM, especially when used in conjunction with synthetic fertilizers, illustrating their joint efficacy in optimizing resource utilization (Ashrafi Esfahani *et al*., 2019; Mahmood *et al*., 2017; Roudgarnejad *et al*., 2021).

Effect of organic amendments and synthetic fertilizers on N content in wheat

Application of synthetic fertilizers, manures, and humic acid dramatically affected wheat shoot and grain nitrogen (N). These amendments improved soil nutrient availability, N uptake, and plant growth, increasing nitrogen concentrations in plant parts. The integration of synthetic fertilizers and organic amendments, including manures and humic acid, markedly increased nitrogen content in wheat shoots. Manures enhanced soil nitrogen levels by augmenting organic matter and microbial activity, leading to increased nitrogen availability for plant absorption (Ashrafi Esfahani *et al*., 2019; Liu *et al*., 2022). Likewise, HA improved soil nutrient dynamics, thus increasing nitrogen concentration in shoots (Delfine *et al*., 2005; Taimur Naseem *et al*., 2015). The combination of synthetic fertilizers and manures enhanced these effects, since the fertilizers supplied readily available nitrogen, while manures facilitated prolonged nutrient release, hence enhancing nitrogen uptake efficiency (Daur, 2014; Taimur Naseem *et al*., 2015). The utilization of synthetic fertilizers in conjunction with manures and HA markedly elevated nitrogen concentration in wheat grains. This enhancement was ascribed to the mechanisms of improved soil nitrogen availability and augmented nitrogen uptake by plants (Adekiya *et al*., 2016; Alizadeh Dehkordi, 2010; Antoun *et al*., 2010; Ashrafi Esfahani *et al*., 2019). The combination of manures and synthetic fertilizers enhanced grain nitrogen content by increasing nutrient availability during critical growth phases (Khayat, 2021). The integrated use of HA, manures, and synthetic fertilizers enhanced nitrogen absorption via various processes. This encompassed the improvement of soil nutrient retention capacity, microbial activity, and nutrient mineralization, which jointly augmented the availability of nitrogen for plant absorption (Daur, 2014; Delfine *et al.*, 2005). Synthetic fertilizers offered an immediate supply of nitrogen, whilst manures and humic acids enabled its prolonged release and effective absorption by plants (Adekiya *et al.*, 2016; Taimur Naseem *et al.*, 2015).

Effect of organic amendments and synthetic fertilizers on P uptake in wheat

Organic additives like manures and humic acid (HA) combined with synthetic fertilizers increased wheat straw and grain phosphorus (P). This improvement is due to improved soil nutrient availability, microbial activity, and plant uptake. The amalgamation of manures and synthetic fertilizers enhanced phosphorus concentration in wheat straw, as evidenced by our results and supported by previous research (Ashrafi Esfahani *et al.*, 2019; Tabbassum *et al.*, 2022). The synergistic application of HA enhanced this impact by optimizing soil nutrient dynamics and plant absorption efficiency (Matuszak-Slamani *et al.*, 2017; Savita *et al.*, 2018). These amendments improved phosphorus availability in the soil, facilitating greater absorption by plants and accumulation in straw (Akande *et al.*, 2006). The integrated use of manures, synthetic fertilizers, and HA markedly enhanced phosphorus buildup in wheat grains. When combined with NPK fertilizers, manures increased soil phosphorus content and maintained its availability over the growth season (Ashrafi Esfahani *et al.*, 2019; Mahmood *et al.*, 2017). HA enhanced soil phosphorus availability and absorption efficiency by improving nutrient retention and microbial activity (Aşık *et al.*, 2009; Nasiroleslami *et al.*, 2021). The collaboration of HA, manures, and synthetic fertilizers enhanced soil conditions, promoting improved phosphorus absorption by plants. HA enhanced microbial proliferation and activity, which was essential for phosphorus solubilization and mobilization (Daur, 2014; Delfine *et al.*, 2005). Manures facilitated prolonged nutrient release, whereas synthetic fertilizers offered immediately accessible phosphorus, establishing an ideal nutrient equilibrium for plant development (Adekiya *et al.*, 2016). This combination markedly improved phosphorus uptake efficiency and accumulation in both straw and grains (Khayat, 2021).

Effect of organic amendments and synthetic fertilizers on K concentration and uptake in wheat

Manures, humic acid (HA), and synthetic fertilizers increased soil, straw, and grain K content, improving plant uptake. This improvement is due to soil nutrient availability and plant nutrient absorption. The incorporation of manures markedly elevated soil potassium levels, subsequently enhancing potassium concentration in wheat straw (Ashrafi Esfahani *et al.*, 2019; Thomas *et al.*, 2019). The use of humic acid further intensified this impact by augmenting nutrient retention in the soil and raising potassium availability for plant absorption(Matuszak-Slamani *et al.*, 2017; Savita *et al.*, 2018). The synergistic use of manures and synthetic fertilizers enhanced nutritional equilibrium, resulting in increased potassium buildup in plant straw. The integration of manures with synthetic fertilizers led to a substantial enhancement in potassium concentration in wheat grains (Ashrafi Esfahani *et al.*, 2019; Nasiroleslami *et al.*, 2021). Humic acid treatment augmented potassium uptake and grain accumulation by enhancing nutrient availability and soil conditions (Antoun *et al.*, 2010; Aşık *et al.*, 2009; Roudgarnejad *et al.*, 2021). The maximum potassium content in cereals was recorded with the integrated use of manures, synthetic fertilizers, and humic acid. The integration of HA, manures, and synthetic fertilizers enhanced the accessibility and absorption of K by wheat plants. HA significantly contributed to the enhancement of soil K retention, the stimulation of microbial activity, and the improvement of root uptake efficiency (Aşık *et al.*, 2009; Delfine *et al.*, 2005). Manures facilitated a gradual release of K and enhanced soil structure, but synthetic fertilizers guaranteed the prompt availability of nutrients, establishing an ideal nutritional equilibrium for plant development (Adekiya *et al.*, 2016; Khayat, 2021; Martins *et al.*, 2003).

Effect of manures and synthetic fertilizers on nutrient use efficiency

The integration of manures into soil significantly enhanced N availability, leading to greater N use efficiency by plants. This enhancement is ascribed to the gradual-release characteristics of organic amendments and their function in augmenting soil nutrient retention and microbial activity (Farrag and Bakr, 2021; Mahmood *et al.*, 2017; Rees and Castle, 2002). The integration of manures and synthetic fertilizers improved N use efficiency by ensuring a balanced nutrient supply (Vieira *et al.*, 2016). The amalgamation of manures with fertilizers markedly elevated soil P levels, resulting in augmented P absorption and higher utilization efficiency. Multiple investigations indicated that the application of manures at varying quantities enhanced P availability and promoted its effective consumption by plants (Abo-Baker, 2017; Farrag and Bakr, 2021; Rees and Castle, 2002). The combined action of manures and synthetic fertilizers established a more advantageous nutritional environment for plant growth, hence optimizing P use efficiency. Fertilizers also augmented the availability of K in the soil, hence improving K uptake and use efficiency. Studies demonstrate that the utilization of farmyard manure enhances K use efficiency by improving soil structure and nutrient retention capacity (Farrag and Bakr, 2021). The synergistic application of synthetic fertilizers and manures significantly improved K utilization efficiency by providing a balanced and continuous nutrient supply (Xi *et al.*, 2019).

Impact of manures and synthetic fertilizers on soil properties

The simultaneous use of manures and synthetic fertilizers elevated soil pH relative to the exclusive use of synthetic fertilizers. Studies by (Pal *et al.*, 2015; Shazma Anwar *et al.*, 2016) corroborate this finding, demonstrating that the use of synthetic fertilizers, whether singularly or in conjunction with organic additions, elevated soil pH. Comparable findings were documented by (Bhatt *et al.*, 2018), corroborating the beneficial effect of integrated manures and synthetic fertilizers on enhancing soil pH. The integrated application of manures, synthetic fertilizers, and humic acid effectively augmented total N levels in soil by minimizing N losses and promoting their retention. Research conducted by (Khayat, 2021; Zhou *et al.*, 2016) indicated substantial increases in total N in soil due to organic and synthetic amendments. The results of (Bhatt *et al.*, 2018; Kalsoom *et al.*, 2020; Kumar and Singh, 2010) corroborated these findings, affirming the synergistic effect of manure and synthetic fertilizers on enhancing soil N availability. The amalgamation of manures and synthetic fertilizers markedly elevated soil P levels. Studies by (Bhatt *et al.*, 2018; Dhaliwal *et al.*, 2015; Sharma *et al.*, 2014) corroborate these findings, indicating that manures augment P availability via enhancing soil microbial activity and nutrient cycling. The efficacy of manures in augmenting soil P concentration was further validated by (Bairwa *et al.*, 2018).

When mixed with synthetic fertilizers, manures greatly increased soil K levels. Research conducted by (Bhatt, 2012; Dhaliwal *et al.*, 2015) validated the synergistic benefits of these amendments in enhancing soil K concentration, presumably attributable to the gradual release of K from organic sources and the prompt availability from synthetic fertilizers. The FYM soil organic matter enrichment and HA's nutrient chelation and absorption promoted nitrogen availability, improving plant physiological characteristics. FYM+HA synergy increased root development, nutrient absorption, and consistent release, while HA promoted nutrient mobility and photosynthetic efficiency, enhancing grain development (Sheoran *et al.*, 2024). Soil organic carbon, microbial activity, and stress tolerance increased yield attributes and harvest index, while FYM helped retain nutrients and HA (Tathe *et al.*, 2024) stimulated hormone activity for effective grain assimilation. Integration maximized plant growth and production. N increases cell elongation, chlorophyll production, and protein creation, enhancing vegetative growth and grain filling. Potassium (K) controls enzymes, osmotic balance, and stress tolerance, while phosphorus (P) improves root development, energy transfer, and blooming. N, P, and K optimize growth, biomass, and assimilate partitioning, increasing yield and harvest index (Afzal *et al.*, 2023).

Conclusions and Recommendations

The combined application of HA+FYM significantly concentration of N, P and K in the plants compared to the sole application of NPK. Total uptake of plant NPK increased by 39%, 47%, and 40%, respectively, with the application of HA+FYM and 75% synthetic fertilizers compared to the individual application of 75% NPK. The N, P and K use efficiency was also improved with the combined application of HA+FYM and synthetic fertilizers. Similarly, after harvesting a significant increase was recorded in soil total N, P and K with the combined application of HA+FYM as compared to the application of either amendments or NPK alone. To decrease the use of commercial fertilizers and improve soil properties, 10 kg ha^{-1} humic acid in combination with FYM and 75% NPK (90-60-45 kg NPK ha^{-1}) is recommended for the enhancement of grain yield, nutrient availability, and soil physicochemical properties. It is suggested that similar research should be conducted at different locations with more NPK levels for wider spread use of organic manures.

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Novelty Statement

This research explored the potential of organic amendments with synthetic fertilizers for nutrient use efficiency and wheat productivity.

Author's Contribution

Sobia Bibi: Principal author, conducted the research and wrote first draft, data collection and analysis, Scientific review.
Maria Mussarat: Dost Muhammad, Scientific writing and data collection.
Zaryab Murad: Seon Yeong Im, Ping Zhuang, Ismail Khan, Abdul Rehman.

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The authors have declared no conflict of interest.

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