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FIELD EXPERIMENT TO EVALUATE THE PHOSPHATE FERTILIZERS EFFECT ON WHEAT' MORPHOLOGICAL TRAITS

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Background: To meet SDG 2, agricultural productivity must double, and wheat production in particular must close the gap between demand and consumption. China leads global wheat production, accounting for 17% with 135.8 million tonnes in 2022 – 2023, followed by India with 105 million tonnes. Russia produces 85.2 million tonnes and is also the world's largest exporter. Pakistan's production was 26.2 million tonnes in 2022. Pakistan's wheat sector faces the challenge of meeting growing demand, as average yields per hectare are below potential and the population is growing rapidly. **Objectives:** The objectives included comparing the impact of DAP, NP, and SSP fertilizers on plant height (cm), number of tillers per plant, spike length (cm), grains per spike, seed index (1000-grain weight in grams), grain yield (kg/ha), and nitrogen, phosphorus, and potassium content (%) in the grains and straw of the TD-1, SKD-1, and TJ-83 varieties. **Methods:** A field experiment was conducted to evaluate the effects of phosphatic fertilizers, including DAP, NP, and SSP, applied at dose of 84 kg P_2O_5 per ha, on soil nutrient dynamics and the morphological traits of three wheat varieties: TD-1, SKD-1, and TJ-83. For the experiment was utilized a randomized complete block design with treatments applied to soil and crops under controlled field conditions. Soil properties such N, P, K, EC, pH, and OM, along with wheat morphological traits, were assessed. **Results:** The results indicate that DAP fertilizer significantly increased soil N and P levels, while SSP was more effective in enhancing soil K. SSP also increased soil EC, whereas pH decreased with all phosphatic fertilizers compared to the control. Among the wheat varieties, TJ-83 exhibited the highest grain yield (3049 kg/ha) with NP fertilizer. Notably, DAP improved the seed index and grain nutrient content compared to other treatments, with by 51.33g for TD-1 variety. These findings align with other studies report by the scientist, highlighting the efficacy of phosphatic fertilizers in improving soil fertility and crop traits under challenging soil conditions. **Conclusion:** This finding contributes to optimizing phosphorus fertilizer use for sustainable wheat production and emphasizes the need for long-term experiments integrating innovative amendments like biochar and nanotechnology to enhance soil health and crop productivity.

Keywords: environmental pollution; phosphatic fertilizers; environmental engineering; nutrients uptake; plant growth; wheat yield; SDG 2.

INTRODUCTION

Wheat (*Triticum aestivum L.*) is a member of Poaceae family and is one of the world's most important grain crops (Tesfaye et al., 2025). It is a crucial global staple food that fulfils the protein needs of a significant portion of the population (Zhang et al., 2024). Wheat is used in producing crumpets, cookies, bread, biscuits, noodles, chapatis, flour, animal feed, roasted grains, and other products (Babu et al., 2021). Wheat production must increase to bridge the gap between demand and consumption as the population grows exponentially (Rask & Rask, 2011). China leads global wheat production, contributing 17% with 135.8 million tonnes in 2022-2023 followed by India with 105 million tonnes, while Russia, production was 85.2 million tonnes and also the top global exporter, meanwhile Pakistan production were 26.2 million tonnes in 2022. (Mottaleb et al., 2023; Dadrasi et al., 2023). Pakistan's wheat sector faces a challenge in meeting the country's growing demand, as the average yield per hectare is lower than its potential, and the population is increasing rapidly (Ahmad & Farooq, 2010). The performance of the wheat sector is crucial to ensuring national food security and has a significant impact on the country economic stability, especially for vulnerable urban populations (Shiferaw et al., 2013). The main reason of low wheat crop production in Pakistan is water and soil degradation, lack of best farming practices, improper use of fertilizer pests control and plant diseases, weeds, climate change, seed quality, limited access to credit and markets, agricultural research and extension, and government policy and support (Khan, 2019; Adnan et al., 2020). Furthermore, wheat crop faces numerous biotic and abiotic stresses despite its low production (Hossain et al., 2021). Under the abiotic stressors the phosphorus is a major limiting nutrient for crop yields in Pakistan, particularly due to the high calcium content in many of its soils, which leads to phosphorus fixation. Phosphate fertilizers are applied to soil to enhance the production of crops (Guelfi et al., 2020). The efficiency of phosphorus base fertilizer use remains sub-optimal, with only 15 – 20% of applied phosphorus being available to the first crop, largely due to the formation of insoluble phosphorus compounds in the soil. This problem is compounded by Pakistan's heavy reliance on imported phosphorus fertilizers, which are increasingly expensive and subject to supply chain disruptions. The soils of Pakistan are alluvial, calcareous, alkaline and 90% deficient in phosphorus (Rashid et al., 2010). The application of P fertilizers to calcareous soils, with pH levels greater than 7.5 has been a major concern due to P fixation (Devau et al., 2011; Bolan et al., 2023). When P is applied to the soil, the plant takes up only small percentage; the remainder is either permanently or temporarily fixed in forms varying in plant availability (Syers et al., 2008; Demiraj et al., 2018; Lahori et al., 2019). The temporarily fixed P, also called residual P, becomes available with time, but at slow rates (Schröder et al., 2011). Amanullah et al. (2009) stated that the P fertilizer source is considered as one of the most important factors affecting crop growth and yield. The P fertilizer use can help to reduce the adverse effect of drought under rainfed conditions (Shirmohammadi et al., 2020).

Phosphorus (P) is an essential nutrient that drives plant metabolism, supporting a wide range of biochemical reactions that govern plant growth and development (Malhotra et al., 2018). Its role in photosynthesis allows plants to utilize solar energy, while also influencing key developmental processes, including root development, stem elongation, flower initiation, seed production, and disease susceptibility, ultimately impacting crop yields and quality. The availability of phosphorus in the soil-plant system is driven by a multitude of factors, including biological, chemical, and physical processes, which are strongly influenced by soil type and environmental conditions, ultimately determining the dynamics of phosphorus transformation and mobility (Kunwar et al., 2018). The widespread occurrence of calcareous soils with high calcium levels in Pakistan is a critical factor contributing to the low efficiency of phosphorus recovery, highlighting the need for strategies to mitigate the adverse effects of calcium on phosphorus availability (Qadir et al., 2024). Due to the limited availability of premium rock phosphate (RP) in Pakistan, there is a growing demand for affordable, indigenous phosphorus sources (Mohanty et al., 2021). Although RP contains 28 – 30% phosphorus, its slow release makes it unsuitable as a fertilizer without additional processing (Billah et al., 2019). Maximizing crop yields requires careful management of phosphorus fertilizer forms and application phases (Roberts & Johnston, 2015). In Pakistan, phosphorus-based fertilizers, including single superphosphate (SSP), di-ammonium phosphate (DAP), and triple superphosphate (TSP), are widely used, with DAP primarily imported from Jordan, the USA, and Morocco (Fayiga & Nwoke, 2016; De Boer et al., 2019). Scientific research has demonstrated that Nitro phosphate (NP) and SSP fertilizers are more effective than DAP in enhancing crop yields, with phosphorus application during sowing proving particularly successful in regions with conditions similar to those in Sindh. The effectiveness of phosphorus application depends heavily on timing, as delayed applications often fail to compensate for early-season losses, highlighting the importance of strategic nutrient management (Hopkins & Hansen, 2019). Khursheed et al. (2024) assessed the impact of different phosphatic fertilizers on phosphorus fractions and morphophysiological parameters of wheat in saline sodic soil. Azeem et al. (2018) examined the influence of DAP, NP, TSP and SSP fertilizers on growth, yield and yield attribute of two maize varieties. Chen et al. (2024) observed the alone and combined application of calcium magnesium phosphate (CMP), single super phosphate (SSP), di-ammonium phosphate (DAP), and mono-ammonium phosphate (MAP) on improving P uptake, growth and yield parameters by maize crop in acidic and alkaline soil. The main purpose of P fertilizers applying and its application at affordable price is a major issue in agriculture. Yet the unbalanced use of P fertilizers can either reduce the nutrient application or may lead to fixation of P causing environmental pollution. The application of P at an affordable rate can reduce the input for farmers. The rise in DAP fertilizer prices available in market has developed interest in the use of NP and SSP. Nitro phosphate and SSP are locally available, making them more affordable fertilizer source This study was conducted at the Wheat Research Institute in Sakrand, District Nawabshah, Pakistan, to evaluate the availability of phosphorus from three sources – DAP, NP, and SSP – and their effects on primary macronutrients, soil chemical properties, and the morphological traits of three wheat varieties: TD-1, SKD-1, and TJ-83, under field conditions. The objectives included comparing the impact of DAP, NP, and SSP fertilizers on plant height (cm), number of tillers per plant, spike length (cm), grains per spike, seed index (1000-grain weight in grams), grain yield (kg/ha), and nitrogen, phosphorus, and potassium content (%) in the grains and straw of the TD-1, SKD-1, and TJ-83 varieties.

MATERIALS AND METHODS

Study area and description

The research study was conducted at the experimental area of Wheat Research Institute Sakrand (Figure 1). The experiment was conducted over a 100 × 100 sq. ft. area using a randomized complete block (RCB) design with a two-factor arrangement and three replications. The treatments included three wheat varieties (TD-1, SKD-1, and TJ-83) and three phosphorus sources (DAP, NP, and SSP), along with a control treatment. This resulted in a total of 36 plots, each with a subplot size of 225 sq. ft. (15 × 15 ft.), consisting of 20 rows spaced 22.5 cm apart. A conceptual flow diagram is indicated in (Figure 2) explain the detailed study design.

Experimental set-up

Recommended dose of P_2O_5 at 84 kg/ha separately from DAP, NP and SSP was applied to each treatment (except control) at the time of sowing. Recommended dose of N (168 kg/ha N) and K (60 kg/ha K_2O) was applied to all the treatments. Potassium was applied in the form of Potassium Sulphate – K_2SO_4 – SOP and all was applied during sowing period. In case of N, it was applied in the form of urea in two phases, half at sowing phase, other half was applied during first irrigation with a total of 5 irrigation phases. The quantity of N added to treatments applied with DAP or NP was adjusted. For sowing of wheat crop, initially the plot was deep ploughed to remove the hard pan at sub-soil layer and followed by precision plot levelling with laser land leveller. The experimental plot was ploughed with Goble Disc Harrow (GDH), and after a soaking dose, a cross-wise cultivator was run and planked. The sowing was done in rows by means of single hand seed drill with a seed rate of 125 kg/ha. The seed was obtained from the wheat research institute Sakrand, Sindh Pakistan.

Soil and plant sampling

A composite soil sample before sowing and fertilizer application from the experimental area at 0 – 15 and 15 – 30 cm depth and was send to laboratory for basic soil analysis. After harvesting, separately composite soil samples from all 36 plots at 0 – 15 and 15 – 30 cm depths were collected. The samples were air dried, ground sieved through 2 mm sieve and analysed for physio-chemical properties were the obtained result are specified in Table 1. The crop was harvested at maturity about 16 weeks after sowing. Whole Plant samples (except roots) were collected from same plots, rinsed with tap water and double washed with distilled water to remove the soil particles. The plant part straw and grain samples were dried separately at 65 °C and ground in an agate mill. After harvesting of three wheat varieties, randomly tree composite soil samples were collected from the rhizosphere of each treated block at 0 – 15cm depth, aiming to test the following parameters: EC, pH, OM, N, P and K.

Soil analysis

All the samples were analysed for some physio-chemical properties by standard methods. Particle size distribution was determined by Bouyoucos hydrometer method (Bouyoucos, 1962). Soil electrical conductivity (EC) and pH were determined in 1:5 soil water extract using EC meter and pH meter respectively.

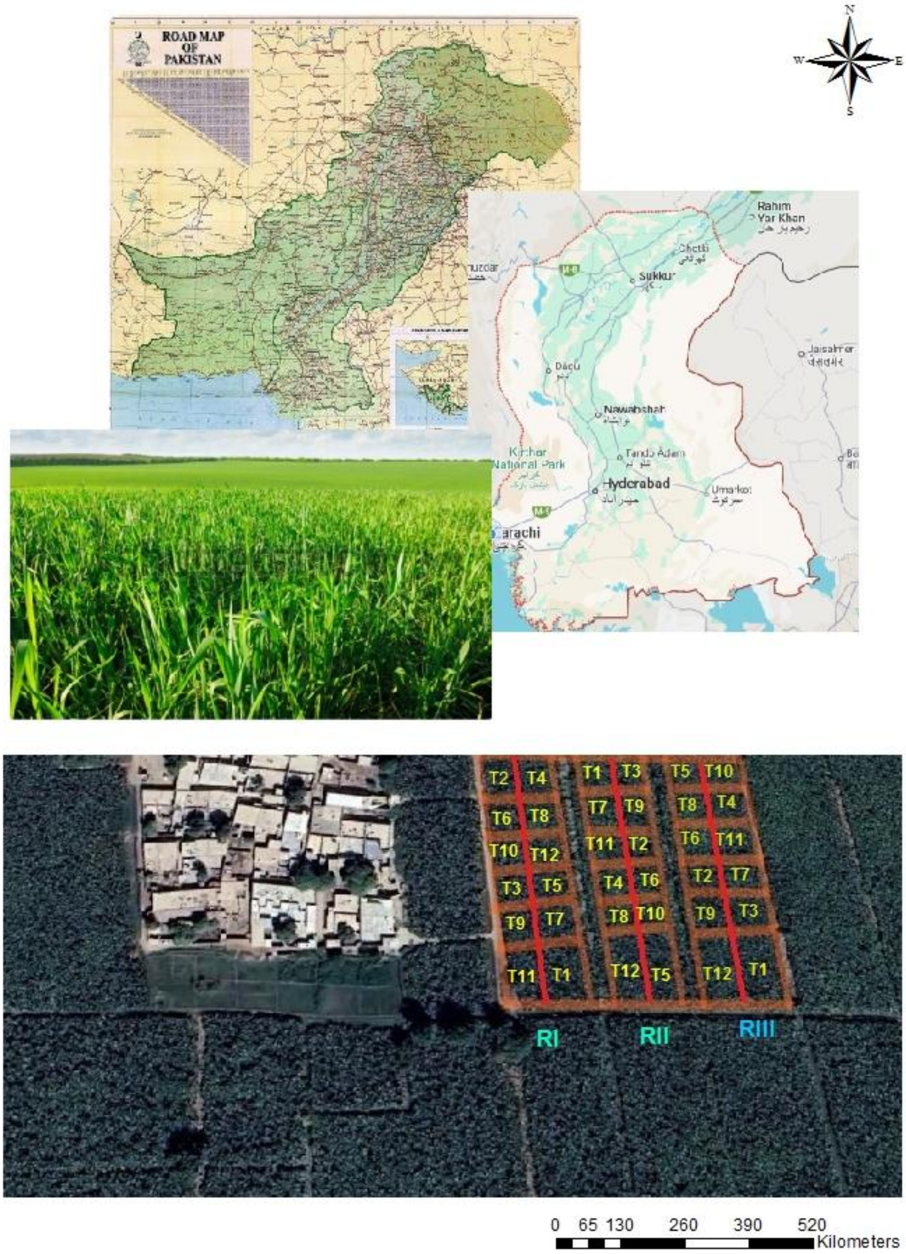

Figure 1. Location of the experimental area: wheat research institute at Sakrand, Sindh Pakistan

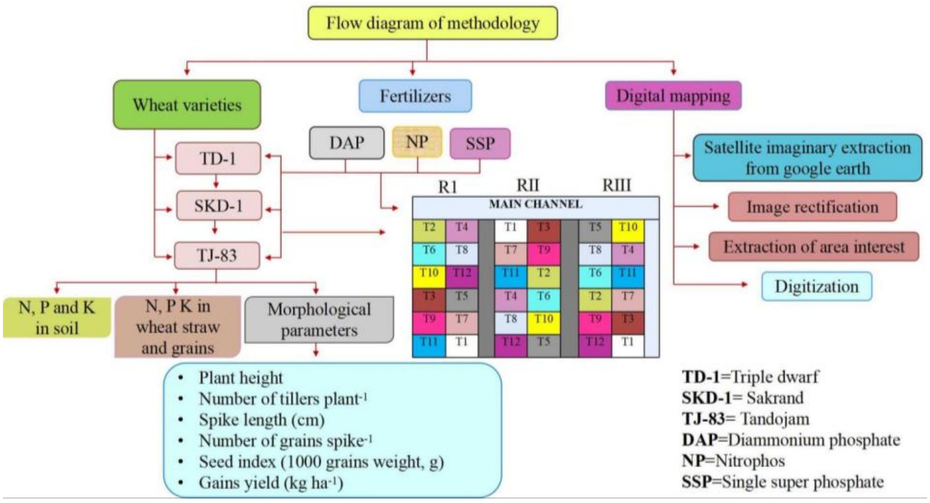

Figure 2. A conceptual flow diagram of experimental area

Table 1. Some physical and chemical properties of the soil used for field experiment

Name of property		Depth, cm	
Texture		0 – 15	15 – 30
	Sand, %	28.00	52.75
	Silt, %	56.50	33.75
	Clay, %	15.50	13.50
Textural class		Silt loam	Sandy loam
EC, dS/m (1 : 2 soil water extract)		0.38	0.29
pH (1 : 2 soil water extract)		7.69	7.24
Organic matter, %		0.91	0.60
$CaCO_3$, %		10.90	8.60
Kjeldahl's N, %		0.043	0.032
NH_4HCO_3-DTPA extractable P, mg/kg		1.60	1.44
NH_4OAc extractable K, mg/kg		166.00	152.00

Organic matter was determined by Walkley-Black method as given in Jackson (1969) which involved oxidation of organic carbon by potassium dichromate ($K_2Cr_2O_7$) and subsequent determination of the unutilized dichromate by oxidation-reduction titration with ferrous ammonium sulphate. Calcium carbonate in soil was determined by acid neutralization method (Kanwar and Chopra, 1959). Kjeldahl's for total N (Jackson, 1962), ABDTPA for P and K (Soltanpour & Workman, 1979) were used for determination.

Determination of nitrogen, phosphorus and potassium in soil

All the samples before and after harvest of wheat were analysed for Kjeldahl's N, and ABDTPA extractable P and K. Kjeldahl's N was estimated by digesting the contents in H_2SO_4 followed by distillation and finally titrating the distillate with acid (Jones, 1991). Available P and K were extracted with AB-DTPA (Soltanpour & Workman, 1979) and the P in the extracts was determined by ammonium molybdate method as given by Murphy & Riley (1962); while K was analysed directly by emission spectroscopy using flame photometer (Knudsen et al., 1982). The N, P and K data of original soil samples are indicated in Table 1.

Agronomic observations

Some agronomic observations were recorded after the harvest of wheat. The method used for each observation is detailed is indicated in Table 2.

Plant analysis

The ground samples of wheat straw and grain were subjected to N, P and K analysis. Nitrogen in wheat straw and grain was analysed by Kjeldahl's method. Nitrogen content was determined by Kjeldahl's method by digesting the contents in H_2SO_4 followed by distillation and finally titrating the distillate with acid (Jones, 1991). Phosphorus and K samples of wheat straw and grain were analysed by wet digestion method using $HClO_4$: HNO_3 mixture (1 : 5). The digests were analysed for P by developing vanadomolybdo phosphoric acid yellow colour method (Cottenie, 1980) and K by emission spectroscopy using flame – photometer (Knudsen et al., 1982).

Statistical analysis

All the data was presented as mean values of three replicates in this investigation. The mean data has been used for make graphs by using Prism 5 software. The redundancy analysis was performed among the studied parameters by using Canoco 5.

Table 2. Agronomic parameters of three wheat verities

Parameter	Details
Plant height, cm	Plant height was recorded at maturity of the crop in randomly selected plants using measuring tape from bottom to tip of spike in centimetres
Tillers, plant^{-1}	Total tillers for randomly selected plants were counted at the time of maturity and averaged
Spike length, cm	The length of all the spikes from randomly selected plants was measured in centimetres with measuring tape and average were worked out
Grains, spike^{-1}	The number of grains in each spike of the randomly selected plants was counted at the time of harvest and average was worked out
Seed index, g	1000 grains per plot were counted at random and weighed to record the seed index
Grain yield, kg/ha	The grain obtained after threshing was weighed and on the basis of grain yield kg/plot and grain yield was calculated in kilograms after the following formula: $\text{Grain yield} = \frac{\text{Grain yield (kg/plot)}}{\text{Plot size (m}^2)} \text{ x } 10000$

RESULTS AND DISCUSSION

Characterization of soil basic properties

This study was based on field experiment involving the effect of DAP, NP and SSP fertilizers by using In a factorial combination along with replicated three times on the growth and yield parameters of wheat varieties. The particle size analysis revealed that the soil before wheat sowing comprised 28.00% sand, 56.50% silt, and 15.50% clay at a depth of 0 – 15 cm. At 15 – 30 cm, the composition shifted to 52.75%

sand, 33.75% silt, and 13.50% clay. The soil's textural class was classified as silt loam at 0 – 15 cm and sandy loam at 15 – 30 cm. The soil was non-saline, with an electrical conductivity (EC) of 0.38 and 0.29 dS/m, and exhibited a medium alkaline reaction (pH 7.69 and 7.24, respectively, at the two depths). It was low in organic matter (< 0.86%) and moderately calcareous, with $CaCO_3$ content of 0.90% at 0 – 15 cm and 8.60% at 15 – 30 cm. Nutrient analysis showed Kjeldahl nitrogen (N) levels of 0.043% and 0.032%, AB-DTPA extractable phosphorus (P) at 1.60 and 1.44 mg/kg, and NH_4OAc extractable potassium (K) at 166.00 and 152.00 mg/kg at 0 – 15 cm and 15 – 30 cm depths, respectively (Babar et al., 2024).

Impact of phosphatic fertilizers on EC, pH, OM, N, P and K in soil

The application of phosphatic fertilizers significantly increased the electrical conductivity (EC) of the soil after harvesting TD-1, SKD-1, and TJ-83 compared to the control. The highest increase in soil EC was observed in the control treatment, rising from 1.01 to 1.12 dS/m following the application of SSP fertilizer after harvesting the TD-1 variety. Similarly, soil EC increased from 0.87 to 1.04 dS/m with NP fertilizer application after harvesting SKD-1, and from 1.03 to 1.06 dS/m with SSP fertilizer application after harvesting TJ-83 (Figure 3a). The rise in soil EC can be attributed to the dissociation of ammonium and phosphate ions from DAP fertilizer, which increases ion concentration in the soil solution. NP fertilizer also influences soil EC, though its effect varies depending on the formulation and application rate. In contrast, SSP fertilizer has a more pronounced impact on soil EC due to its higher phosphate content. Studies have demonstrated that SSP can significantly elevate soil EC, particularly when applied in larger quantities. These findings are consistent with those of Sánchez-Rodríguez et al. (2024), who reported an increase in soil EC following the application of DAP and SSP fertilizers under laboratory incubation conditions. The maximum reduction in soil pH was observed with the application of DAP fertilizer, decreasing from 7.5 to 7.3 after harvesting TD-1. Similarly, soil pH declined from 7.8 to 7.1 with NP fertilizer application after harvesting SKD-1, and from 7.6 to 7.2 with SSP fertilizer application after harvesting TJ-83 (Figure 3b). These results indicate that phosphatic fertilizers significantly lower soil pH, with SSP fertilizer causing the most substantial reduction. This acidifying effect can be attributed to the ammonium ion (NH_4^+) in DAP, which undergoes nitrification and releases hydrogen ions (H^+), thereby reducing soil pH. NP fertilizer typically has a slightly acidic to neutral effect on soil pH, as the nitrate ion (NO_3^-) contributes to soil acidity, while the phosphate ion (PO_4^{3-}) helps buffer pH. In contrast, SSP fertilizer has a stronger acidifying effect due to the residual sulfuric acid (H_2SO_4) used in its production, as well as the release of hydrogen ions (H^+) from phosphate ions (PO_4^{3-}). These findings align with those of Sánchez-Rodríguez et al. (2024), who reported a significant decrease in soil pH following SSP fertilizer application. The organic matter (OM) content in the soil exhibited varied responses to different phosphatic fertilizers. After harvesting TD-1, OM content increased from 0.82% to 0.86% with DAP fertilizer application but decreased from 0.82% to 0.78% with SSP fertilizer. Similarly, after harvesting SKD-1, OM content rose from 0.84% to 0.85% with DAP fertilizer but declined from 0.84% to 0.80% with SSP fertilizer. Furthermore, after harvesting TJ-83, OM content increased from 0.81% to 0.87% with DAP fertilizer but decreased from 0.81% to 0.79% with SSP fertilizer (Figure 3c). These results suggest that DAP fertilizer has a neutral to slightly positive effect on soil organic matter (SOM), likely due to the stimulation of microbial activity by ammonium ions (NH_4^+), which enhances organic matter decomposition and SOM accumulation. In contrast, SSP fertilizer may reduce SOM due to its acidic nature, which can inhibit microbial activity. These observations are partially supported by Solangi et al. (2015), who found no significant changes in OM content at a 0 – 15 cm soil depth following DAP and SSP fertilizer applications in wheat cultivation. Conversely, Lahori et al. (2019) reported an increase in OM content with rock phosphate application under a 0 – 90 day incubation study. The soil nitrogen (N) content exhibited a notable increase following the application of DAP fertilizer, surpassing the effects of NP and SSP fertilizers. Specifically, the N content rose from 0.0561% to 0.0971% after harvesting the TD-1 variety, from 0.0659% to 0.0916% after harvesting SKD-1, and from 0.0568% to 0.0921% after harvesting TJ-83 (Figure 3d). These findings align with the observations of Saleem et al. (2021), who reported a significant enhancement in N solubility after 30 days of incubation in clay loam soil treated with $KFeO_2$-coated DAP fertilizer. Similarly, the phosphorus (P) concentration in the soil demonstrated a marked increase with the application of DAP fertilizer compared to NP and SSP fertilizers. Post-harvest soil analysis revealed that P levels increased from 1.91 to 3.09 mg/kg for TD-1, from 1.69 to 3.23 mg/kg for SKD-1, and from 1.71 to 3.12 mg/kg for TJ-83 (Figure 3e). These results are consistent with the findings of Solangi et al. (2015), who observed a comparable rise in soil P content with DAP and SSP fertilizers relative to control treatments. Additionally, Lahori et al. (2019) demonstrated enhanced P solubility and increased organic matter (OM) content in P-deficient soils amended with rock phosphate over a 0 – 90 day incubation period. Further supporting these results, Khursheed et al. (2024) confirmed that the total P availability in saline-sodic soils significantly improved with the application of DAP, SSP, and NP fertilizers. Similarly, Sánchez-Rodríguez et al. (2024) reported a significant improvement in soil P solubility with the use of DAP and SSP fertilizers. The potassium (K) content in the soil also showed a consistent increase following the application of DAP fertilizer, outperforming NP and SSP fertilizers. Post-harvest measurements indicated that K levels rose from 169.2 to 176.4 mg/kg for TD-1, from 171.6 to 181.9 mg/kg for SKD-1, and from 182.4 to 187.6 mg/kg for TJ-83 (Figure 3f). These findings are corroborated by Solangi et al. (2015), who reported a positive impact of DAP fertilizer on soil K levels, with an increase from 170.16 to 176.77 mg/kg at a 0 – 15 cm soil depth compared to untreated soil.

Impact of phosphatic fertilizers on morphological traits of three wheat varieties

The plant height of three wheat varieties – TD-1, SKD-1, and TJ-83 – was evaluated under field conditions following the application of diammonium phosphate (DAP), nitrogen-phosphorus (NP), and single superphosphate (SSP) fertilizers. The maximum plant height increased from 58.83 cm in the control treatment to 74.10 cm with NP fertilizer for TD-1, from 61.97 cm to 75.60 cm with DAP for SKD-1, and from 64.93 cm to 93.07 cm with NP for TJ-83. These differences in plant height can be attributed to the inherent characteristics of the varieties: TJ-83 is a tall variety, SKD-1 is of medium height, and TD-1 is a dwarf variety, with a height approximately three times smaller than the other varieties. Notably, NP fertilizer demonstrated the highest potential for enhancing plant height in TJ-83, followed by TD-1 and SKD-1 (Figure 4a). Ali and Khalid (2015) reported that SSP fertilizer resulted in the maximum number of tillers. Similarly, Zhou et al. (2023) observed an increase in plant height in Tartary buckwheat with the application of low phosphorus fertilizer at a rate of 40 kg/ha. In this study, the number of tillers per plant increased from 8.33 in the control to 14.00 with SSP application for TD-1, from 7.00

to 10.00 with NP for SKD-1, and from 7.00 to 9.33 with DAP for TJ-83. These results indicate that NP fertilizer was highly effective in increasing the number of tillers per plant in the TJ-83 variety (Figure 4b). Khan et al. (2010) also found SSP fertilizer to be highly effective in increasing tiller numbers, followed by triple superphosphate (TSP), NP, and DAP.

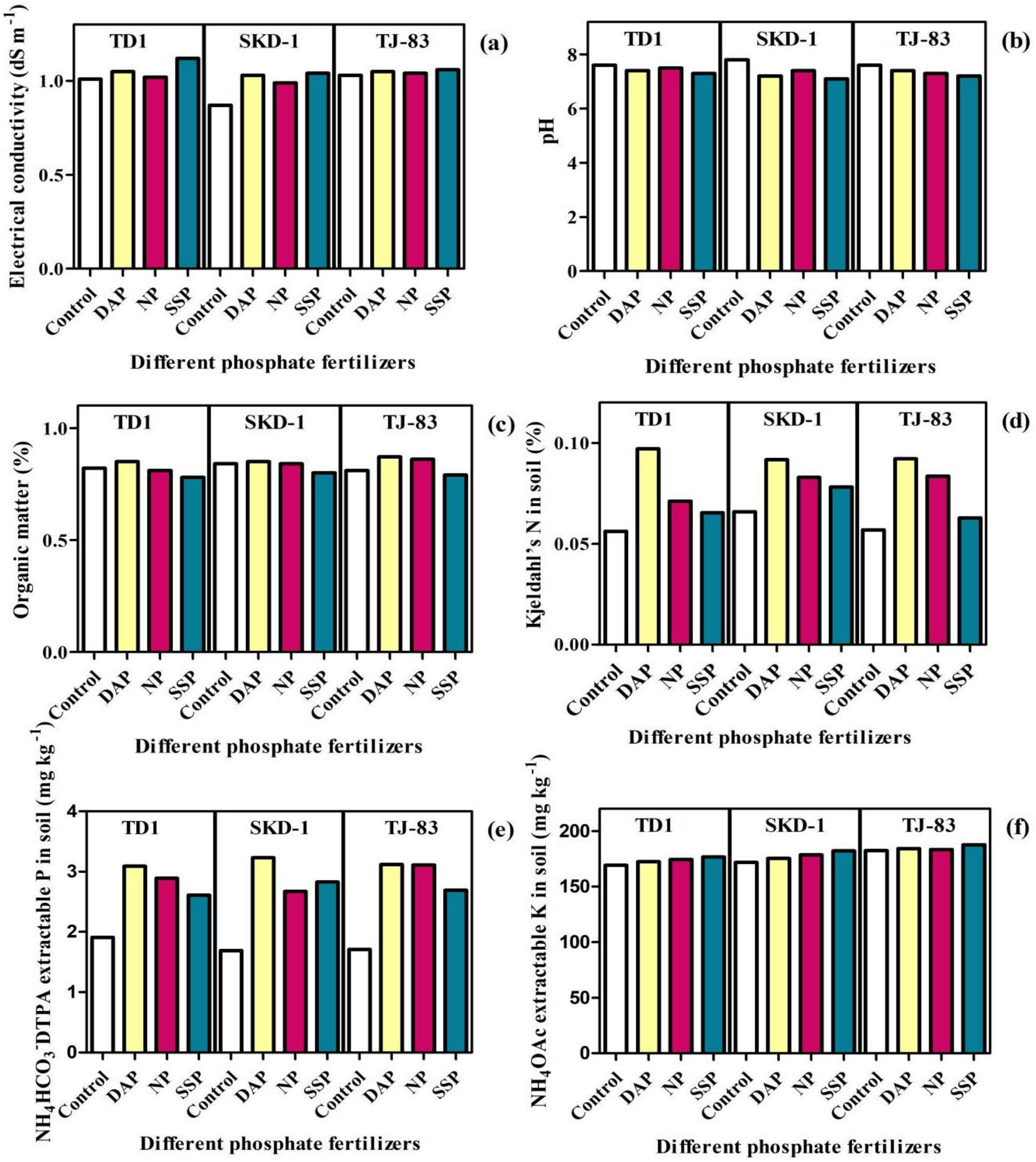

Figure 3. Impact of different phosphatic fertilizers on soil: a – EC; b – pH; c – OM; d – N; e – P; f – K in soil after harvesting of wheat varieties

In contrast, Ali et al. (2012) reported a greater number of tillers with DAP compared to NP fertilizer. The highest spike length increased from 6.60 cm in the control to 9.94 cm with DAP for TD-1, from 7.02 cm to 10.31 cm with DAP for SKD-1, and from 6.32 cm to 11.84 cm with DAP for TJ-83. These findings suggest that DAP fertilizer significantly improved spike length, particularly in the TJ-83 variety (Figure 4c). Khan et al. (2010) also reported that DAP and SSP fertilizers resulted in the highest spike length compared to the control. The number of grains per spike increased from 21.26 in the control to 42.60 with DAP for TD-1, from 24.80 to 46.67 with DAP for SKD-1, and from 27.13 to 61.60 with DAP for TJ-83. These results highlight the effectiveness of DAP fertilizer in maximizing the number of grains per spike, particularly in TJ-83 (Figure 4d). Reddy and Singh (2003) noted that SSP fertilizer yielded the highest grain production, followed by NP and DAP. Zhou et al. (2023) also found that medium phosphorus application (80 kg/ha) resulted in the highest grain weight per plant in Tartary buckwheat. The seed index (1000-grain weight, g) increased from 32.67 g in the control to 51.33 g with NP for TD-1, from 46.00 g to 46.33 g with SSP for SKD-1, and from 33.00 g to 48.33 g with SSP for TJ-83. NP fertilizer showed the highest potential for increasing the seed index in TD-1, followed by SKD-1 and TJ-83 (Figure 4e). Liang et al. (2024) reported that the application of polyphosphate (poly P) fertilizer significantly increased the 1000-grain weight of wheat under field conditions. The highest grain yield (kg/ha) increased from 1234 in the control to 3330 with NP for TD-1, from 1391 to 3345 with NP for SKD-1, and from 1185 to 3049 with NP for TJ-83. These results underscore the effectiveness of NP fertilizer in increasing grain yield, particularly in TJ-83 (Figure 4f). Zhou et al. (2023) also observed the highest yield in Tartary buckwheat with medium phosphorus application (80 kg/ha) compared to the control.

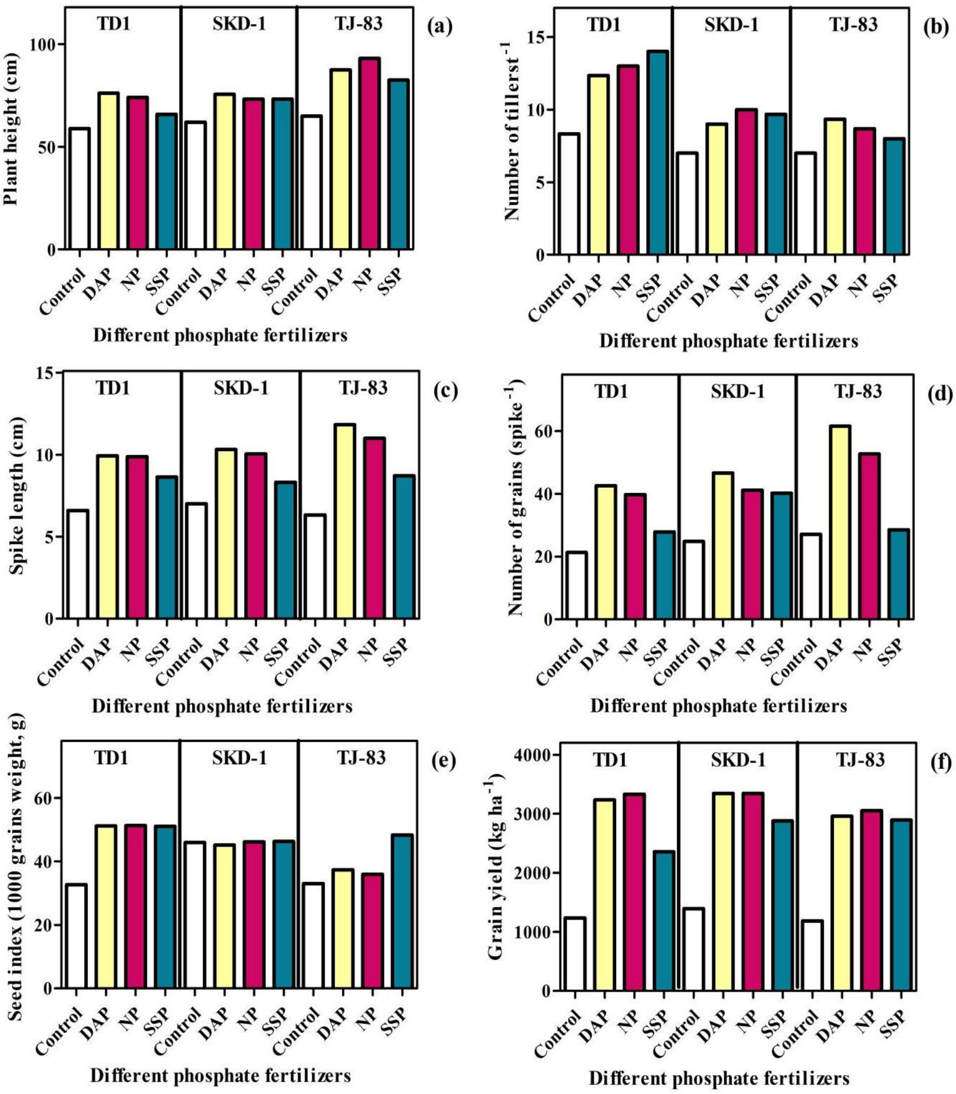

Figure 4. Impact of different phosphatic fertilizers on plant: a – height; b – number of tillers; c – spike length; d – number of grains per spike; e – seed index; f – grain yield of three wheat varieties

Impact of phosphatic fertilizers on N, P and K content in wheat straw and grains

The nitrogen (N) content in wheat straw significantly increased from the control treatment values of 0.007% to 0.016% for TD-1, 0.007% to 0.017% for SKD-1, and 0.007% to 0.018% for the TJ-83 variety following the application of diammonium phosphate (DAP) fertilizer. These results indicate that DAP fertilizer was highly effective in enhancing N content in wheat straw, particularly for the TJ-83 variety (Figure 5a). Ma et al. (2013) reported that nitrogen uptake in maize shoots increased by 11 – 31% with the application of banded phosphorus combined with ammonium (MAP, DAP, or ASP), followed by banded phosphorus combined with urea (UP). Similarly, the phosphorus (P) content in wheat straw increased from control treatment values of 0.0193% to 0.0956% for TD-1, 0.0288% to 0.0541% for SKD-1, and 0.0256% to 0.0648% for TJ-83 with the addition of NP fertilizer. These findings suggest that NP fertilizer has significant potential for increasing P content in wheat straw, particularly for the TD-1 variety (Figure 5b). Solangi et al. (2015) observed that the maximum P concentration in wheat straw was achieved with the application of DAP fertilizer. Chen et al. (2024) found that P uptake in maize shoot biomass was higher with the application of DAP and single superphosphate (SSP) fertilizers compared to control soil. Khursheed et al. (2024) also reported increased P uptake in wheat plant tissue with the application of DAP, NP, and SSP fertilizers compared to control soil. The potassium (K) content in wheat straw increased from control treatment values of 2.60% to 3.44% with NP fertilizer for TD-1, 2.64% to 3.27% with SSP fertilizer for SKD-1, and 2.67% to 3.60% with NP fertilizer for TJ-83. These results highlight that NP fertilizer was highly effective in enhancing K content in wheat straw, particularly for the TJ-83 variety (Figure 5c). Khursheed et al. (2024) also noted that K accumulation in wheat plant biomass was enhanced with the addition of DAP, NP, and SSP fertilizers compared to control soil. The nitrogen (N) content in wheat grain increased from control treatment values of 1.12% to 1.79% with DAP fertilizer for TD-1, 1.13% to 1.80% for SKD-1, and 1.14% to 1.83% for TJ-83. The highest N accumulation was observed in the TJ-83 variety with DAP fertilizer, likely due to the 18% N_2O content in DAP. These results suggest that the TJ-83 variety has a greater potential for N accumulation in seeds compared to TD-1 and SKD-1 (Figure 5d). Khursheed and Mahammad (2015) reported that total N content in wheat grain increased from 2.90% to 3.97% with the application of DAP fertilizer. The phosphorus (P) content in wheat grain increased from control treatment values of 0.246% to 0.406% with SSP fertilizer for TD-1, 0.228% to

0.259% for SKD-1, and 0.279% to 0.246% with DAP fertilizer for TJ-83. The highest P accumulation was observed in the TD-1 variety with SSP fertilizer, likely due to the 46% gypsum ($CaSO_4 \cdot 2H_2O$) content in SSP, which may neutralize or reduce soil pH, thereby increasing P solubility in the soil and its uptake by wheat grains (Figure 5e). Solangi et al. (2015) also reported that the highest P accumulation in wheat grains occurred with the application of DAP and SSP fertilizers compared to control soil. The potassium (K) content in wheat grain increased from control treatment values of 1.200% to 1.569% with DAP fertilizer for TD-1, 1.300% to 1.340% with SSP fertilizer for SKD-1, and 1.200% to 1.334% with SSP fertilizer for TJ-83. These results indicate that DAP fertilizer has significant potential for increasing K content in wheat grains, particularly for the TD-1 variety, followed by SKD-1 and TJ-83 (Figure 5f). Solangi et al. (2015) found that the maximum K content in wheat grains was achieved with the application of DAP fertilizer compared to the control treatment.

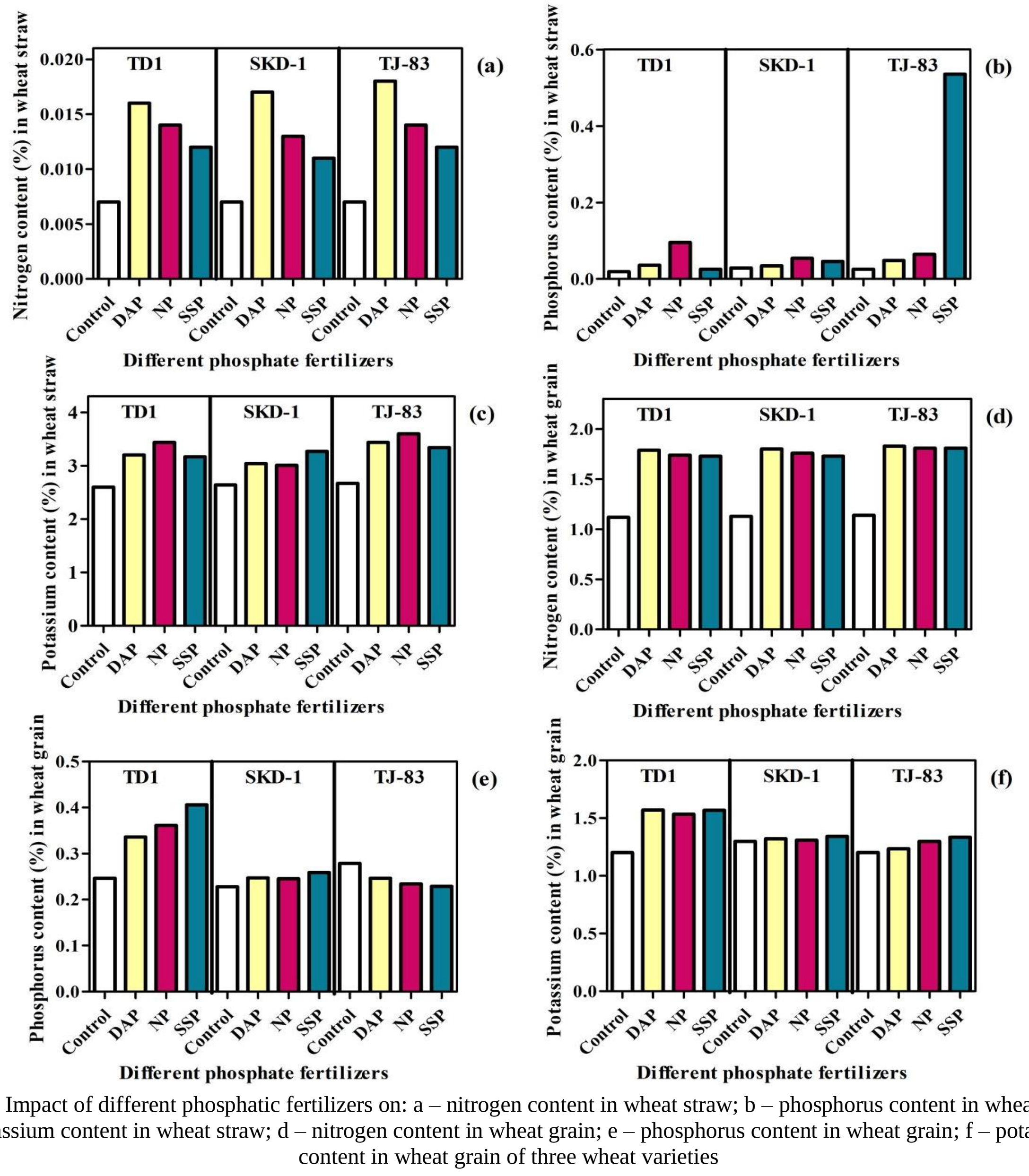

Figure 5. Impact of different phosphatic fertilizers on: a – nitrogen content in wheat straw; b – phosphorus content in wheat straw; c – potassium content in wheat straw; d – nitrogen content in wheat grain; e – phosphorus content in wheat grain; f – potassium content in wheat grain of three wheat varieties

Redundancy analysis of studied traits

Redundancy analysis (RDA) was performed to evaluate the relationships among soil electrical conductivity (EC), pH, organic matter (OM), N, P, K, plant height, number of tillers per plant, spike length, number of grains per spike, seed index, grain yield, and N, P, K content in wheat straw and grains for the TD-1, SKD-1, and TJ-83 varieties following the application of DAP, NP, and SSP fertilizers (Figure 6). The RDA results explained 98.81% of the total variance in soil parameters. Soil pH was negatively correlated and distantly related to EC, N, P, K in soil, plant height, number of tillers per plant, spike length, number of grains per spike, seed index, grain yield, and N, P, K in wheat straw and grains for all varieties. Soil EC was significantly correlated and closely associated with P in wheat straw, K in soil, P in wheat grains, seed index, K in wheat grains, number of tillers per plant, K in wheat straw, and N in wheat grains. Soil organic matter (OM) was significantly correlated with N in soil, number of grains per spike, spike length, N in wheat straw, plant height, P in soil, and grain yield following the application of phosphatic fertilizers.

CONCLUSION

In conclusion, the application of phosphatic fertilizers (DAP, NP, and SSP) significantly increased soil electrical conductivity

(EC) and decreased soil pH compared to the control. DAP fertilizer increased soil organic matter (OM), whereas SSP fertilizer had a negative impact on OM.

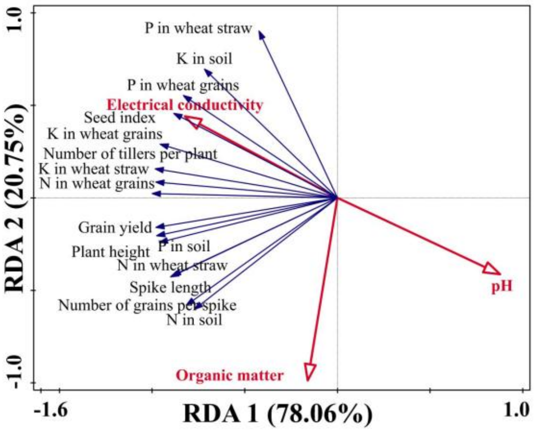

Figure 6. Redundancy analysis among the soil nutrients and morphological traits of wheat varieties after application of phosphatic fertilizers

The concentrations of N, P, and K in soil were enhanced with the application of phosphatic fertilizers. DAP fertilizer was particularly effective in increasing N and P in soil, while SSP fertilizer showed greater potential for enhancing K in soil compared to the control. Phosphatic fertilizers also significantly improved plant height, number of tillers per plant, spike length, number of grains per spike, seed index (1000-grain weight), and grain yield for the TD-1, SKD-1, and TJ-83 varieties compared to the control treatment. Additionally, phosphatic fertilizers increased N, P, and K content in wheat straw and grains. The highest N content in wheat straw was observed in the TJ-83 variety with DAP fertilizer, while the highest P content in wheat straw was noted in the TJ-83 variety with SSP fertilizer. The highest K content in wheat straw was observed in the TJ-83 variety with NP fertilizer. In wheat grains, the highest N accumulation was found in the TJ-83 variety with DAP fertilizer, the highest P accumulation in the TD-1 variety with SSP fertilizer, and the highest K accumulation in the TD-1 variety with DAP fertilizer. For future research, long-term field experiments are recommended to evaluate the consistent effects of these fertilizers on wheat growth and yield. Further studies should also investigate the impact of phosphatic fertilizers co-amended with pristine biochar, modified biochar, nanotechnology, press mud compost, and minerals on wheat growth, yield, and soil health.

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Author's statements

Contributions

Conceptualization: K.H.K., M.N.; Data curation: K.H.K., M.N., A.H.L.; Formal Analysis: E.D., A.H.L.; Funding acquisition: M.M.; Investigation: H.B., Z.A.K.; Methodology: A.H.L.; Project administration: M.M.; Resources: M.M.; Software: A.H.L., A.A.; Supervision: M.M.; Validation: M.A.P.; Visualization: M.K.; Writing – original draft: K.H.K., E.D., A.H.L.; Writing – review & editing: S.S., E.D.

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The authors declare no competing interests.

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