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Impact of Integration between soil application of phosphorus and foliar spraying of nano potassium, iron, and boron on the productivity and quality of peanuts

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A two-year field experiment was carried out to assess the impact of three levels of soil application of phosphorus (untreated control (P0), 55.8 (P1), and 93.0 (P2) kg phosphorus pentoxide (P_2O_5) ha^{-1}) and foliar application of nano-fertilizer treatments (i.e., untreated control; 500 ppm nano potassium (K1); 1000 ppm nano potassium (K2); 50 ppm nano boron (B1); 100 ppm nano boron (B2); 75 ppm nano iron (Fe1); 150 ppm nano iron (Fe2)) on yield and quality parameters of peanuts. The results revealed significant differences among phosphorus fertilizers levels on yield, yield components, and quality parameters of peanuts, wherein the increasing rate of P to 93.0 kg P_2O_5 ha^{-1} (P2) enhanced the number of pods $plants^{-1}$, number of branches $plants^{-1}$, seed index, pod yield, seed yield, protein yield, and oil yield compared to control (P0), during the 2020 and 2021 seasons. Likewise, peanut plants treated with nano boron at 100 ppm (B1) gave the highest number of pods $plants^{-1}$, while application of nano Fe at 75 ppm (Fe1) and 150 (Fe2) gave the highest number of branches $plants^{-1}$. On the other hand, the application of 1000 ppm nano potassium (K2) showed the highest values of seed index and pod, seed, protein, and oil yield. The combinations of P and nano K, B, and Fe fertilization displayed significant increases in the number of pods $plants^{-1}$, number of branches $plants^{-1}$, and seed index. The interaction between P2 and nano B2 recorded the highest number of pods $plants^{-1}$. In addition, the application of P2 with K2 recorded the highest values of seed index and pod and seed yield. Results also indicated that spraying with nano potassium of 1000 ppm (K2) increased the potassium uptake compared to other treatments in both seasons except for spraying with potassium 500 ppm (K1) in the second season. For the combinations, P1-K2, P2-K1, and P2-K2 were the best combined treatments with the highest value for potassium uptake in peanut seeds in both seasons along with P1-K1 and P1-Fe2 in the second season.

Keywords: nanoscale fertilizer; phosphorus fertilizer; peanuts yield

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INTRODUCTION

The third-most significant source of protein and one of the principal sources of cooking oil is the peanut (*Arachis hypogaea* L.), which also contains a significant amount of oil (44 to 56%) and digestible protein (25 to 30%) according to Fageria et al. (1997), Kamara et al. (2011), and Silitonga et al. (2018). In Egypt, peanuts were cultivated on about 58000 acres in the 2021 growing season, producing a total of 90865 tons (FAO, 2021). Their symbiotic fixation of atmospheric nitrogen (N_2) also decreases the usage of synthetic nitrogenous fertilizers, reducing greenhouse gas emissions (Badar et al., 2015). Due to the symbiotic fixation of atmospheric N_2, after peanuts are harvested, the soil's mineral nitrogen content increases (Hossain et al., 2016). Soil fertility is thereby markedly increased, and its biological properties are improved, especially in recently restored low-fertility soils (Liu et al., 2019; Desoky et al., 2021).

Lower crop yields result from a lack of mineral nutrients in recently reclaimed sandy soils (Abd El-Hady et al., 2022). To increase the productivity and quality of leguminous crops in recently reclaimed soils, several techniques are being researched (Abd El-Mageed et al., 2021). Improved feeding techniques, which significantly affected plant growth and production, may have been used to make such an achievement. To maximize the quality and productivity of leguminous crops, the root structure must be modified to boost water intake and make the best use of soil nutrients (Gahoonia and Nielsen, 2004; Abd El-Hady et al., 2022). Among necessary nutrients for crop growth and quality, phosphorus (P) has a pronounced impact on plant root development (Tarafdar, 2013; Jeetarwal et al., 2015; Tammam et al., 2022). Complex legumes require more phosphorus than other crops because it is essential to produce nodules and the fixation of atmospheric nitrogen. P is also one of the major sources of nitrogen input to agricultural soils. Given the significant role that phosphorus plays in the physiological processes of the plant, improving the soil's inadequate fertility with phosphorus boosts the production of peanuts (Mohammadi and Sohrabi, 2012; Badar et al., 2015; Abd El-Hady et al., 2022). It is necessary to maintain biological activities like the symbiotic N_2 fixation of Rhizobium. Both the growth of root hairs and nutrient uptake are prolific (Míguez-Montero et al., 2020). As a result, the implementation of phosphorus enhances root growth, biological processes, physiological abilities, and metabolic processes, which greatly boosts the production of legumes, especially in recently reclaimed soil conditions (Abdel Rahman et al., 2021).

Modern agriculture needs nano-fertilizers because they have the right formulations and delivery systems to provide the best plant uptake and utilization (Fraceto et al., 2016; Adisa et al., 2019; Mittal et al., 2020). Nano-fertilizers improve nutrient usage efficiency and environmental quality by reducing nutrient losses, caused by leaching, and avoid chemical changes. They are based on various metals and metal oxides for agricultural applications (Saharan et al., 2016; Raliya et al., 2017). Compared to bulk particles or ionic salts, nanoscale particles are smaller and have distinct dynamics, both of which offer substantial benefits (Wiesner et al., 2006; Chugh et al., 2021). According to what nano-fertilizers have shown of an increase in production by providing targeted nutrient delivery/gradual release, reduction of fertilizer input, and increase in nutrient usage efficiency, their use may improve plant nutrient delivery efficiency (Kah et al., 2019; Soliman et al., 2024). Roots can more easily absorb nutrients thanks to the physical/chemical reduction in the size of nano-fertilizers, which boosts their surface-mass ratio (Meena et al., 2017; Qureshi et al., 2018). Many plant functions, such as transport, assimilation, tissue storage, protein synthesis, photosynthesis, enzyme activation, and nitrogen fixation, depend on potassium (K) (Yadav et al., 2003; Read et al., 2006). The plant's capacity to develop and produce components of cotton plants (i.e., lint, fruit, and seed yields) is affected by each of these activities (Hawkesford et al., 2012; Preetha and Balakrishnan, 2017; Afify et al., 2019; Rezk et al., 2021). Also, it was discovered that the usage of nano K fertilizers had a substantial impact on growth promotion and enhanced both the seed yield and oil content in peanuts by 91.5% in the seed yield, 120% in the pod yield, and 99.8% in the oil yield/acre compared to control (Afify et al., 2019). It can be shown that potassium has an impact on peanut development and production since potassium fertilizer was added to the soil to increase peanut growth. In soils with low potassium concentrations, peanut plants often respond well to potassium administration (Almeida et al., 2015; Ouda et al., 2018).

Both proper seed germination and high-quality seeds, as well as ground nuts' ability to absorb nitrogen, depend on boron. Moreover, boron encourages root and nodule formation, which helps plants fix nitrogen in their tissues. Borax is involved in the transformation of sugars and starches, cell growth and elongation, and the synthesis of proteins and amino acids (Naiknaware et al., 2015; Genaidy et al., 2020; Rezk et al., 2021). By encouraging the production of roots and nodules, boron helps plants fix nitrogen (Hanumanthappa et al., 2019). Of all important elements, boron affects groundnut growth by preventing flowers from falling, and it also plays a role in the production of lipids and carbs (Susan Poonguzhali et al., 2019; Ramya et al., 2022).

Iron is a crucial metal required for numerous metabolic processes in plants. Although plants only need moderate amounts of iron for development, the lack of iron negatively affects their physiological processes and metabolism as well as their yield (Palmqvist et al., 2017). Well-aerated soils typically have significant iron availability. Iron normally forms insoluble iron complexes in these soils at neutral pH, making them unavailable to plants. Fertilizers with added iron will thereby enhance the amount of iron available to plants. When compared to control and/or synthetic iron sources, investigations have shown that nano Fe fertilizers enhance seed germination and crop growth characteristics (Rezk et al., 2021). In photosynthetic cells, where it is needed for chlorophyll, cytochrome, the creation of Fe-S clusters, and the electron transport chain, about 80% of Fe may be detected (Briat et al., 2007; Hansch and Mendel, 2009; Saudy et al., 2022). Also, according to Varotto et al. (2002)**,** in the cytochrome complex, the ferredoxin molecule, and photosystems PS-I and PS-II, all molecules contain Fe atoms as structural elements. This shows that Fe is directly connected to crop plant photosynthetic activity, which leads to productivity (Briat et al., 2007). To determine how peanuts behave to different concentrations of phosphorus as well as potassium, boron, and iron in nanoform, this field study was conducted.

MATERIALS AND METHODS

Experimental Site Conditions

A field experiment was performed at the Ismailia Experimental Farm, Agricultural Research Center (ARC), Ismailia Governorate, Egypt (30°37′05.0′′N, 32°14′26.8′′E) during the 2020 and 2021 seasons. Prior to planting, the physical and chemical properties of the experimental soil were determined according to Page et al. (1982) and Klute (1986) and are shown in Table 1. The test site is situated in an area with dry, scorching summers and little precipitation. A station near the experimental site gave the monthly minimum and maximum temperatures as well as the relative humidity at 2 meters (%) for the two growing seasons (Table 2). In both seasons, wheat served as the previous crop.

Plant Material

The Giza-6 genotypes, a commercial cultivar in Egypt, was received for this experiment from the Agricultural Research Center in Giza, Egypt. The proper Rhizobium strain was used to vaccinate the seeds (*Rhizobium leguminosarum*) and sown on May 15th and 21st in the 2020 and 2021 seasons, respectively (about 96.0 kg ha^{-1}), with a 20 cm distance between hills, and then sowing irrigation was applied. At 21 days after sowing (DAS), plants were thinned to two plants per hill followed by irrigation. When preparing the seedbed, calcium sulphate was added at a rate of 3.6 tons ha^{-1} all at once. At sowing and 25 and 40 DAS, three equal applications of 75 kg N ha^{-1} of nitrogen fertilizer (in the form of ammonium nitrate, 33.5% N) were made. A trickle irrigation system was used to water the peanut plants. A control head (media and screen filters, pressure gauges, and control valves) for the irrigation system was installed. Both the main line and the submain line were made of PVC pipeline with a diameter of 75.0 mm and a maximum operating pressure of 6.0 bar, respectively. The lateral lines had polyethylene tubes with a diameter of 16 mm, emitter spacing of 20.0 cm, and manufacturing emitter discharge of 4.0 L h^{-1} at an operating pressure of 1.0 bar. The commercial peanut production guidelines were followed for all other agricultural practices, such as weed, disease, and pest control.

Preparation of Nanoparticles

The preparation process was carried out in the Laboratory of the Genetic Engineering Department, Faculty of Agriculture, Ain Shams University, Egypt. It is a destructive method where bulk materials are pressed or crushed down into the nanometer-size range through a mechanical approach of ball milling (Wirunchit et al., 2021). The nitrogen hydroxyapatite nanohybrid contains 10% K_2O (potassium derived from monopotassium phosphate, MKP), with hydroxyapatite comprising 60% and the remaining 30% being other elements. It is a white powder, odorless, and insoluble in water, with an average particle size of 30 × 90 nm and a needle-like structure. Iron oxide nanoparticles exhibit monodispersed particles resembling quasi-spheres, resulting in an odorless, brown powder insoluble in water, with an average particle size of 35 × 75 nm and a needle-like structure. Boron nano-powder is insoluble in cold water, hot water, and diethyl ether, with a particle size of 40 × 80 nm. Finally, the size of the milled particles was determined by transmission electron microscopy (TEM). Figure 1 shows pictures taken using a transmission electron microscope (TEM) of nanoparticle crystals for K, B, and Fe.

Experimental Design and Growth Conditions

The experiment was implemented in a split-plot design with three replicates, where phosphorus fertilizer was applied at three levels: untreated control (P0), 55.8 (P1), and 93.0 (P2) kg phosphorus pentoxide (P_2O_5 ha^{-1}), which occupied the main plots and nano-fertilizer treatments (i.e., untreated control; 500 ppm nano potassium (K1); 1000 ppm nano potassium (K2); 50 ppm nano boron (B1); 100 ppm nano boron (B2); 75 ppm nano iron (Fe1); 150 ppm nano iron (Fe2)) were distributed in the subplots as a foliar application. The used concentrations of nano-macro K and nano-micro B and Fe nutrients were chosen, equivalent to 20% of the conventional fertilizer foliar application. Phosphorus pentoxide (55.8 kg P_2O_5 ha^{-1}) was recommended under fertility soil conditions and the amount was increased by 67% (93.0 kg P_2O_5 ha^{-1}) and without treatment as a control. The overall plot area was 10.5 m^2, consisting of five ridges with 0.6 m width and 3.5 m length. Calcium superphosphate, with a pH of 2.0, comprising 15.5% P_2O_5, 19.5% calcium, and 11.5% sulfur, was used as the P source. To prepare the soil for cultivation, P fertilizer was added. At 50 and 65 DAS, the nano-fertilizer treatments in the form of oxides were sprayed in two equal amounts. A knapsack sprayer was used to apply the spray solutions, and it had one nozzle that used 480 L of water per hectare as a solvent/carrier.

Morphological Traits of Peanut Plants after Treatment

At the maturity stage after 119 DAS on 20 September 2020 and 26 September 2021, ten plants were randomly chosen from each plot to determine the means of number of pods plants^{-1}, number of branches plants^{-1}, and seed index (100-seed weight (g)). Additionally, the yield of pods and seeds (tons ha^{-1}) was calculated by harvesting the entire plot area.

Plant Analysis for Proteins and Oil Contents

According to AOAC (2012), total nitrogen and seed oil content were measured using the modified micro Kjeldahl technique with the Soxhlet apparatus and hexane as the organic solvent. The total nitrogen concentration was multiplied by 6.25 to determine the crude protein content. Then, by multiplying oil%

Table 1. Physicochemical soil parameters of the experimental site in both the 2020 and 2021 seasons and their average.

Parameter	Abbreviation	Season 1	Season 2	Average
Acidity	**pH**	7.35	7.27	7.31±0.1
Salinity (dS m^{-1})	**$EC_{1:2.5}$**	0.41	0.35	0.38±0.02
Soluble cations (meq. L^{-1})				
Sodium	**Na^+**	1.38	1.34	1.36±0.01
Potassium	**K^+**	0.39	0.43	0.41±0.02
Calcium	**Ca^{2+}**	1.47	1.53	1.50±0.04
Magnesium	**Mg^{2+}**	0.86	0.94	0.90±0.01
Soluble anions (meq. L^{-1})				
Chloride	**Cl^-**	0.76	0.84	0.80±0.02
Carbonate	**CO_3^{2-}**	0.00	0.00	0.00±0.00
Bicarbonate	**HCO_3^-**	2.62	2.58	2.60±0.2
Sulfate	**SO_4^{2-}**	0.73	0.81	0.77±0.02
Organic matter %	**OM**	0.86	0.94	0.90±0.03
Some available micronutrients (mg kg $^{-1}$ soil)				
Iron	**Fe**	0.2572	0.2580	0.2576±0.01
Zinc	**Zn**	0.0123	0.0129	0.0126±0.001
Manganese	**Mn**	0.4338	0.4336	0.4337±0.03
Copper	**Cu**	0.6794	0.6806	0.6800±0.03
Boron	**B**	0.25	0.29	0.27±0.01
Some available macronutrients (mg kg $^{-1}$ soil)				
Nitrogen	**N**	8.13	8.19	8.16±0.3
Phosphorous	**P**	4.28	4.76	4.52±0.2
Soil texture				
% Sand	**Loam sandy soil**	86.77	86.83	86.80±0.2
% Silt		1.96	2.04	2.00±0.1
% Clay		11.27	11.13	11.20±0.1

Values are the mean of 3 replicates ± standard error.

Table 2. Climatic data for the study area for both the 2020 and 2021 seasons.

Month	T2M_MIN	T2M_MAX	T2M_RANGE	Rain (mm) day^{-1}	RH2M	Wind speed
The 2020 season						
May	20.80	32.99	12.19	0.00	78.59	2.89
June	22.15	34.24	12.09	0.00	82.90	2.64
July	25.00	36.89	11.89	0.00	84.99	2.13
August	26.26	37.15	10.89	0.00	81.19	1.95
September	26.24	36.34	10.1	0.00	82.36	2.57
The 2021 season						
May	21.31	34.48	13.17	0.00	83.78	3.14
June	22.90	34.61	11.71	0.00	82.86	2.39
July	25.97	38.03	12.06	0.00	82.71	1.82
August	27.17	38.34	11.17	0.00	81.65	2.22
September	25.65	34.86	9.21	0.00	75.16	2.81

Rain = precipitation (mm day^{-1}), Wind = wind speed at 2 meters (m s^{-1}), RH2M = relative humidity at 2 meters (%), T2M_MAX = maximum temperature at 2 meters (°C), T2M_MIN = minimum temperature at 2 meters (°C), and T2M_RANGE = average temperature at 2 meters (°C).

and protein% by seed yield ha^{-1}, oil yields and protein yields were computed according to El-Habbasha et al. (2005).

Uptake of Elements by Peanuts Plant

Phosphorus was measured in the digested solution using a vanado-molybdate color reaction according to the method described by Chapman and Pratt (1978) and Watanabe and Olsen (1965). The flame photometer (Eppendorf, DR Lang) was used to measure potassium in the digested suspension according to Chapman and Pratt (1978). Boron was described colorimetrically using the azomethine-H method described by JrJ (2001). One-gram sample was mixed with 100 mg CaO and dry-ached in a muffle furnace at 450°C for 5 hours. The ash was dissolved by 10 ml H_2SO_4 (1 N) and left overnight. Two ml of the supernatant solution were pipetted into a test tube, and 4 ml buffer solution (prepared by dissolving 250 g acetate ammonium in 500 ml H_2O + 125 ml 99% acetic

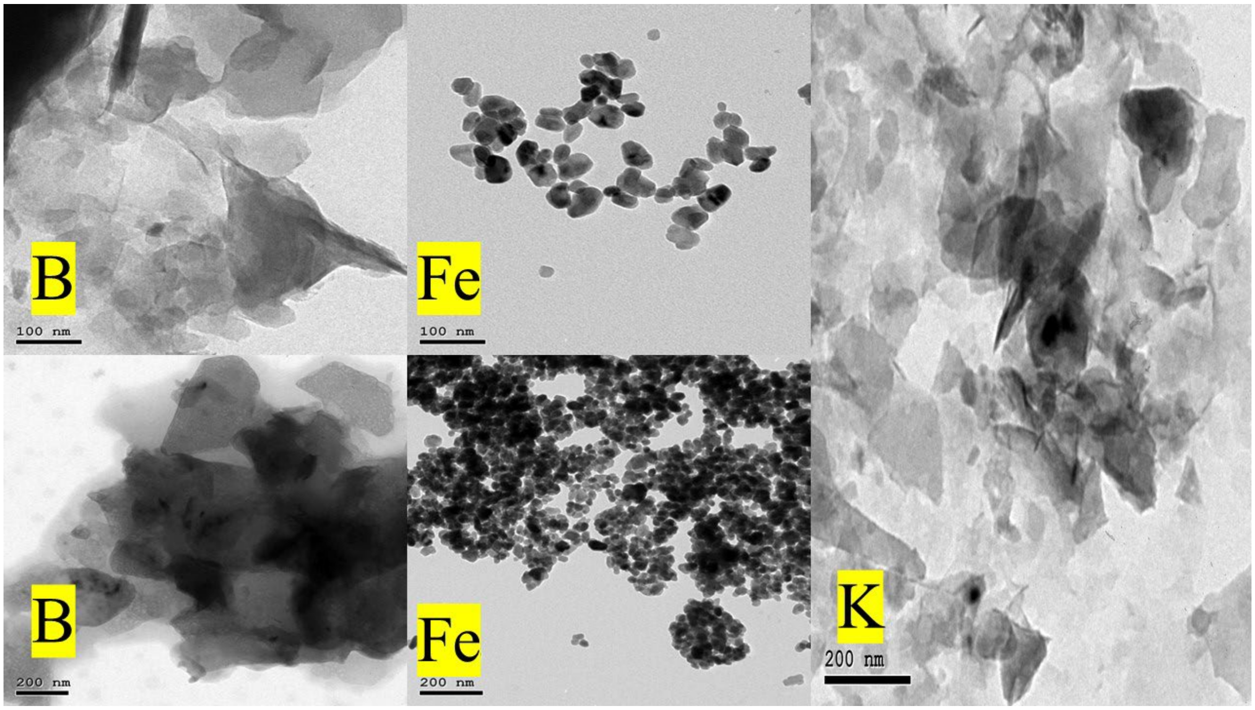


Figure 1. Pictures taken using a transmission electron microscope (TEM) of nano-oxide crystals for K, B, and Fe.

acid + 6.7 g Na_2 EDTA + 6 ml 80 % thioglycolic acid) was added. After shaking, 2 ml azomethine-H reagent (prepared by dissolving 0.9 g azomethine-H (Merck n° 11962) + 2 g ascorbic acid in a minimum amount of water (diluted to 100 ml)) was added. After 2 hours, B was measured at 410 nm using the UVNIS-Spectrophotometer (Perkin-Elmer Lambda 2) apparatus. Fe was extracted by diethylene triamine penta acetic acid (DTPA) solution and measured by Atomic Absorption Spectrometer apparatus JrJ B (2001). The uptake of P, K, B, and Fe (kg ha^{-1}) was calculated by multiplying the seed nutrient content by the seed yield ha^{-1}.

Statistical Analysis

Prior to performing an analysis of variance (ANOVA), the collected data were tested for homogeneity of variances and normality distribution of residuals using Bartlett (1937) and Shapiro and Wilk (1965) tests. ANOVA was carried out using R statistical software version 4.4.1 on data from two seasons. The distinction between treatments was made using Tukey's HSD test ($P \leq 0.05$). A biplot of principal component analysis (PCA) was performed using R software to study the relationship among the studied traits.

RESULTS

Effect of Phosphorus Fertilizers on Yield Components and Pod, Seed, Protein, and Oil Yield of Peanuts

The application of P fertilization had a significant impact on the measured yield traits, significantly increasing the number of pods $plants^{-1}$, number of branches $plants^{-1}$, and seed index (Table 3) and pod, seed, oil, and protein yields (Table 4) during the 2020 and 2021 growing seasons. The increasing rate of P to 93.0 kg P_2O_5 ha^{-1} (P2) enhanced the number of pods $plants^{-1}$ by 45.3% and 47.4%, the number of branches $plants^{-1}$ by 32.2% and 22.6%, and the seed index by 16.9% and 12.6%, compared to those in the P0 control, during the 2020 and 2021 growing seasons, respectively (Table 3).

Treatments with P fertilization significantly affected pod, seed, oil, and protein yields (Table 4) during the 2020 and 2021 growing seasons. The application of 93.0 kg P_2O_5 (P2) exhibited the highest values of pod, seed, oil, and protein yields, compared to control (P0). The P2 treatment enhanced the pod yield by 61.5% and 56.1%, seed yield by 82.1% and 58.0%, protein yield by 82.5% and 68.2%, and oil yield by 125.3% and 85.7% during the 2020 and 2021 growing seasons, respectively. We noticed that these P1 and P2 have no significant difference in pod, seed, and protein yields during the 2020 growing season (Table 4). Tables 3-4 also show an increase in most of the traits of the yield components in the second season compared to the first season. Perhaps the previous result is due to the rise in temperatures in the second season, which led to an increase in the vital processes of the peanut plant, which is reflected in the yield components. As shown in soil analysis (Table 1), there was an increase in K, Ca, Mg, P, N, and organic matter in the second season in comparison to the first season, which led to the development of cell walls, wherein water absorption, xylem permeability, disease resistance, and enzyme activities involved in the production of primary and secondary metabolites, and nitrogen fixation and reduction are just a few of the metabolic processes that micronutrients play a role in for plant growth (Adhikary et al., 2018), and this is reflected in high yield compared with the yield of the first season.

Effect of Nanoparticles on Yield Components and Pod, Seed, Protein, and Oil Yield of Peanuts

Likewise, peanut plants treated with nano K, B, or Fe fertilization outperformed unfertilized plants (control), whereas the application of nano boron at 100 ppm (B1) gave the highest value of the number of pods plants^{-1} outperforming the control by 121.9% and 114.2% during the 2020 and 2021 growing seasons, respectively. Meanwhile, the application of nano Fe at 150 (Fe2) and 75 ppm (Fe1) gave the highest value of the number of branches plants^{-1} outperforming the control by 22.7% and 19.5% during the 2020 growing season and by 16.0% and 11.1% during the 2021 growing season, respectively (Table 3). On the other hand, the application of 1000 ppm nano potassium (K2) achieved the highest value of seed index outperforming the control by 31.5% during the 2020 growing season, while during the 2021 growing season, the application of 1000 ppm nano potassium (K2) and 500 ppm nano potassium (K1) achieved the highest value of seed index outperforming the control by 26.0% and 24.1%, respectively. All pod, seed, protein, and oil yields responded significantly to the nano-fertilizer form of the applied nutrient compared with the untreated control. In this situation, the use of 1000 ppm potassium (K2) surpassed the untreated control by 46.7% and 32.1% for pod yield, 54.4% and 39.0% for seed yield, 70.1% and 75.2% for protein yield, and 81.9% and 56.3% for oil yield during the 2020 and 2021 growing seasons, respectively. Also, results in Table 4 revealed that, except for oil yield during the 2020 growing season, there was an insignificant difference between 1000 ppm potassium (K2) and 500 ppm potassium (K1) for pod, seed, protein, and oil yields during the 2020 and 2021 growing seasons (Table 4).

Evaluation of the Effect of Interaction between Phosphorus Fertilizers and Nanoparticles on Yield Components and Pod, Seed, Protein, and Oil Yield of Peanuts

The combinations of P and nano K, B, and Fe fertilization displayed significant effects on the number of pods plants^{-1}, number of branches plants^{-1}, and seed index (Table 3). Concerning the interaction between P2 and nano B2, the highest number of pods plants^{-1} was recorded with an increase of 297.8% compared to the untreated control during the 2020 growing season, while the interaction between P1-B2 and P2-B2 resulted in an enhancement in the number of pods plants^{-1} by 277.2% and 273.4% compared to the untreated control during the 2021 growing season. The interaction between P2-Fe2 and P2-Fe1 gave the highest values of the number of branches plants^{-1}, outperforming the control by 67.3% and 60.9% during the 2020 growing season, while the interaction between P2 with nano K, B, and Fe fertilization and P1 with nano Fe surpassed the untreated control in the number of branches plants^{-1} during the 2021 growing season. On the other hand, the application of P2 with K2 recorded the highest values of seed index surpassing the control by 52.1% and 50.6% during the 2020 and 2021 growing seasons, respectively. We noticed that these P1-K2 and P2-K2 have no significant difference during the 2020 growing season**.** The interactions of P2-K2 and P2-K1 exhibited the highest value of pod yield represented by 144.9% and 134.1% and seed yield represented by 181.3% and 176.8% compared to the untreated control during the 2020 growing season. Meanwhile, application of P2-K1, P2-K2, P2-Fe1, P2-Fe2, and P1-K2 achieved the highest values exceeding the control in pod yield by 132.5%, 134.6%, 130.5%, 131.0%, and 126.3%, respectively, and in seed yield by 181.2%, 166.3%, 162.1%, 171.9%, and 161.2%, respectively, during the 2021 growing season. On the other hand, the maximum protein yield was achieved when peanut plants were treated with P2-K1, P2-K2, P1-K1, and P1-K2 outperforming the unfertilized plants (control) by 192.8%, 214.1%, 194.9%, and 189.6% during the 2020 growing season, respectively, while, during the 2021 growing season, the maximum protein yield was achieved when peanut was treated with P2-K1, P2-K2, P1-K1, P1-K2, and P2-Fe2 outperforming the unfertilized plants (control) by 285.6%, 244.3%, 208.1%, 237.2%, and 252.0%, respectively. In this respect, the application of P2 with K2 gave the highest oil yield exceeding the unfertilized plants (control) by 280.4% during the 2020 growing season whilst the maximum protein yield was obtained when peanuts treated with P2-K1 and P2-K2 outweighed the untreated control by 262.9% and 259.7%, respectively, during the 2021 growing season (Table 4).

Effects of Phosphorus and Nano K, B, and Fe Fertilization and Their Interaction on Macronutrient and Micronutrient Uptake of Peanut Seeds

Macronutrient (i.e., P and K) and micronutrient (i.e., B and Fe) uptake of peanut seeds was significantly affected by the main effects of phosphorus and nano K, B, and Fe fertilization and their interaction (Figures 2-5). By increasing the phosphorus fertilizers rate up to 93.0 kg P_2O_5 ha^{-1}, there was an increase in phosphorus uptake in peanut seed in both growing seasons (Figure 2). Spraying of 500 ppm nano K, 1000 ppm nano K, and 75 ppm nano Fe showed higher values of seed phosphorus uptake in both growing seasons, in addition to foliar application with 150 ppm nano Fe in the 2020 season. There was a significant interaction effect of phosphorus and nano K, B, and Fe fertilization on seed phosphorus uptake (Figure 2). In general, spraying 500 ppm nano K (K1) or 1000 ppm nano K (K2) and treating peanut plants with 93.0 kg P_2O_5 ha^{-1} was the most effective interaction treatment for increasing seed phosphorus uptake over two growing seasons. There was an insignificant difference among 1000 ppm potassium (K2), 500 ppm potassium (K1), and 75 ppm iron (Fe1) under 93.0 kg P_2O_5 ha^{-1} in the 2020 season only.

Concerning the peanut seeds, potassium uptake was significantly affected by the main effects of phosphorus and nano K, B, and Fe fertilization and their interaction (Figure 3). Thus, peanuts treated with phosphorus fertilizer (55.8 (P1) or 93.0 (P2)) exceeded the untreated control (P0) in potassium uptake of peanut seeds over two growing seasons. On the other hand, spraying with nano potassium at 1000 ppm (K2) increased the potassium uptake compared to other treatments in both seasons except for spraying with potassium 500 ppm (K1) in the second season. For the combinations, P1-K2, P2-K1, and P2-K2 were the best combined treatments with the highest value for potassium uptake in peanut seeds in both seasons along with P1-K1 and P1-Fe2 in the second season.

All treatments, phosphorus and nano K, B, and Fe fertilization, and their interaction showed increases in B uptake greater than the untreated control treatment (Figure 4). Application of phosphorus at rates of 55.8 kg P_2O_5 ha^{-1} (P1) and 93.0 kg P_2O_5 ha^{-1} (P2) increases boron uptake in seeds compared to the untreated control. Spraying of 1000 ppm nano potassium (K2) showed a higher value of boron uptake in seeds in the 2020 and 2021 seasons. Besides, spraying of 500 ppm nano potassium (K1) or 100 ppm nano boron (B2) achieved a higher value of boron uptake in seeds in the 2021 season only. As for the interaction, both foliar applications of 500 ppm nano potassium (K1) and 1000 ppm nano potassium (K2) with 93.0 kg P_2O_5 ha^{-1} (P2) treatment achieved the highest values of boron uptake in both the 2020 and 2021 seasons, and there was no significant difference between these treatments and spraying of 1000 ppm nano potassium with 55.8 kg P_2O_5 ha^{-1} (P1).

Iron uptake (Fe uptake) was significantly changed for phosphorus and nano K, B, and Fe fertilization and their interaction (Figure 5). The increasing rate of P to 93.0 kg P_2O_5 ha^{-1} (P2) enhanced Fe uptake compared to those in the P0 control. On the other hand, spraying of 500 ppm nano potassium (K1), 1000 ppm nano potassium (K2), or 150 ppm nano Fe (Fe2) in both seasons and 75 ppm nano Fe (Fe1) in the second season achieved the highest value of Fe uptake. Likewise, treatments of P2-K1, P2-Fe1, and P2-Fe2 in both seasons and P1-K1, P1-K2, and P1-Fe1 in the second season and P2-K2 in the first season enhanced Fe uptake compared to the other treatments.

Effect of Different Treatments on Peanut Traits Using Multivariate Data Analysis (PCA).

The principal component analysis was used to investigate the relationship between the evaluated treatments and the studied traits (Figures 6-7). The first two PCs explained 91.76% and 91.86% of the variability in both seasons. PC1 displayed 86% and 84.5% of the variation and was associated with the combinations of P and nano K, B, and Fe fertilization (Figures 6-7). PC1 classified P and nano K, B, and Fe fertilization into two categories: fertilization with phosphorus alone (P0, P1, and P2) with control and nano K, B, or Fe fertilization, alone (K1, K2, B1, B2, Fe1, or Fe2). For plants not treated with phosphorus, the results were on the negative side, while the combinations between P and nano K, B, and Fe fertilization (P1-K1, P2-K1, P1-K2, P2-K2, P1-B1, P2-B1, P1-B2, P2-B2, P1-Fe1, P2- Fe1, P1-Fe2, and P2-Fe2) were on the positive side in the two growing seasons. PC2 exhibited 5.76% and 7.36% variation in both seasons and seems to correspond with P and

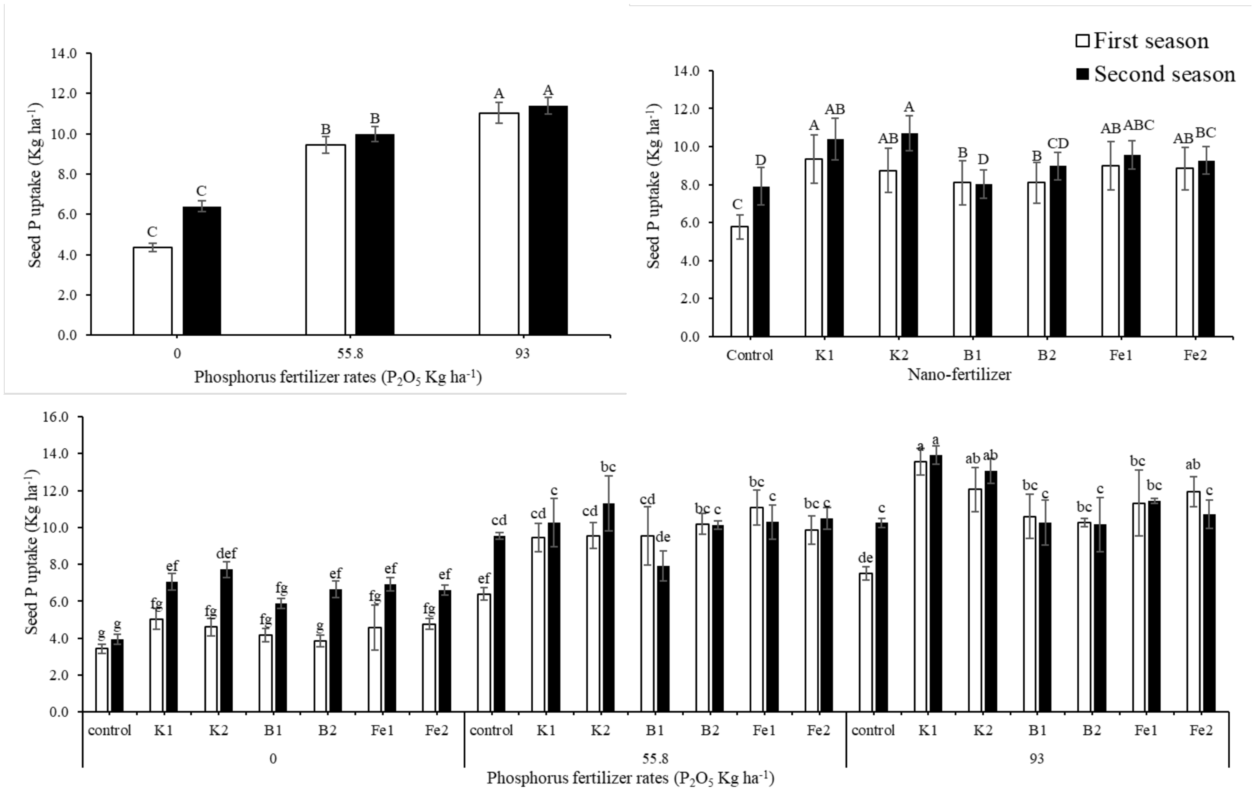


Figure 2. Effect of phosphorus and nano-fertilizer treatments of potassium, boron, and iron on seeds phosphorus uptake of peanut. Control = untreated, K1= 500 ppm, K2= 1000 ppm, B1= 50 ppm, B2= 100 ppm, Fe1= 75 ppm, and Fe2= 150 ppm.

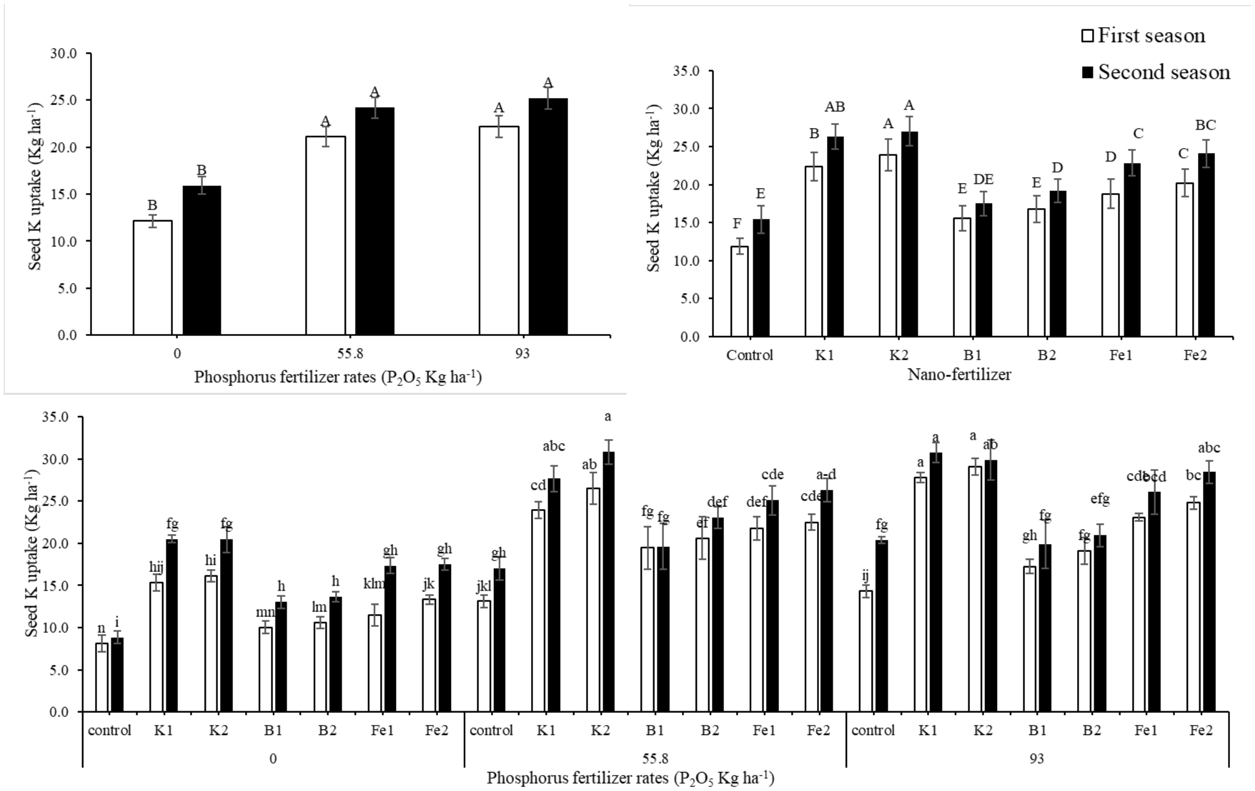


Figure 3. Effect of phosphorus and nano-fertilizer treatments of potassium, boron, and iron on seeds potassium uptake of peanut. Control = untreated, K1= 500 ppm, K2= 1000 ppm, B1= 50 ppm, B2= 100 ppm, Fe1= 75 ppm, and Fe2= 150 ppm

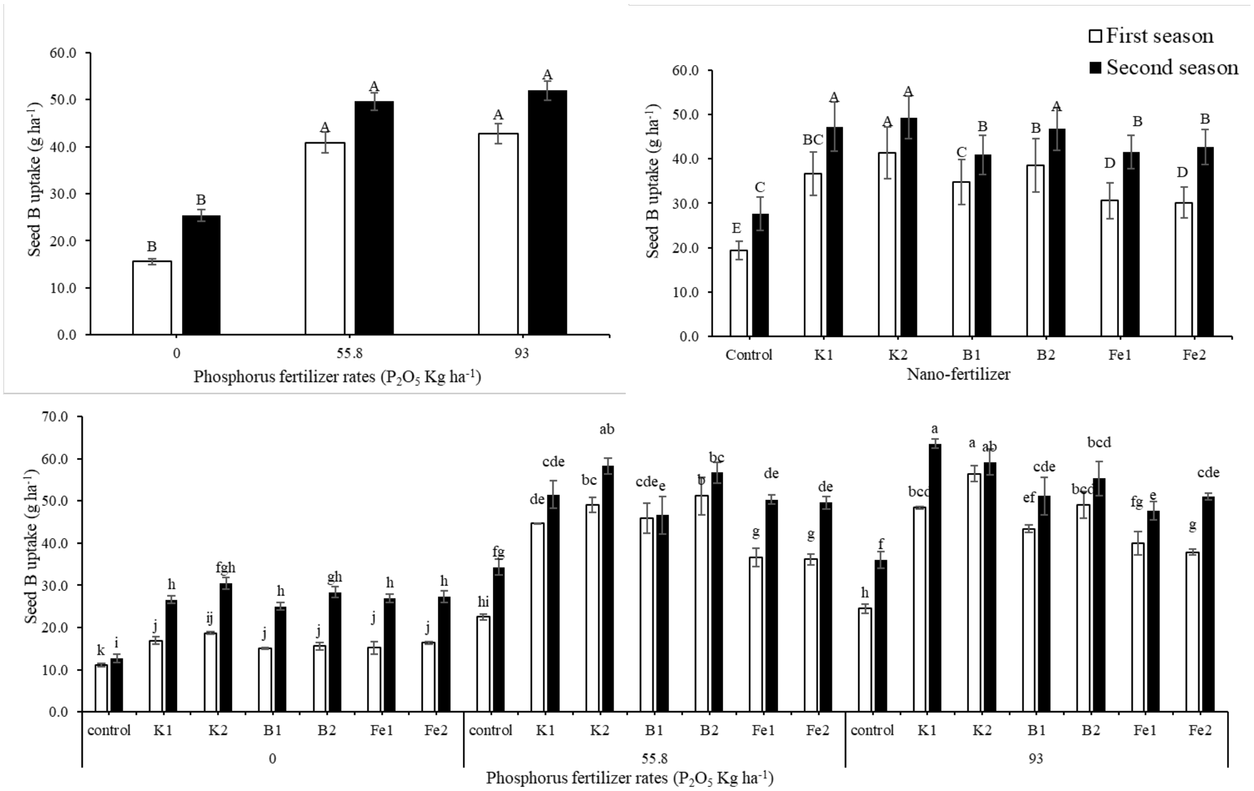


Figure 4. Effect of phosphorus and nano-fertilizer treatments of potassium, boron, and iron on seeds boron uptake of peanut. Control = untreated, K1= 500 ppm, K2= 1000 ppm, B1= 50 ppm, B2= 100 ppm, Fe1= 75 ppm**,** and Fe2= 150 ppm.

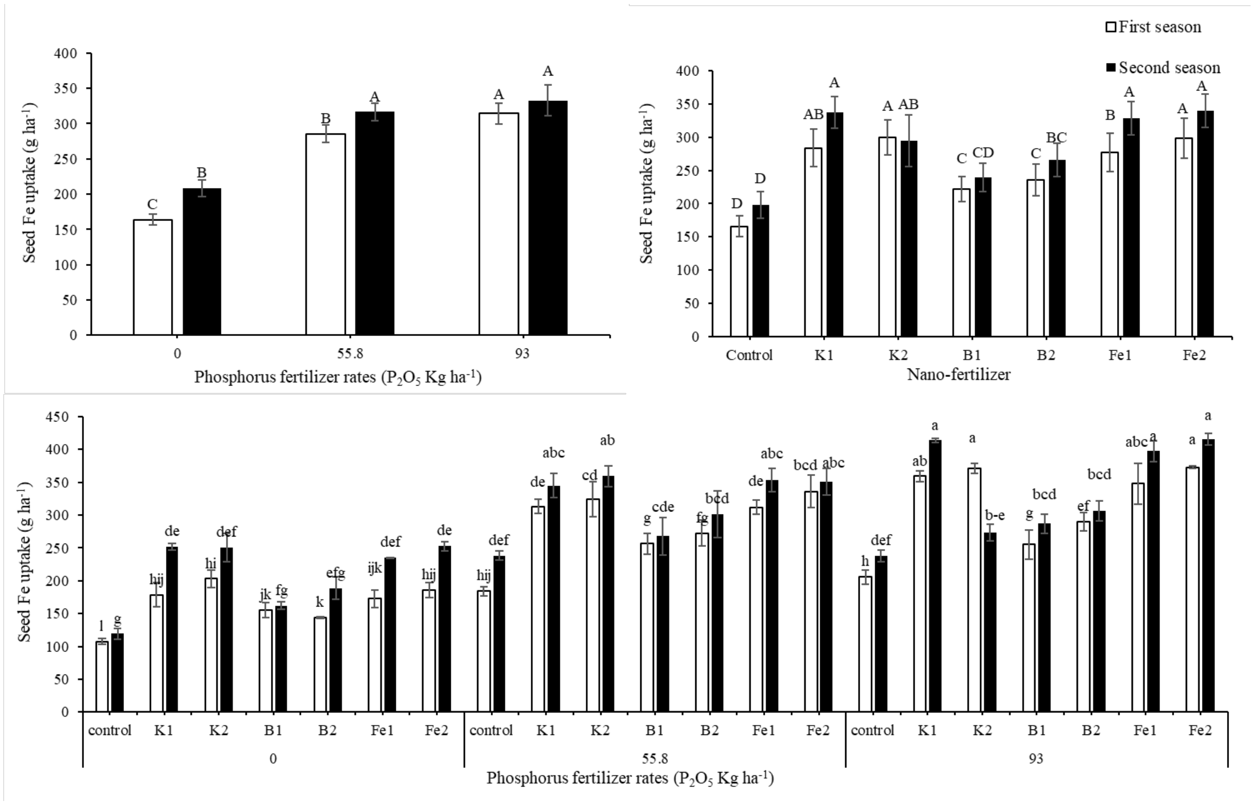
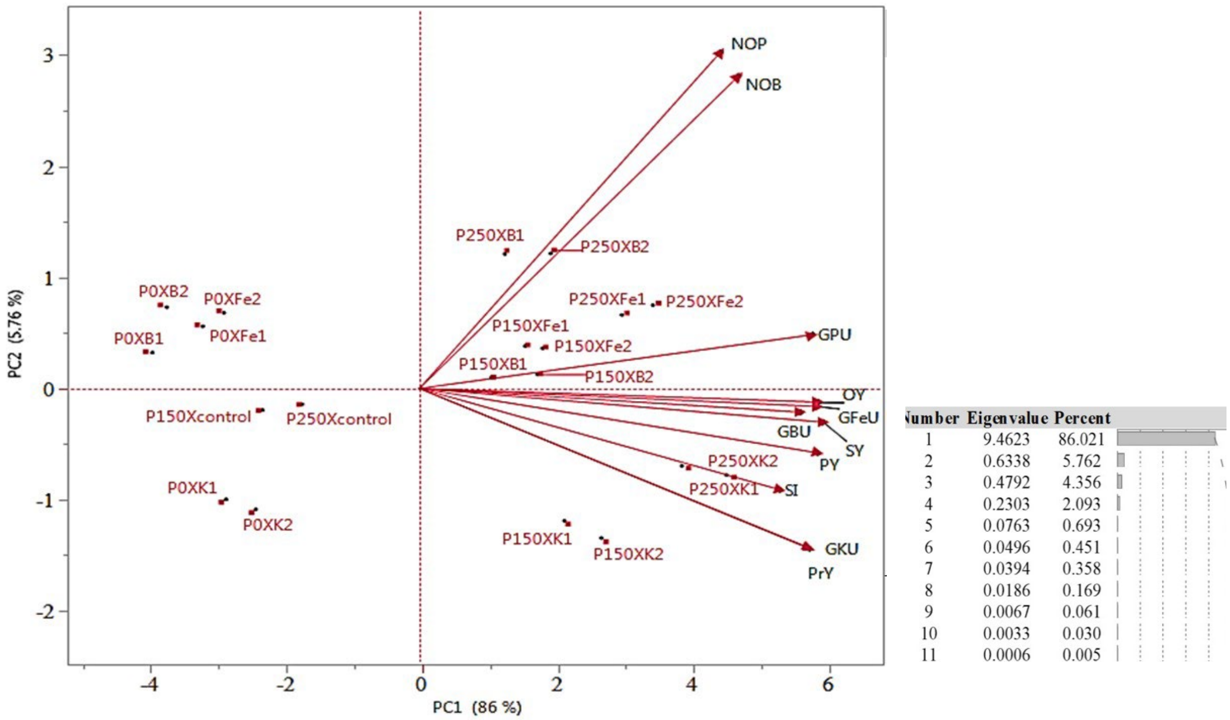
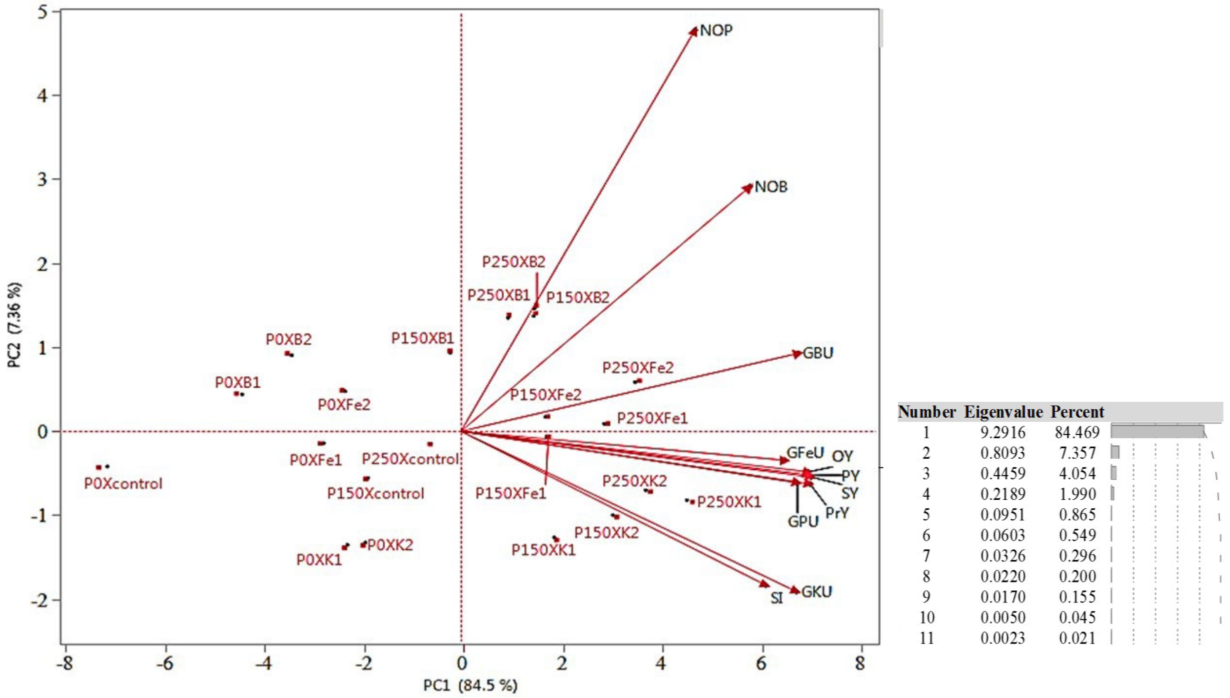


Figure 5. Effect of phosphorus and nano-fertilizer treatments of potassium, boron, and iron on seeds iron uptake of peanut. Control = untreated, K1= 500 ppm, K2= 1000 ppm, B1= 50 ppm, B2= 100 ppm, Fe1= 75 ppm**,** and Fe2= 150 ppm.



Number	Eigenvalue	Percent
1	9.4623	86.021
2	0.6338	5.762
3	0.4792	4.356
4	0.2303	2.093
5	0.0763	0.693
6	0.0496	0.451
7	0.0394	0.358
8	0.0186	0.169
9	0.0067	0.061
10	0.0033	0.030
11	0.0006	0.005

Figure 6. PC biplot for the studied traits of peanut under P and nano K, B, and Fe fertilization, in the first growing season. P0= untreated, P1=55.8 P_2O_5, P2=93 P_2O_5, NOP= number of pods plants^{-1}, NOB= number of branches plants^{-1}, GPU = grain phosphorus uptake, OY= oil yield (Kg ha^{-1}), GFeU = grain ferric uptake, GBU=grain boron uptake, SY=seed yield (Kg ha^{-1}), PY=pods yield (Kg ha^{-1}), SI=seed index (g), GKU=grain potassium uptake, and PrY=protein yield (Kg ha^{-1}).



Number	Eigenvalue	Percent
1	9.2916	84.469
2	0.8093	7.357
3	0.4459	4.054
4	0.2189	1.990
5	0.0951	0.865
6	0.0603	0.549
7	0.0326	0.296
8	0.0220	0.200
9	0.0170	0.155
10	0.0050	0.045
11	0.0023	0.021

Figure 7. PC biplot for the studied traits of peanut under P and nano K, B, and Fe fertilization, in the second growing season. P0= untreated, P1= 55.8 P_2O_5, P2= 93 P_2O_5, NOP= number of pods plants^{-1}, NOB= number of branches plants^{-1}, GPU = grain phosphorus uptake, OY= oil yield (Kg ha^{-1}), GFeU = grain ferric uptake, GBU=grain boron uptake, SY=seed yield (Kg ha^{-1}), PY=pods yield (Kg ha^{-1}), SI=seed index(g), GKU=grain potassium uptake, and PrY=protein yield (Kg ha^{-1}).

Table 3. Effect of phosphorus and nano-fertilizer treatments of potassium, boron, and iron on yield components of peanut.

Treatments		Number of pods plants^{-1}		Number of branches plants^{-1}		Seed index (g)	
		1st season	2nd season	1st season	2nd season	1st season	2nd season
P_2O_5 kg ha^{-1}							
Zero (P0)		21.04±1.16 C	22.34±1.36 C	3.70±0.13 C	5.76±0.13 C	67.00±1.49 C	68.67±1.35 C
55.8 (P1)		25.58±1.03 B	28.63±1.39 B	4.60±0.13 B	6.73±0.12 B	74.76±1.57 B	74.90±1.37 B
93.0 (P2)		30.57±1.35 A	32.94±1.22 A	4.89±0.13 A	7.06±0.09 A	78.29±1.29 A	77.30±1.35 A
Nano-fertilizer							
Control		14.13±1.21 G	17.01±1.79 F	4.06±0.22 B	6.12±0.23 D	61.78±2.49 F	64.27±2.05 C
K1 (500 ppm)		24.48±1.37 F	25.56±1.60 E	4.09±0.29 B	6.2±0.25 D	78.22±1.69 B	79.78±1.80 A
K2 (1000 ppm)		25.71±1.48 E	26.54±1.59 DE	4.14±0.22 B	6.38±0.28 CD	81.22±2.19 A	81.00±2.29 A
B1 (50 ppm)		29.96±1.49 B	32.67±1.50 B	4.22±0.29 B	6.42±0.3 CD	72.78±1.61 DE	72.67±1.19 B
B2 (100 ppm)		31.36±1.77 A	36.62±1.59 A	4.41±0.2 B	6.59±0.24 BC	71.22±2.23 E	71.89±1.34 B
Fe1 (75 ppm)		26.88±1.37 D	27.38±1.73 D	4.85±0.23 A	6.8±0.18 AB	74.78±1.67 C	73.61±1.47 B
Fe2 (150 ppm)		27.61±1.17 C	30.01±1.65 C	4.98±0.23 A	7.1±0.21 A	73.44±1.98 CD	72.17±1.57 B
Interaction							
P0	**Control**	9.47±0.35 n	10.57±0.50 j	3.3±0.15 g	5.37±0.19 f	52.67±0.67 m	57.33±2.19 h
	K1	19.63±0.57 k	20.23±0.57 hi	3.33±0.12 g	5.37±0.19 f	72.00±0.58 ghi	74.00±2.08 cd
	K2	20.87±0.18 j	20.83±0.41 h	3.37±0.10 g	5.40±0.10 f	73.67±2.33 fgh	74.67±1.86 cd
	B1	25.47±0.24 g	27.80±0.46 f	3.44±0.49 g	5.40±0.10 f	67.33±0.67 kl	68.67±1.2 efg
	B2	25.73±0.55 g	30.53±1.37 de	3.89±0.3 fg	5.87±0.30 ef	65.00±1.15 kl	67.67±1.45 fg
	Fe1	22.20±0.46 i	21.2±0.76 h	4.27±0.4 ef	6.30±0.17 cde	70.67±0.88 hij	69.67±1.86 ef
	Fe2	23.93±0.55 h	25.2±1.01 g	4.28±0.17 ef	6.63±0.38 bcd	67.67±0.88 jkl	68.67±3.38 efg
P1	**Control**	15.47±0.29 m	18.33±0.47 i	4.46±0.29 def	6.17±0.17 de	64.00±1.15 l	66.33±0.88 g
	K1	24.87±0.35 gh	25.3±0.61 g	4.30±0.53 ef	6.30±0.12 cde	80.67±1.20 cd	81.67±1.76 b
	K2	25.27±0.47 g	27.4±0.53 f	4.34±0.23 def	6.77±0.39 bcd	84.67±2.91 ab	82.00±4.36 b
	B1	28.93±0.35 e	32.53±1.46 d	4.43±0.44 def	6.83±0.44 bc	73.33±1.45 gh	74.00±1.53 cd
	B2	30.67±1.01 d	39.87±0.70 a	4.54±0.30 c-f	6.87±0.30 bc	72.67±4.48 ghi	73.33±2.33 cd
	Fe1	26.83±0.37 f	28.27±1.27 f	4.98±0.29 a-d	7.00±0.29 ab	74.33±2.33 fgh	75.17±2.33 cd
	Fe2	27.03±0.29 f	28.73±0.84 ef	5.14±0.33 abc	7.17±0.33 ab	73.67±2.19 fgh	71.83±1.86 de
P2	**Control**	17.47±0.07 l	22.13±1.76 h	4.43±0.17 def	6.83±0.17 bc	68.67±2.19 ijk	69.13±2.6 efg
	K1	28.93±0.7 e	31.13±0.64 d	4.63±0.54 cde	6.93±0.23 ab	82.00±1.73 bc	83.67±2.33 ab
	K2	31.00±0.40 cd	31.4±1.25 d	4.72±0.20 b-e	6.97±0.2 ab	85.33±0.88 a	86.33±2.40 a
	B1	35.47±0.74 b	37.67±0.68 bc	4.77±0.26 b-e	7.03±0.26 ab	77.67±1.20 def	75.33±0.88 c
	B2	37.67±0.47 a	39.47±0.53 ab	4.81±0.32 b-e	7.03±0.32 ab	76.00±2.52 efg	74.67±0.33 cd
	Fe1	31.6±0.40 cd	32.67±0.47 d	5.31±0.31 ab	7.10±0.31 ab	79.33±2.91 cd	76.00±2.31 c
	Fe2	31.87±0.13 c	36.1±0.40 c	5.52±0.29 a	7.50±0.29 a	79.00±3.06 cde	76.00±1.15 c

nano K, B, and Fe fertilization. All agronomic traits (i.e., number of pods plants^{-1}, number of branches plants^{-1}, seed index, pod, seed, oil, and protein yields, and nutrient uptake) were positively correlated with P and nano K, B, and Fe fertilization, on the positive side of PC1 in both seasons, which is consistent with the obtained results in Tables 3-4 and Figures 2-5**.** Thereupon, the PCA biplot emphasizes the foregoing displayed results (Figures 6-7). The agronomic traits were positively intercorrelated; the seed yield presented strong associations with all agronomic traits. Furthermore, the long and short arrows indicate the strengths and weaknesses of the correlation between the evaluated traits and studied coefficients.

Table 4. Effect of phosphorus and nano-fertilizer treatments of potassium, boron, and iron on yields of peanut.

Treatments		Pods yield (kg ha⁻¹)		Seed yield (kg ha⁻¹)		Protein yield (kg ha⁻¹)		Oil yield (kg ha⁻¹)	
		1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
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DISCUSSION

Newly reclaimed sandy soils are plagued by environmental stresses such as nutrient shortage (Abd El-Hady et al., 2022). So, it is essential to search for environmentally friendly techniques to stimulate growth and productivity in these challenging circumstances (Desoky et al., 2021). The current investigation was conducted in a low-fertility sandy soil with extremely low concentrations of macronutrients like phosphate and potassium and micronutrients like boron and iron. In the newly sandy soil, the recommended P rate was 55.8 kg P_2O_5 ha^{-1}, with control (0 kg P_2O_5 ha^{-1}) and higher (93.0 kg P_2O_5 ha^{-1}) treatment rates also used. Roots can regulate water and nutrient uptake while also providing anchoring and mechanical support. P is necessary for the growth and development of roots (Singh and Singh, 2016; Du et al., 2021) and participates in metabolic processes, cell division, the production of nuclei, nodulation, N_2 fixation, and the use of starch (Singh et al., 2005; Singh and Singh, 2016). P, especially the highest amount (P2), considerably enhanced all yield components (i.e., number of pods $plants^{-1}$, seed index, and pod and seed yields) and ensured that macro- (N, P, and K) and micronutrient (Fe, B) uptake was more absorbed in peanuts plant (Wang et al., 2016; Su et al., 2022). The number of active nodules, nitrogen activity, and dry weight of active nodules were all increased by phosphorus fertilization, which also enhanced N fixation and N absorption efficiency. Fertilization with phosphorus enhanced the root characteristics of plants, such as basal root length, total surface area, total root tips, total root forks, total dry weight, and root dry weight **(**Ramtekey et al., 2021; Abd El-Hady et al., 2022). Similarly, improvements in active nodule and dry weight stimulate increases in effective N fixation and N uptake in plants, according to Jindal et al. (2008) and Rashid et al. (2010). In addition, Mohamed et al. (2021) and Abd El-Hady et al. (2022) demonstrated that increasing the P level increased root dry weight and macronutrient uptake. Such an increase affected yield and yield components, as well as increasing the nutrient content of the seeds.

Nanotechnology has a wide range of current uses, and nanoparticles are frequently used in agriculture. According to reports, nanoparticles are typically used to increase agricultural yield through the use of nano-fertilizers that effectively employ their nutrients (Tarafdar et al., 2013; Ditta et al., 2015; Panpatte et al., 2016; Rizwan et al., 2017). Several research studies revealed that the application of nano-fertilizers significantly increases crop yield over control or without the application of a nano-fertilizer. It is mainly because increasing the growth of plant parts and metabolic processes such as photosynthesis leads to higher photosynthetic accumulation and translocation to the economic parts of the plant. Foliar application of nanoparticles as a fertilizer significantly increases the yield of the crop (Tarafdar et al., 2012). As for nutritional value, nano-fertilizers provide more surface area and more availability of nutrients to the crop plant which helps to increase these quality parameters of the plant (such as protein, oil, and sugar content) by enhancing the rate of reaction or synthesis process in the plant system. The application of zinc and iron on the plant increases the total carbohydrate, starch, IAA, chlorophyll, and protein content in the grain (Rajaie and Ziaeyan, 2009). Nano Fe_2O_3 (nFe_2O_3) increases photosynthesis and growth of the peanut plant (Liu et al., 2005).

Application of nano K, B, and Fe fertilizer treatments could successfully meet the nutritional needs of crop plants because nutrients in the form of nanoparticles have a small size, a high sorption capacity, and a diffusible nature with rapid and perfect absorption/uptake by plants. As a result, peanut yield and its components were improved by nano K, B, and Fe fertilizer treatments and seeds' macronutrient uptake. Although potassium is not present in any compounds or plant structures, it does play a crucial regulatory role in plants. It is necessary for almost all aspects of plant development and reproduction. Potassium is necessary for many biological processes, including protein synthesis, ionic equilibrium maintenance, control of plant stomata and water consumption, activation of plant enzymes, and photosynthesis. It is known to activate at least sixty enzymes involved in plant development (Zhou and Huang, 2007). Potassium deficiencies make plants more vulnerable to extreme high and low temperatures, drought, and excess water. Moreover, they are more vulnerable to worm, disease, and pest infestations (Zhou and Huang, 2007). According to Benzon et al. (2015), the use of nanomaterials boosted N, P, and K uptake, which in turn increased biomass production. The development of cell walls, respiration, water absorption, xylem permeability, disease resistance, enzyme activities involved in the production of primary and secondary metabolites, and nitrogen fixation and reduction are just a few of the metabolic processes that micronutrients play a role in for plant growth (Adhikary et al., 2018). Moreover, plants with micronutrient deficits produce lesser yields and, in extreme circumstances, die (Adhikary et al., 2018). The use of an iron fertilizer remains a successful strategy for treating plants' iron deficiencies. An iron fertilizer application is still an effective method for alleviating iron deficiency in plants. However, conventional fertilizers including inorganic-Fe fertilizers, chelated-Fe fertilizers, and organic-Fe fertilizers are frequently useless or unprofitable when used in soil amendment and foliar applications (Cesco et al., 2000; Lucena et al., 2010). The limitation of inorganic Fe fertilization applied to Fe-deficient soil is noticeably much more visible as a result of the rapid reduction of ferrous iron into ferric forms that are unavailable to plants and the reduced mobility of Fe in the phloem (Fageria et al., 2009; Wei et al., 2012). To address problems with conventional iron supplementation methodology and to improve the nutritional value of harvested food, nanotechnology-based approaches for agrochemical delivery systems are being studied as a novel form of iron administration. Iron oxide nanoparticles (nFe_2O_3) are typically used in nanomaterial applications because of their improved surface-to-volume ratio, superparamagnetic properties, and inherent biocompatibility (Cheng et al., 2015, 2016; Perez et al., 2002; He et al., 2011). nFe_2O_3 has been shown to have both beneficial and harmful effects on plants in a number of investigations. For instance, it has been shown that nFe_2O_3 can physiologically improve seed germination, root growth, and chlorophyll content in plants cultivated in soil culture, mung bean grown in silica sediment, and watermelon planted on quartz sand (Li et al., 2013; Alidoust and Isoda, 2013, 2014; Rui et al., 2016). Hu et al.'s (2017a, b) research also demonstrated that nFe_2O_3 had no detrimental effects on *Citrus maxima* development and was effective in reducing nutrient loss, probably as a result of its strong adsorption capacity and slow Fe release when applied topically. On the other hand, Li et al. (2016) found that nFe_2O_3 significantly reduced the root length of maize cultivated hydroponically and caused oxidative stress in the roots at concentrations greater than 50 mg/L. Optimal seed germination and seed quality, as well as the ability of peanuts to absorb nitrogen, all depend on boron. Moreover, boron encourages the formation of roots and nodules, helping plants to fix nitrogen in their tissues. Boron deficiency in peanut seeds causes a "sacred heart," which affects the quality and yield of peanuts (Naiknaware et al., 2015). The transformation of sugars and starches, cell growth and elongation, and the creation of proteins and amino acids involve the element borax (Naiknaware et al., 2015). Poor seed quality and production result from boron deficiency in groundnut plants and soil. Nano boron sources can be used to treat boron deficiency (Hanumanthappa et al., 2019).

CONCLUSIONS

Conventional forms of phosphorus fertilization and foliar spraying with nano potassium, iron, and boron are essential for improving peanut productivity and quality. In addition, increasing the rate of P to 93.0 kg P_2O_5 ha^{-1} (P2) of soil application caused enhancement in agronomic treats. In addition, peanut plants treated with nano boron (B1), nano Fe (Fe1 and Fe2), and nano potassium (K2) achieved high peanut productivity and quality. The combinations of phosphorus (soil application) and nano K, B, and Fe fertilization (foliar application) were essential for improving peanut productivity and quality. Subsequently, it is recommended to apply conventional forms of phosphorus fertilization (93.0 kg P_2O_5 ha^{-1}) and foliar spraying with nano potassium, iron, and boron to peanut plants at the aforementioned rates to enhance plant growth, yield, and quality and improve agricultural and environmental sustainability under newly reclaimed low-fertility soil.

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