Environment, Biodiversity & Soil Security

http://jenvbs.journals.ekb.eg/

Synergistic Effect of Biochar and Nano P-Fertilizers on Soil Nutrient Availability, Productivity, and Quality of Common Bean Plant (*Phaseolus vulgaris* L.)

Sara A. El-Shabasy[1*], Tarek M. El-Zehery[2] and Amr M. Abdelghany[3]

[1] *Soil Chemistry and Physics Research Department, Soil, Water and Environment Research Institute of Agriculture Research Center, Giza, 12619, Egypt.*

[2] *Soils Department, Faculty of Agriculture, Mansoura University, Mansoura, Egypt*

[3] *Spectroscopy Department, Physics Division, National Research Center, 33 El-Behouth St., Dokki, 12311, Cairo, Egypt*

THIS study investigated the effects of biochar and Nano-phosphorus (Nano-superphosphate), applied individually and in combination, on the biomass production, yield, nutrient uptake of common bean (*Phaseolus vulgaris* L.) and soil fertility over two consecutive growing seasons (2022–2023). The experiment followed a randomized complete block design (RCBD) with eight treatments, T_1: 100 % Superphosphate (control); T_2: 100 % Superphosphate + biochar; T_3: 75 % super phosphate; T_4: 75 % superphosphate + biochar; T_5: 50 % Nano-superphosphate; T_6: 50 % Nano-superphosphate + biochar; T_7: 25 % Nano-superphosphate; T_8: 25 % Nano super phosphate + biochar. Results showed that all measured parameters, fresh and dry weight, seed and straw weight, and nutrient uptake significantly improved ($p \leq 0.01$) with increasing treatment intensity from T_3 to T_6. The most notable enhancements were observed under T_6, which outperformed the full dose of conventional superphosphate (T_1), indicating that partial substitution of mineral phosphorus with Nano-phosphorus, when combined with biochar, can enhance crop productivity while reducing fertilizer use. The addition of biochar consistently increased biomass by approximately 30% and seed yield by 18–22%, and it significantly improved soil nutrient availability. Seed nitrogen uptake more than doubled from T_3 to T_6, while seed protein content rose from approximately 19.3% to 24.5%. Similar significant increases were observed in phosphorus and potassium concentrations and uptake. Soil analysis revealed that available nitrogen (N), phosphorus (P), and potassium (K) increased by up to 29%, 57%, and 121%, respectively, under T_6 compared to the lowest treatment (T_3). These results highlight the synergistic effect of biochar and Nano-superphosphate in enhancing nutrient availability, plant nutrient uptake, and yield components in common bean, especially under high-pH soil conditions. The use of 50% Nano-superphosphate combined with biochar is proposed as an economically and environmentally sustainable strategy to reduce phosphorus input without compromising crop performance. Notably, even a 25% Nano-superphosphate substitution achieved results comparable to 100% superphosphate, underscoring the potential to reduce fertilizer inputs without sacrificing yield or quality. Future research should investigate the long-term impacts of these amendments on soil microbial communities and physical properties, particularly in alkaline soils prevalent in Egyptian agriculture.

Keywords: Biochar, Common bean (*Phaseolus vulgaris* L.), Nano Superphosphate, Nutrient uptake, Soil fertility.

1. Introduction

Phosphorus (P) plays a fundamental role in plant physiology, being an essential element in numerous biological molecules, and critical metabolic functions such as photosynthesis, respiration, and energy transfer (**Bhat et al., 2024**). However, in agricultural systems, the availability of phosphorus is frequently limited, particularly in calcareous and alkaline soils, which are predominant in arid and semi-arid regions (**Khan et al., 2023**). In these soil types, phosphorus readily reacts with calcium to form sparingly soluble compounds, including tri-calcium phosphate ($Ca_3(PO_4)_2$), which significantly reduces its bioavailability to plants (**El naqma et al., 2024**). As a result, a substantial proportion of phosphorus applied through conventional fertilizers becomes immobilized in the soil matrix, leaving only a small fraction accessible for plant uptake (**Jahan et al., 2025**). This issue is particularly pronounced in Egyptian soils, which commonly exhibit high pH values promote calcium-phosphate precipitation (**Farid et al., 2023**). The inefficient utilization of phosphorus fertilizers presents

*Corresponding author e-mail: el.shabasy.sara@gmail.com
Received: 18/8/2025; Accepted: 8/10/2025
DOI: 10.21608/JENVBS.2025.412361.1271

a dual challenge: it impairs crop productivity and contributes to environmental degradation (**Ramos Cabrera, et al. 2024**). Studies indicate that plants typically absorb only 10–25% of the applied phosphorus, with the remainder either fixed in the soil or lost through surface runoff, which may contribute to eutrophication in aquatic ecosystems (**Jiang et al., 2021**). This inefficiency has become increasingly problematic in light of growing food demands and the projected depletion of phosphate rock reserves, which are the primary raw material for phosphorus fertilizer production (**Jupp et al., 2021**).

Legumes like common bean (*Phaseolus vulgaris* L.), are especially sensitive to phosphorus deficiency due to their high nutrient requirements during early growth stages (**Shohag et al., 2024**). In Egypt, common bean represents a staple legume crop valued for its high protein content and nutritional benefits. However, achieving optimal growth and yield under phosphorus-limiting conditions remains a challenge, particularly in soils prone to nutrient fixation and poor nutrient mobility (**Aslani & Souri, 2018; Okasha and Khalifa 2020**). Given these challenges, recent advances in agricultural technology, such as nano-phosphorus fertilizers and biochar, have garnered attention as potential solutions. Nanotechnology has introduced nano-phosphorus fertilizers as a potential solution to improve phosphorus use efficiency (**Poudel et al., 2023**). These nano-scale fertilizers are engineered to possess high surface area and reactivity, allowing for controlled nutrient release and enhanced uptake by plant roots (**Bayoumi et al., 2022; Taha, and Omar 2024**). Their application has been associated with improved nutrient delivery, reduced leaching, and increased crop resilience to abiotic stress, including drought and disease (**Abdalla et al., 2022; Ansari 2023**). Preliminary investigations suggest that nano-phosphorus fertilizers can contribute to improved growth, yield, and quality in several crops, although further research is needed to confirm these effects under varying soil conditions and crop systems (**Wali et al., 2020; Ibrahim, 2022**).

In parallel, biochar has emerged as a promising soil amendment derived from the pyrolysis of organic biomass under limited oxygen conditions (**Amalina et al., 2022, Elbagory et al., 2024**). It is characterized by a high carbon content, porous structure, and considerable cation exchange capacity (CEC), which enable it to enhance soil physical and chemical properties (**Abdelhafez et al., 2024**). Biochar application has been reported to improve nutrient retention, increase soil fertility, and promote plant growth across various agroecosystems (**Nepal et al., 2023, Kheir et al., 2023**). Moreover, it has the potential to reduce nutrient losses through leaching and mitigate greenhouse gas emissions by stabilizing organic carbon in the soil (**Luo et al., 2025; Meier et al., 2025**). The integration of nano-phosphorus fertilizers with biochar represents a novel strategy for optimizing nutrient dynamics in the soil–plant system. Biochar may serve as a carrier for nano-nutrients, enhancing their stability and retention in the root zone while mitigating the risks of fixation and leaching (**Li et al., 2018**). This combination is particularly promising for improving phosphorus availability in alkaline clay soils, where conventional fertilizers exhibit low efficiency (**Solangi et al., 2023; Meier et al., 2025**). Furthermore, the use of biochar derived from agricultural residues aligns with sustainable farming practices and circular economy principles, offering an environmentally sound approach to waste valorization and soil fertility management (**Luo et al., 2025**).

Despite the individual benefits of nano-fertilizers and biochar, limited empirical data exist regarding their combined application in legume cultivation under Egyptian soil conditions. Understanding their interactive effects on soil nutrient dynamics, crop performance, and seed quality is crucial for the development of sustainable nutrient management strategies. The present investigation was undertaken to assess the combined effects of nano-phosphorus fertilizers and biochar application on soil fertility and crop yield. Additionally, the study will examine the chemical composition of seeds and straw of *Phaseolus vulgaris* L. grown in clay soil under Egyptian conditions.

2. Materials and Methods

2.1. Experimental location and soil sampling

This study was conducted during two consecutive winter seasons (2022 and 2023) at the Experimental Farm of the Faculty of Agriculture, Mansoura University, Egypt (31°22'59.88" N, 31°05'31.38" E). Common bean (*Phaseolus vulgaris* L. cv. Giza 6) was cultivated under controlled pot conditions. Before planting, a composite soil sample was collected from the 0–25 cm depth layer of the experimental field. Initial soil properties are presented in Table 1. Analyses were performed following standard procedures outlined by **Sparks et al. (2020) and Dane and Topp (2020)**. Soil pH was determined in a 1:2.5 soil-to-water suspension, while electrical conductivity (EC) was measured in a saturated soil paste extract. Particle size distribution was determined using the hydrometer method described by **Gee and Bauder (1986)**. Available nitrogen (N), phosphorus (P), and potassium (K) were assessed according to the method of **Haynes (2008)**. The soil was evenly packed into plastic pots (23 cm height × 27 cm diameter), each containing 8 kg of clay soil. All pots were irrigated to maintain 100% field capacity (FC), adjusted every two days throughout the experimental period.

TABLE 1. Some physical and chemical properties of clay soils before adding studied soil conditioners and cultivation of plants

Seasons	pH	EC dS m^{-1}	Soluble cations meq L-1				Soluble anions, meq L^{-1}			
			Na^+	K^+	Ca^{2+}	Mg^{2+}	CO_3^{-2}	HCO_3^-	Cl^-	SO_4^{-2}
2022	8.16	2.92	1.38	0.13	0.87	0.54	0.00	0.40	1.34	1.18
2023	8.21	2.87	1.33	0.14	0.85	0.55	0.00	0.42	1.25	1.20

	Particle size distribution %				Soil texture	OM.%	Available nutrients mg.kg^{-1}		
	C. sand	F. sand	Silt	Clay			N	P	K
2022	3.50	15.05	36.00	45.45	Clayey	1.3	22.56	7.54	200.9
2023	3.62	15.28	36.55	44.55	Clayey	1.4	23.50	7.15	349.36

* pH in 1:2.5 suspension; EC and soluble cations and anions in paste extract

2.2. Seed Inoculation and Soil Amendments

Seeds of common bean were inoculated with Rhizobium spp., obtained from the Soil, Water and Environment Research Institute (ARC, Giza, Egypt). The inoculum was mixed with seeds using a honey solution just before sowing. Biochar, sourced commercially from the Mansoura district and some properties are showed in Table 2. It was applied at a rate of 48 g/pot (equivalent to 0.6% w/w or 16,800 kg/ha) as mentioned in **Elbagory et al., 2024** and mixed thoroughly into the soil before sowing.

TABLE 2. Some characteristics of biochar

pH	EC dS.m^{-1}	Total nutrients % N	P	K	OC %	OM %	CEC %	C:N Ratio
11.14	4.90	2.2	0.86	2.1	44	35.4	45.00	20:1

* pH and EC in 1:10 suspension

2.3. Preparation of Nano-Superphosphate Fertilizer

Nano-scale superphosphate fertilizer was prepared using a mechanical grinding process that reduces particle size to the nanometer range. Milling of the powdered sample was carried out using a Retsch High-Performance Ball Mill Emax (manufactured by Retsch GmbH, Germany) at the Spectroscopy Department, National Research Center, Cairo, Egypt. The process involved placing the superphosphate fertilizer into the milling chamber along with zirconium oxide balls of varying sizes. The milling parameters were set to a rotational speed of 1500 rpm, with a total milling duration of 4 hours. A ball-to-powder mass ratio of 1:1 was maintained. During the milling process, the impact and shearing forces generated between the zirconium balls and fertilizer particles progressively reduced the particle size. To minimize agglomeration and ensure a uniform particle size distribution, periodic stops were employed to prevent overheating.

Fig. 1 (a) reveal that the Fourier Transform Infrared (FTIR) spectroscopy is crucial for characterizing nano superphosphate fertilizers, as it reveals their chemical structure, phosphate bonding, and crystallinity. The spectrum provided shows a sharp, intense peak at 1400 cm^{-1}, corresponding to P=O stretching in phosphate (PO_4^{3-}) or hydrogen phosphate (HPO_4^{2-}) groups, confirming the presence of key fertilizer components. The broad peak at 1000 cm^{-1} represents P–O stretching, suggesting polymeric phosphate chains, while the shoulders at 1200 cm^{-1} (asymmetric P–O–P) and 965 cm^{-1} (symmetric P–O–P) indicate condensed phosphate structures. The sharp peak at 872 cm^{-1} likely arises from P–O–H bending or metal-phosphate (M–O–P) interactions, such as calcium-bound phosphates, which influence solubility and nutrient release. Additionally, the low-frequency peaks (711, 460, and 363 cm^{-1}) correspond to lattice vibrations and metal-oxygen (M–O) bending, confirming the nano-crystalline nature of the material. The decrease in peak intensities with increasing dopant content suggests structural modifications, which FTIR helps monitor for optimizing fertilizer efficiency. Overall, this technique is indispensable for verifying phosphate speciation, polymerization, and crystallinity, ensuring the fertilizer's controlled-release properties and agricultural effectiveness. (**Karpukhina et al. 2019 and Abdelghany et al., 2014**).

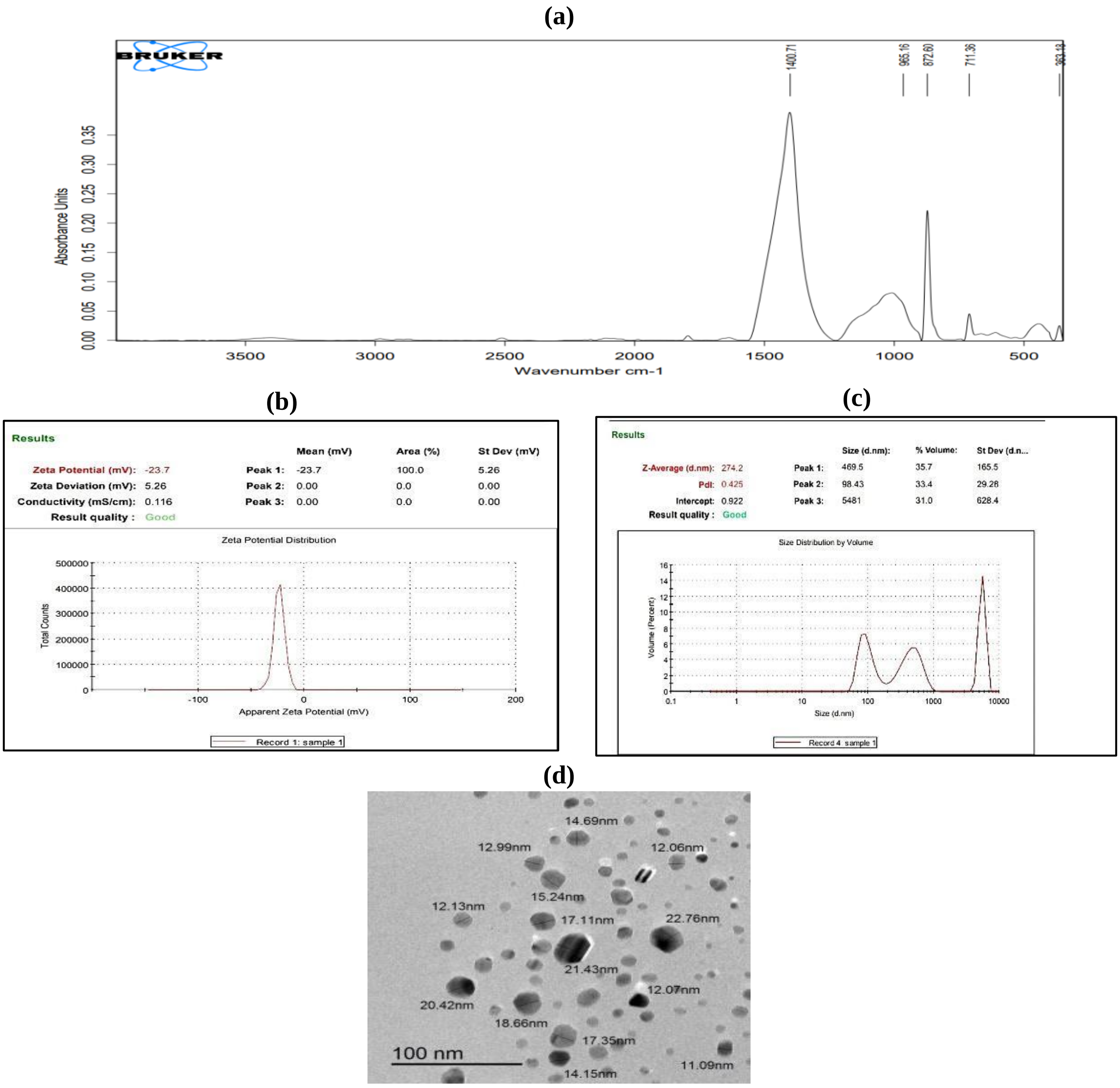

Figure 1. Some characterizes of Nano-Superphosphate. (a): FTIR Analysis, (b) Zeta Potential, (c) Zeta Size analyses and (d) The Transmission Electron Microscopy (TEM)

Fig. 1 (b, c, d) reveal the Zeta Potential, Zeta Size analyses and Transmission Electron Microscopy (TEM), provide comprehensive insights into the physicochemical properties and stability of nano-phosphate fertilizer particles. TEM imaging reveals distorted spherical nanoparticles with sizes ranging from 11 to 23 nm, indicating successful nano-formulation but with some irregularity in morphology, likely due to synthesis conditions or surface interactions. The zeta potential of -23.7 mV, represented by a single sharp peak, suggests moderate colloidal stability driven by negative surface charges from phosphate (PO_4^{3-}) or hydroxyl (OH^-) groups. While this negative charge provides some electrostatic repulsion to prevent aggregation, its magnitude is below the threshold (±30 mV) typically required for long-term stability, making the particles prone to gradual agglomeration.

This is corroborated by the tri-modal particle size distribution from dynamic light scattering (DLS), showing peaks at 98.43 nm (small aggregates), 468.5 nm (larger clusters), and 5481 nm (micrometer-sized flocs) , which starkly contrast with the primary particle sizes observed in TEM. The discrepancy arises because DLS measures the hydrodynamic diameter of particles in suspension, including any agglomerates or adsorbed solvent layers, whereas TEM provides the actual dry particle size. The observed aggregation can be attributed to weak electrostatic stabilization (-23.7 mV) , high surface energy of nanoparticles , and environmental factors like ionic strength or pH fluctuations that screen surface charges and promote particle-particle interactions. The presence of micron-sized aggregates (5481 nm) further suggests sedimentation or bridging flocculation, possibly due to organic matter or polyvalent ions in the suspension. These findings highlight the need for surface modification strategies, such as polymer coatings or optimized pH control, to enhance dispersion stability and ensure uniform nutrient delivery. Understanding these properties is critical for formulating effective nano-fertilizers with controlled release kinetics and minimal aggregation during storage and application (**Abdelghany, et al., 2021 and Farea et al., 2020)**.

2.4. Experimental Design and Treatments

The experiment was arranged in a randomized complete block design (RCBD) with three replicates. Eight treatments were established to evaluate the effects of superphosphate, nano-superphosphate, and biochar, alone and in combination, as follows:

- T_1: 100 % Superphosphate (control)
- T_2: 100 % Superphosphate + biochar
- T_3: 75 % Superphosphate
- T_4: 75 % Superphosphate + biochar
- T_5: 50 % Nano-superphosphate
- T_6: 50 % Nano-superphosphate + biochar
- T_7: 25 % Nano-superphosphate
- T_8: 25 % Nano-superphosphate + biochar

Sowing was carried out on October 3rd in both seasons. Three seeds were planted per pot (three holes), and thinned to two plants at the seedling stage. All pots received the recommended dose of phosphorus fertilizers were applied before sowing at the following rates: superphosphate: 480 kg/ha (100%) or 360 kg/ha (75%) and Nano-superphosphate: 240 kg/ha (50%) or 120 kg/ha (25%). Nitrogen (40 kg N/ ha) as calcium nitrate (15.5% NO_3^-) and potassium (120 kg K/ha) as potassium sulfate (48% K_2O), split into two equal doses after planting.

2.5. Data Collection and Measurements

Soil Sampling

After harvest, soil samples were collected from each pot to determine available N, P, and K content using the method of **Haynes (2008)**.

Plant Sampling and Measurements

At 120 days after sowing, three plants were randomly sampled per pot. The following measurements were taken: plant fresh weight (g/pot), plant dry weight (g/pot), seed dry weight (g/pot) and straw dry weight (g/pot).

Nutrient content in plant tissue:

Plant samples were oven-dried at 70°C, ground, and digested using a 1:1 mixture of perchloric and sulfuric acids (**Peterburgski, 1968**). Nitrogen: Kjeldahl method, phosphorus: Spectrophotometry, and potassium: Flame photometry (**Walinga et al., 2013**). Nutrient uptake (mg/pot) was calculated using:

$$NPK\ uptake\ (mg/pot) = \frac{\%\ N, P, or\ K \times Dry\ matter\ (g/pot)}{100} \times 1000$$

Crude protein content (%) was estimated using:

Crude Protein (%) = N% × 5.7 (**AOAC, 2006**)

2.6. Statistical Analyses

The data were analyzed using analysis of variance (ANOVA) based on a randomized complete block design (RCBD). Treatment means were compared using Duncan's Multiple Range Test (DMRT) at a 5% significance level (**Gomez and Gomez, 1984**). All statistical analyses were performed using the CoStat V 6.303 (1998-2004 CoHort Software) software package.

3. Results

3.1. Biomass and yield

All measured parameters, including fresh weight, dry weight, seed weight, and straw weight, showed significant increases across treatment levels from T_3 to T_6 in both 2022 and 2023 ($p \leq 0.01$), indicating a consistent improvement with higher treatment intensities (Figures 2 and 3). Biochar addition had a strong positive effect on plant development. Compared to treatments without biochar, those with biochar exhibited consistent gains: fresh weight increased by about 31% in both years, dry weight rose by approximately 31% in 2022 and 30% in 2023, seed dry weight increased by 22.2% in 2022 and 18.6% in 2023 and straw dry weight rose by over 32% across both years. These outcomes underline biochar's role in enhancing vegetative and reproductive growth. Applying Nano-superphosphate at 50% of the standard phosphorus dose (T_5) led to improved biomass and yield over the full dose of conventional superphosphate (T_1): fresh and dry weights rose by 8–9%, seed and straw weights also increased of about 8–10%. However, 25% of Nano-superphosphate (T_7) did not yield significant improvements, suggesting this level was insufficient to match traditional fertilization efficacy.

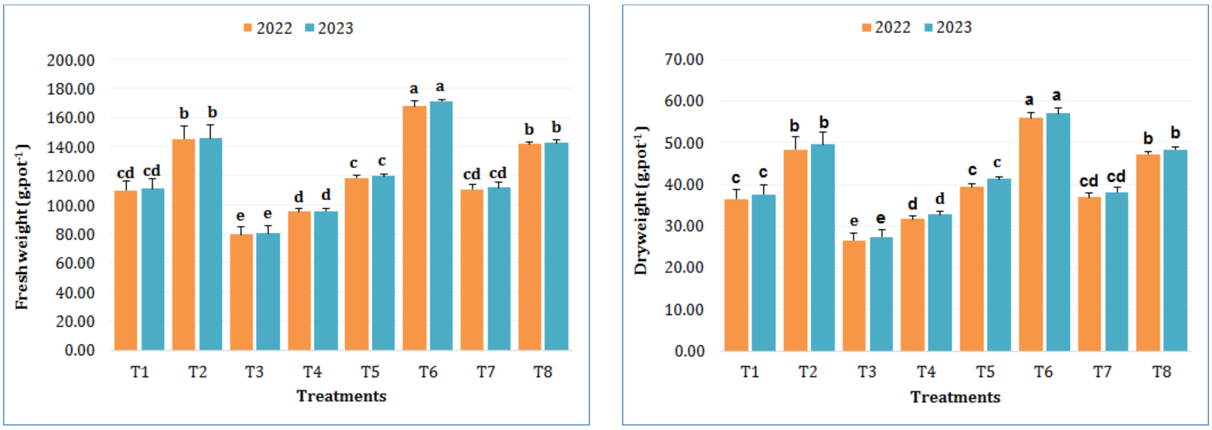

Figure 2. Effect of biochar and phosphorus fertilizer on fresh weight of common Bean (*Phaseolus vulgaris* L.). T_1: 100 % Super phosphate (control); T_2: 100 % Super phosphate + biochar; T_3: 75 % super phosphate; T_4: 75 % super phosphate + biochar; T_5: 50 % Nano super phosphate; T_6: 50 % Nano super phosphate + biochar; T_7: 25 % Nano super phosphate; T_8: 25 % Nano super phosphate + biochar

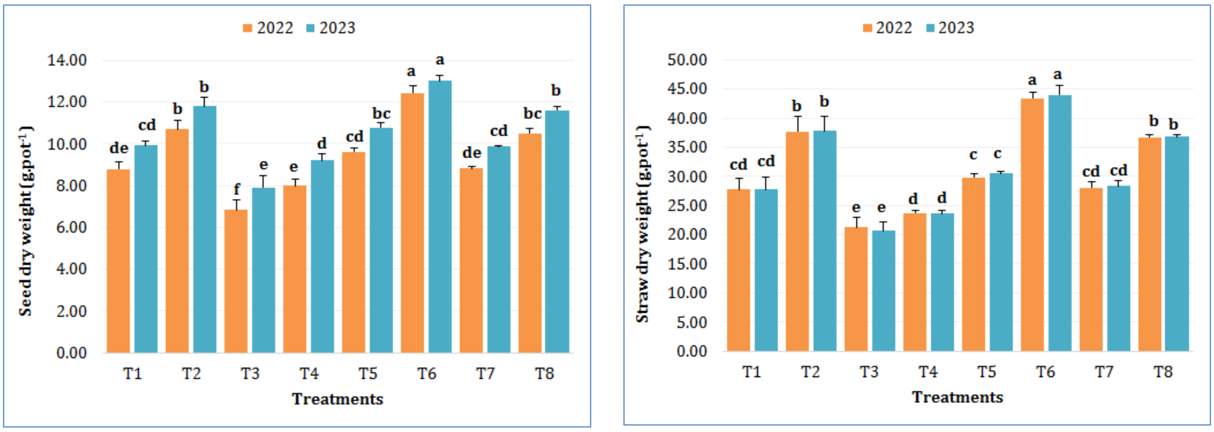

Figure 3. Effect of biochar and phosphorus fertilizer on yield of common Bean (*Phaseolus vulgaris* L.). T_1: 100 % Super phosphate (control); T_2: 100 % Super phosphate + biochar; T_3: 75 % super phosphate; T_4: 75 % super phosphate + biochar; T_5: 50 % Nano super phosphate; T_6: 50 % Nano super phosphate + biochar; T_7: 25 % Nano super phosphate; T_8: 25 % Nano super phosphate + biochar

The interaction between biochar and nano-phosphorus treatments produced a consistent and significant positive effect on biomass and yield. As shown in Figure 2, fresh weight increased from 79.53 g/pot in T_3 to 167.66 g/pot in T_6 in 2022 and from 80.4 to 171.39 g/pot in 2023. Dry weight increased from 26.55 g/pot in T_3 to 55.89 g/pot in T_6 in 2022 and from 27.46 to 57.02 g/pot in 2023. Seed weight rose from 6.84 g/pot in T_3 to 12.43 g/pot in T_6 in 2022, and from 7.91 to 13.00 g/pot in 2023 and straw weight increased from 21.22 g/pot in T3 to 43.45 g/pot in T_6 in 2022, and from 20.68 to 44.02 g/pot in 2023 (Figure 3). These results demonstrate that the combined application of biochar and Nano-superphosphate, particularly at the 50% of Nano-superphosphate substitution level (T_6), significantly enhanced biomass accumulation and yield components compared to individual treatments.

3.2. Nutrient content and uptake of common bean

Regarding the effect of nano phosphorus fertilizer with addition of biochar on nutrient content and uptake of common bean as illustrated in Tables (3-5). It could be noticed biochar application led to marked increases in both nutrient content and uptake in seeds and straw: seed nutrient concentration (N, P, K) improved by 5–11%, seed nutrient uptake: N (28%), P (35%), K (29%), straw nutrient concentration: N (14–15%), P (about 21%), K (8–11%), and straw nutrient uptake: N (52–54%), P (62–63%), K (44–48%) in both season 2022 and 2023, respectively. Using 50% of Nano-superphosphate (T_5) enhanced nutrient accumulation in plants compared to full superphosphate (T_1). The 25% nano-P level (T_7) remained ineffective in improving nutrient status.

TABLE 3. Effect of biochar and phosphorus fertilizer on nitrogen content and uptake in seed and straw of common bean plant

Treatment	N % in seed		N uptake in seed mg/pot		N % in straw		N uptake in straw mg/pot		% protein in seed	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
T1	3.39c	3.52cd	29.88de	34.89d	1.1cd	1.15d	30.67cd	31.81cd	21.19c	22cd
T2	3.53b	3.85ab	37.74b	45.51b	1.31ab	1.33ab	49.39b	50.31b	22.06b	24.06ab
T3	3.08e	3.14e	21.12f	24.85e	0.98e	1e	20.85e	20.71e	19.25e	19.63e
T4	3.23d	3.35d	25.87e	30.86d	1.04d	1.09d	24.77de	25.69d	20.19d	20.94d
T5	3.47bc	3.69bc	33.32cd	39.73c	1.15c	1.23c	34.33c	37.55c	21.69bc	23.06bc
T6	3.7a	3.92a	46.03a	50.93a	1.37a	1.4a	59.55a	61.66a	23.13a	24.5a
T_7	3.37c	3.51cd	29.75de	34.64d	1.12cd	1.15d	31.46cd	32.46cd	21.06c	21.94cd
T_8	3.49bc	3.85ab	36.68bc	44.62b	1.29b	1.34b	47.41b	49.21b	21.81bc	24.06ab
F-test	**	**	**	**	**	**	**	**	**	**
LSD. at 5%	**0.08**	**0.11**	**0.05**	**0.04**	**2.66**	**2.92**	**4.69**	**4.45**	**0.08**	**0.11**

T_1: 100 % Super phosphate (control); T_2: 100 % Super phosphate + biochar; T_3: 75 % super phosphate; T_4: 75 % super phosphate + biochar; T_5: 50 % Nano super phosphate; T_6: 50 % Nano super phosphate + biochar; T_7: 25 % Nano super phosphate; T_8: 25 % Nano super phosphate + biochar

TABLE 4. Effect of biochar and phosphorus fertilizer on phosphorus content and uptake in seed and straw of common bean plant

Treatment	P % in seed		P-uptake in seed mg/pot		P % in straw		P-uptake in straw mg/pot	
	2022	2023	2022	2023	2022	2023	2022	2023
T1	0.703d	0.727c	6.2de	7.21de	0.038b	0.04bc	1.04cd	1.08de
T2	0.793b	0.803ab	8.49b	9.49b	0.044ab	0.045b	1.63b	1.68b
T3	0.637f	0.65e	4.37f	5.15f	0.026e	0.029d	0.56e	0.6f
T4	0.67e	0.68d	5.36e	6.27e	0.035b	0.036c	0.82d	0.85e
T5	0.747c	0.76bc	7.18cd	8.18cd	0.041b	0.042bc	1.22c	1.28cd
T6	0.837a	0.84a	10.41a	10.92a	0.051a	0.056a	2.22a	2.46a
T_3 T7	0.707de	0.717cd	6.23de	7.07e	0.035b	0.037bc	1cd	1.08de
T_4 T8	0.783b	0.793b	8.23bc	9.19bc	0.042b	0.042bc	1.56b	1.58bc
F-test	**	**	**	**	**	**	**	**
LSD. at 5%	**0.021**	**0.027**	**0.01**	**0.01**	**0.64**	**0.65**	**0.18**	**0.23**

T1: 100 % Super phosphate; T2: 100 % Super phosphate + biochar;T3: 75 % super phosphate; T4: 75 % super phosphate + biochar; T5: 50 % Nano super phosphate; T6: 50 % Nano super phosphate + biochar ;T_7: 25 % Nano super phosphate; T_8: 25 % Nano super phosphate + biochar

TABLE 5. Effect of biochar and phosphorus fertilizer on potassium content and uptake in seed and straw of common bean plant

Treatment	K % in seed		K-uptake in seed mg/pot		K % in straw		K-uptake in straw mg/pot	
	2022	2023	2022	2023	2022	2023	2022	2023
T1	1.35bc	1.38bc	11.92d	13.72cd	4.2cd	4.41bc	116.74cd	122.57cd
T2	1.4b	1.47ab	14.97b	17.4b	4.68ab	4.72ab	177.19b	178.83b
T3	1.1d	1.12d	8.42f	9.91e	3.5e	3.75e	74.73e	77.95e
T4	1.26c	1.32c	10.07e	12.21d	3.98d	4.11c	94.49d	97.14d
T5	1.39b	1.44bc	12.88cd	15.54bc	4.37bc	4.55b	130.43c	138.83c
T6	1.48a	1.66a	18.46a	21.53a	4.92a	4.98a	213.97a	219.1a
T_7	1.34bc	1.37bc	11.85de	13.52cd	4.2cd	4.38bc	118.08cd	124.01cd
T_8	1.38b	1.46b	14.5bc	16.88b	4.56b	4.66ab	167.67b	171.53b
F-test	**	**	**	**	**	**	**	**
LSD. at 5%	**0.04**	**0.12**	**0.20**	**0.23**	**1.09**	**1.60**	**17.55**	**19.04**

T_1: 100 % Super phosphate (control); T_2: 100 % Super phosphate + biochar; T_3: 75 % super phosphate; T_4: 75 % super phosphate + biochar; T_5: 50 % Nano super phosphate; T_6: 50 % Nano super phosphate + biochar; T_7: 25 % Nano super phosphate; T_8: 25 % Nano super phosphate + biochar

Table (3) show that the seed N concentration increased by ~20–25% from T3 to T_6, N uptake in seeds more than doubled: 21.12 - 24.85 mg/pot (T3) to 46.03 – 50.93 mg/pot (T_6), straw N concentration increased by about 40% and straw N uptake nearly tripled: 20.8 mg to 60 mg/pot. Seed protein content rose from about 19.3% (T_3) to about 24.5% (T_6). Data also show that T_2 and T_8 performed comparably to T_6. A similar trend was observed for the seed P concentration increased by 31.40–29.23% from T_3 to T_6, N uptake in seeds more than doubled: 4.37 - 5.15 mg/pot (T_3) to 10.41 - 10.92 mg/pot (T_6), straw N concentration increased by 93.67-93.10% and straw N uptake from 0.56 - 0.6mg to 2.22 - 2.46 mg (Table 4). The lowest potassium concentrations were recorded in the T_3, with values of 1.10% in 2022 and 1.12% in 2023. The highest concentrations were observed in T_6 (1.48% and 1.66%, respectively). In 2022, uptake ranged from 8.42 mg/pot (T_3) to 18.46 mg/pot (T6), and in 2023 from 9.91 to 21.53 mg/pot, followed by T_2 and T_8, which also recorded significantly elevated K concentrations compared to most other treatments (Table 5). A similar upward trend was observed for potassium concentrations and uptake in straw. Significant increases were also observed in T_2 and T_8, indicating a positive effect of increasing treatment levels on potassium accumulation in vegetative tissues (Table 5).

3.3. Soil nutrients availability

The application of biochar significantly enhanced plant growth and yield parameters compared to treatments without biochar. Across both seasons, available nitrogen content increased by 9.19% in 2022 and 8.39% in 2023, available potassium increased by 21.13% and 21.35% in 2022 and 2023, respectively and phosphorus availability increased by 19.11% in 2022 and 14.34% in 2023 (Figure 4). Application of Nano-superphosphate at 50% of the recommended phosphorus dose (T_5) significantly improved all measured parameters compared to the full rate of conventional superphosphate (T_1). Increases recorded for T_5 over T_1 were 2.58% (2022) and 1.75% (2023) for available nitrogen content, 7.22% (2022) and 6.99% (2023) for available potassium and 5.19% (2022) and 2.77% (2023) for phosphorus availability (Figure 4). In contrast, the application of 25% of Nano-superphosphate (T_7) did not result in significant differences compared to T1 in any of the measured parameters, indicating that the 25% replacement level was insufficient to match the performance of the full superphosphate dose (Figure 4).

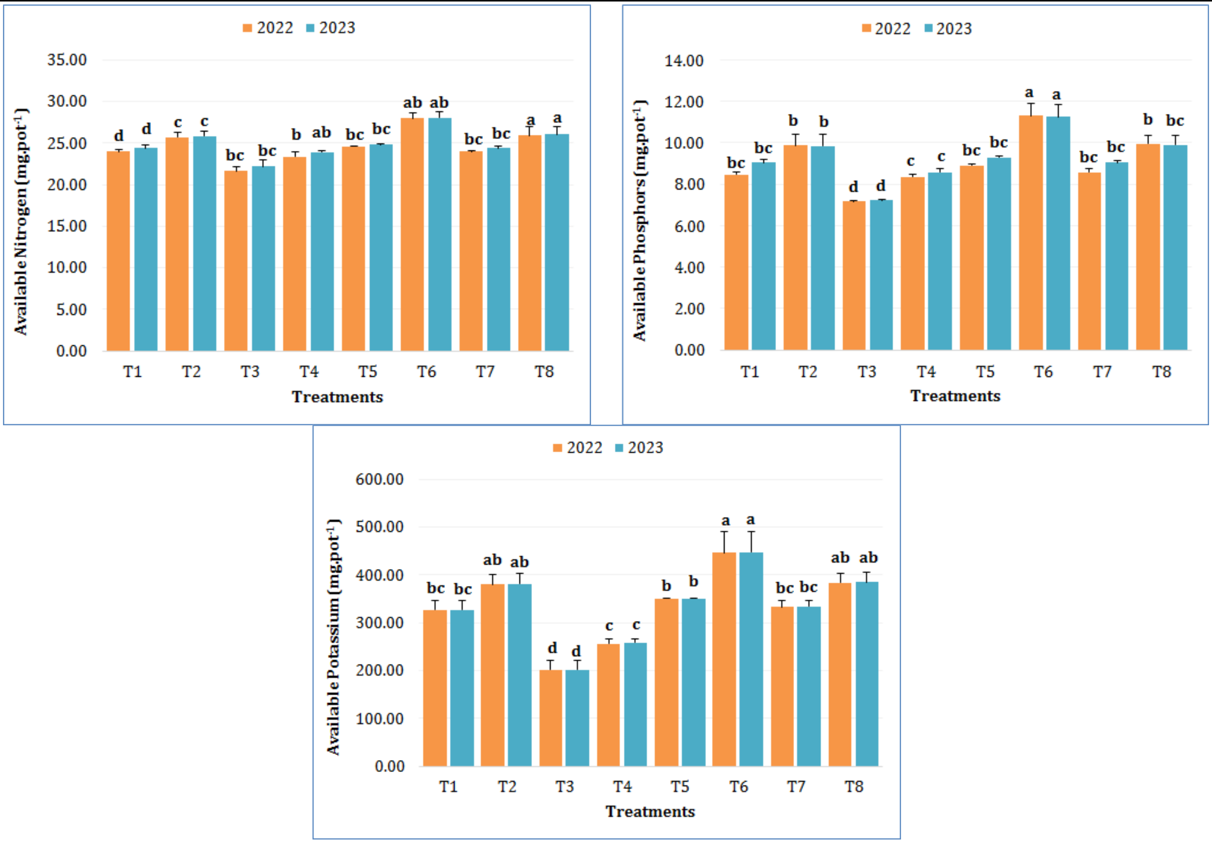

Figure 4. Effect of biochar and phosphorus fertilizer on soil nutrients availability. T_1: 100 % Super phosphate (control); T_2: 100 % Super phosphate + biochar; T_3: 75 % super phosphate; T_4: 75 % super phosphate + biochar; T_5: 50 % Nano super phosphate; T_6: 50 % Nano super phosphate + biochar; T_7: 25 % Nano super phosphate; T_8: 25 % Nano super phosphate + biochar

Available nitrogen content in the soil showed a significant upward trend with increasing treatment levels. In 2022, the lowest nitrogen availability was recorded in T_3 (21.62 mg/kg), whereas the highest value was observed in T_6 (27.96 mg/kg). A similar pattern was seen in 2023, with T_3 at 22.15 mg/kg and T6 at 28.02 mg/kg. That increased by 29.32 and 26.50% in 2022 and 2023. Treatments T_8 through T_5 also exhibited moderate but statistically significant increases compared to the T3 (Figure 4). Available potassium increased markedly with higher treatment levels. In 2022, T_3 had the lowest potassium level (202.1 mg/kg), which steadily increased across treatments, reaching a maximum in T_6 (446.66 mg/kg). This trend persisted in 2023, where T_3 again showed the lowest value (202.09 mg/kg) and T_6 the highest (447.44 mg/kg). That increased by 121.01 and 121.41% in 2022 and 2023. The increases observed from T_7 onwards were statistically significant compared to T_3 (Figure 4). Phosphorus availability also demonstrated a clear increasing trend across treatments. The lowest phosphorus content was recorded in T_3 (7.17 mg/kg in 2022 and 7.22 mg/kg in 2023), while T_6 exhibited the highest levels (11.3 mg/kg in 2022 and 11.24 mg/kg in 2023). That increased by 57.60 and 55.68% in 2022 and 2023. The differences across treatments were statistically significant, particularly from T_8 upward (Figure 4).

4. Discussion

This study demonstrates that both biochar and nano-phosphorus (Nano-superphosphate) applications significantly enhance biomass, yield, nutrient uptake, and soil fertility in common bean (*Phaseolus vulgaris* L.) over two growing seasons. The combined treatment of biochar with 50% Nano-superphosphate (T_6) consistently produced the most pronounced benefits. These results align with existing literature, confirming the potential of both biochar and Nano-fertilizers as effective soil amendments in modern, sustainable agriculture. Biochar is widely recognized for improving soil physical and chemical properties, such as aeration, water retention, nutrient-holding capacity, and cation exchange, owing to its porous structure and aromatic carbon framework (**Nepal et al., 2023; Kheir et al., 2023; Elbagory et al., 2024; Abdelhafez et al., 2024; Luo et al., 2025**). Our findings of increased soil NPK availability and uptake under combined treatments reflect these benefits, particularly the sustained release of nutrients and enhanced nutrient use efficiency.

Meier et al. (2025) similarly reported that biochar-based controlled-release fertilizers improved nutrient retention and release efficiency, achieving nitrogen and phosphorus recovery rates of 55% and 18.5%, respectively, while boosting wheat biomass and grain yield by 15%. Likewise, **Prapagdee and Tawinteung (2017)** found significant improvements in soil fertility and bean productivity following biochar application. **Uwingabire et al. (2024)** also reported that applying 3 t/ha of biochar increased soil pH, organic carbon, total nitrogen, available phosphorus, and cation exchange capacity, with corresponding improvements in common bean yield. Phosphorus availability in soil is often limited, as only 5–30% of applied P becomes available to plants, especially in highly weathered tropical soils (**Ghodszad et al., 2021**). Incorporating P into biochar, either pre- or post-pyrolysis, can slow its release, reduce fixation, and improve long-term availability (**Wali et al., 2020; da Silva Carneiro et al., 2021**). **Jiang et al. (2021)** observed increased phosphorus availability and uptake in rice under biochar application at 48 t/ha. **Yao et al. (2019)** noted that biochar at 10 g/kg significantly reduced exchangeable aluminum while increasing available phosphorus. Nanotechnology also plays a vital role in enhancing soil fertility and promoting carbon sequestration, thereby contributing to climate-resilient agriculture (**Abdalla et al., 2022; Bayoumi et al., 2022; Ansari, 2023; Taha and Omar 2024**). In our study, Nano-superphosphate and biochar treatments significantly improved nitrogen, phosphorus, and potassium uptake in common bean. The zeta potential analysis (–23.7 mV) suggested moderate colloidal stability due to negative surface charges from phosphate or hydroxyl groups. Although this value is below the ±30 mV threshold for long-term stability, it offers sufficient electrostatic repulsion to delay agglomeration (**Abdelghany et al., 2021; Farea et al., 2020**).

The highest nitrogen uptake and seed protein content were observed under the biochar with 50% Nano-superphosphate (T_6) treatment, suggesting improved nitrogen availability and use efficiency under Nano-superphosphate. This is likely due to enhanced nitrogen availability, supporting protein biosynthesis, a key determinant of crop nutritional value. Similarly, phosphorus and potassium uptake peaked under T_6, demonstrating that the synergistic effect of Nano-superphosphate and biochar creates an optimal nutrient environment. Biochar's nutrient retention and slow-release capabilities likely contributed to these results. FTIR analysis revealed nano shoulders at 1200 cm^{-1} (asymmetric P–O–P) and 965 cm^{-1} (symmetric P–O–P), indicating the presence of condensed phosphate structures. Additionally, active functional groups such as P–O–H or metal–phosphate (M–O–P) interactions may influence nutrient solubility and release, enhancing nutrient binding and plant availability. The enhanced efficacy of Nano-fertilizers can be attributed to their small particle size and high surface area, which increase nutrient uptake by plant roots and reduce fertilizer requirements (**Mali et al., 2020**). Targeted delivery of nutrients by Nano-NPK fertilizers improves chlorophyll production and photosynthesis, ultimately boosting yield (**Gil-Díaz et al., 2022; Ibrahim, 2022**). When applied to vegetable crops, nano‑P promotes root development and improves NPK use efficiency, contributing to vigorous plant growth (**Taha and Omar, 2024**).

Combining biochar with Nano-superphosphate appears to have additive or synergistic effects on crop performance. Biochar likely enhances Nano‑P retention in the root zone, reducing leaching and ensuring a steady nutrient supply during critical growth stages. Similar outcomes were reported by **Wali et al. (2020)** in chickpea, where P-enriched biochar combined with reduced mineral fertilizer improved photosynthetic performance, nutrient availability, and soil moisture. Our results indicate that increased nutrient uptake (particularly N, P, and K) under biochar with 50% Nano‑superphosphate (T_6) treatment not only improved biomass quality but also raised seed protein content. This underscores the role of integrated biochar and Nano-superphosphate application in boosting both yield and nutritional quality, crucial for achieving sustainable agricultural productivity while reducing dependency on conventional phosphate fertilizers.

5. Conclusions

Based on the results obtained, all crop traits measured at harvest were significantly improved by the application of Nano-superphosphate and biochar treatments across both seasons. The data confirm that Nano-superphosphate enhances nutrient availability and uptake by plants, while biochar contributes to soil fertility by improving water retention, nutrient storage, and microbial activity. When applied together, biochar and Nano-superphosphate exhibit a synergistic effect, enhancing overall soil health and supporting better common bean growth, increased yield, and improved seed quality. This integrated approach not only improves key soil properties but also promotes more efficient use of nutrients, ultimately reducing fertilizer waste and environmental impact. Importantly, the combining biochar with 50% Nano-superphosphate treatment consistently delivered the most favorable outcomes. Moreover, 25% Nano-superphosphate produced results comparable to 100% superphosphate application, suggesting the potential for significant reductions in fertilizer input without compromising crop performance. This approach presents both environmental and economic benefits, offering a sustainable solution for enhancing crop productivity while conserving finite phosphorus resources and reducing input costs. Further research is recommended to assess the long-term effects of biochar and Nano-superphosphate application on microbial communities and physical soil properties, especially under alkaline (high-pH) soil conditions prevalent in many Egyptian agricultural regions. These investigations will help optimize the use of these amendments for broader agro-ecological adoption.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

Competing interests: The authors declare that they have no conflict of interest in the publication.

Funding: Not applicable.

Authors' contributions: Authors SAE, TMR, AMA write the original draft and SAE, TMR, edit and finalize the manuscript. All authors read and agree for submission of manuscript to the journal.

Acknowledgments: The authors would like to acknowledge the support of the Soils Department, Faculty of Agriculture, Mansoura University for their assistance in the preparation and analysis of soil samples. Additionally, we extend our gratitude to the Agricultural Research Center, Giza, Egypt, for their valuable support in the agricultural analyses, as well as to the Spectroscopy Department, Physics Division, National Research Center, Cairo, Egypt, for their expertise in preparing and analyzing the nano-materials used in this study.

References

A.O.A.C. (2006). ″Official Methods of Analysis. 18th Ed. Association of Official Analytical Chemists″, Inc., Gaithersburg, MD, Method 04.9780935584776, 0935584773, OCLC Number / Unique Identifier: 1085712083

Abdalla Z, El-Sawy S, El-Bassiony AEM, Jun H, Shedeed S, Okasha A, Bayoumi Y, El-Ramady H, Prokisch J. (2022). Smart Fertilizers vs. Nano-fertilizers: A Pictorial Overview. Environment, Biodiversity and Soil Security, 6(2022), 191-204. https://doi.org/10.21608/jenvbs.2022.153990.1184

Abdelghany AM, ElBatal FH, ElBatal HA, EzzElDin FM. (2014). Optical and FTIR structural studies of CoO-doped sodium borate, sodium silicate and sodium phosphate glasses and effects of gamma irradiation-a comparative study. Journal of Molecular Structure, 1074, 503-510). https://doi.org/10.1016/j.molstruc.2014.06.011.

Abdelghany AM, Farea, MO, Oraby AH. (2021). Structural, optical, and electrical reinforcement of gamma-irradiated PEO/SA/Au NPs nanocomposite. Journal of Materials Science: Materials in Electronics, 32(5), 6538-6549. https://doi.org/10.1007/s10854-021-05371-1

Abdelhafez, AA, Farid, Y, Sayed A, Abbas H, Farid I.M. , Abbas MH. (2024). Impacts of Acidified Biochar on Wheat growth under Deficit Irrigation systems. Environment, Biodiversity and Soil Security, 8(2024), pp.213-229. https://doi.org/10.21608/JENVBS.2025.343443.1260

Amalina F, Abd Razak A.S, Krishnan, S, Sulaiman H, Zularisam, AW , Nasrullah M. (2022). Advanced techniques in the production of biochar from lignocellulosic biomass and environmental applications. Cleaner Materials, 6, p.100137. https://doi.org/10.1016/j.clema.2022.100137

Amira, M. Okasha and Khalifa T. H. H. (2020). The role of activated phosphorous sources in enhancing soil quality and rice productivity under saline sodic soil conditions. ASAJS, 3(8):81-108. https://doi.org/10.21608/ASAJS.2020.11955

Ansari M A (2023). Nanotechnology in Food and Plant Science: Challenges and Future Prospects. Plants, 12(13), 2565. https://doi.org/10.3390/plants12132565

Aslani M, Souri M.K. 2018. Growth and Quality of Green Bean (Phaseolus vulgaris L.) under Foliar Application of Organic Chelate Fertilizers. (3): 146–154. https://doi.org/10.1515/opag-2018-0015

Bayoumi Y, Shalaby T, Abdalla Z, Shedeed S, Abdelbaset N, El-Ramady H, Prokisch J. (2022). Grafting of Vegetable Crops in the Era of Nanotechnology: A photographic Mini Review. Environment, Biodiversity and Soil Security, 6(2022), 133-148. https://doi.org/10.21608/jenvbs.2022.147280.1181

Bhat MA, Mishra AK, Shah SN, Bhat MA, Jan S, Rahman S, Baek K-H, Jan AT (2024). Soil and Mineral Nutrients in Plant Health: A Prospective Study of Iron and Phosphorus in the Growth and Development of Plants. Current Issues in Molecular Biology 46(6), 5194-5222. https://doi.org/10.3390/cimb46060312

da Silva Carneiro JS, Ribeiro ICA, Nardis BO, Barbosa CF, Lustosa Filho JF, Melo LCA. (2021). Long-term effect of biochar-based fertilizers application in tropical soil: Agronomic efficiency and phosphorus availability. Science of the Total Environment, 760, p.143955. https://doi.org/10.1016/j.scitotenv.2020.143955

Dane, J. H., & Topp, C. G. (Eds.). (2020). Methods of soil analysis, Part 4: Physical methods. John Wiley & Sons. https://doi.org/10.2136/sssabookser5.4

El naqma K, Elawady R, Ramadan M, elsherpiny M (2024). Improving Soil Phosphorus Availability and Its Influence on Faba Bean performance: Exploring Mineral, Bio and Organic Fertilization with Foliar application of Iron and Zinc. Egyptian Journal of Soil Science 64(2), 619-630. https://doi.org/10.21608/ejss.2024.265778.1713

Elbagory M, Shaker E.M, El-Nahrawy S, Omara A.E.-D, Khalifa TH. (2024) The Concurrent Application of Phosphogypsum and Modified Biochar as Soil Amendments Influence Sandy Soil Quality and Wheat Productivity. Plants 2024, 13, 1492. https://doi.org/10.3390/plants13111492

Farea MO, Abdelghany AM, Oraby AH. (2020). Optical and dielectric characteristics of polyethylene oxide/sodium alginate-modified gold nanocomposites. RSC advances, 10(62), 37621-37630. DOI https://doi.org/10.1039/D0RA07601E

Farid, IM, El-Shinawy R, Elhussiny O, Abbas H, Abbas, MH, Bassouny MA. (2023). Phosphorus and micronutrient interactions in soil and their impacts on maize growth. Egyptian Journal of Soil Science, 63(4). https://doi.org/10.21608/EJSS.2023.220182.1610

Gee GW , Bauder JW. (1986) Particle Size Analysis. In: Klute, A., Ed., Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods, 2nd Edition, American Society of Agronomy, Inc., Madison, 383-411. https://doi.org/10.2136/sssabookser5.1.2ed.c15

Ghodszad L, Reyhanitabar A, Maghsoodi MR, Lajayer BA ,Chang, SX .(2021). Biochar affects the fate of phosphorus in soil and water: A critical review. Chemosphere, 283, p.131176. https://doi.org/10.1016/j.chemosphere.2021.131176

Gil-Díaz M, García-Gonzalo P, Mancho C, Hernández LE, Alonso J, Lobo MC. (2022). Response of spinach plants to different doses of two commercial nanofertilizers. Scientia Horticulturae, 301, 111143. https://doi.org/10.1016/j.scienta.2022.111143

Gomez K A , Gomez, AA (1984). “Statistical Procedures for Agricultural Research”. John Wiley and Sons, Inc., New York.pp:680.

Haynes RJ 2008. A Comparison of two modified kjeldahl digestion techniques for multi-element plant analysis with conventional wet and dry ashing methods. Communications in Soil Science and Plant Analysis 11(5): 459-467. https://www.tandfonline.com/doi/abs/10.1080/00103628009367053.

Ibrahim GA. (2022). Role of bio and Nano fertilization in increasing growth and productivity of spinach in sandy soil. Egyptian Journal of Desert Research, 72(2), 265-283. https://doi.org/10.21608/ejdr.2022.142700.1109

Jahan N, Mahmud U, Khan MZ (2025). Sustainable plant-soil phosphorus management in agricultural systems: challenges, environmental impacts and innovative solutions. Discover Soil, 2(1), 1-8. https://doi.org/10.1007/s44378-025-00039-2

Jiang B, Shen, J, Sun, M, Hu, Y, Jiang,W, Wang J, Wu J. (2021). Soil phosphorus availability and rice phosphorus uptake in paddy fields under various agronomic practices. Pedosphere , 31, 103–115. https://doi.org/10.1016/S1002-0160(20)60053-4

Jupp AR, Beijer S, Narain GC, Schipper W , Slootweg, JC. (2021). Phosphorus recovery and recycling–closing the loop. Chemical Society Reviews, 50(1), pp.87-101. https://doi.org/10.1039/D0CS01150A

Karpukhina E, Mikheev I, Perminova I, Volkov D, Proskurnin M. (2019). Rapid quantification of humic components in concentrated humate fertilizer solutions by FTIR spectroscopy. Journal of Soils and Sediments, 19, 2729-2739., https://doi.org/10.3390/agronomy13041141

Khan F, Siddique AB, Shabala S, Zhou M, Zhao C (2023). Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. Plants 12(15), 2861. https://doi.org/10.3390/plants12152861

Kheir AMS, Govind A, Zoghdan MG, Khalifa TH, Aboelsoud HM, Shabana MMA . The Fusion Impact of Compost, Biochar, and Polymer on Sandy Soil Properties and Bean Productivity. Agronomy 2023, 13, 2544. https://doi.org/10.3390/agronomy13102544

Li Y, Hu S, Chen J. (2018). Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. J Soils Sediments 18, 546–563. s in vegetated soil: A review. https://doi.org/10.1016/j.bgtech.2023.100040

Luo P, Zhang W, Xiao D, Hu J, Li N, Yang J. (2025). Biochar-Based Fertilizers: Advancements, Applications, and Future Directions in Sustainable Agriculture—A Review. Agronomy, 15(5), 1104. https://doi.org/10.3390/agronomy15051104

Mali SC, Raj S, Trivedi R. (2020). Nanotechnology a novel approach to enhance crop productivity. Biochemistry and Biophysics Reports, 24, 100821. https://doi.org/10.1016/j.bbrep.2020.100821

Meier S, Pedro MSC, Rubén P, Natalia R, María-Eugenia G, Sigrid M, Gabrijel O, Khan N, Juan H, Alex S. (2025). Biochar-based controlled-release ammonium phosphate fertilizer: Synthesis and impact on soil nutrient dynamics, wheat growth, and yield under controlled conditions. Environmental Technology & Innovation 39: 104269. https://doi.org/10.1016/j.eti.2025.104269

Nepal J, Ahmad W, Munsif F, Khan A, Zou Z. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. Frontiers in Environmental Science, 11, p.1114752. https://doi.org/10.3389/fenvs.2023.1114752

Peterburgski AV. (1968)."Handbook of Agronomic Chemistry". KolosPuplishing House, Moscow, (pp. 29-86). https://doi.org/ 10.21608/EJSS.2024.267390.1717

Poudel A, Singh SK, Jiménez-Ballesta R, Jatav, SS, Patra A. and Pandey A, (2023). Effect of nano-phosphorus formulation on growth, yield and nutritional quality of wheat under semi-arid climate. Agronomy, 13(3), p.768. https://doi.org/10.3390/agronomy13030768

Prapagdee S , Tawinteung N. (2017). Effects of biochar on enhanced nutrient use efficiency of green bean, Vigna radiata L. Environmental Science and Pollution Research, 24(10), pp.9460-9467. https://doi.org/10.1007/s11356-017-8633-1

Ramos Cabrera EV, Delgado Espinosa ZY, Solis Pino AF. (2024). Use of phosphorus-solubilizing microorganisms as a biotechnological alternative: a review. Microorganisms, 12(8), p.1591. https://doi.org/10.3390/microorganisms12081591

Shohag MJI, Máximo Salgado E, Curtis Gluck M, Liu G. (2024). Evaluating the Impact of Phosphorus and Solid Oxygen Fertilization on Snap Bean (Phaseolus vulgaris L.): A Two-Year Field Study. Plants.; 13(23):3384. https://doi.org/10.3390/plants13233384

Solangi F, Zhu X, Khan S, Rais N, Majeed A, Sabir MA, Iqbal R, Ali S, Hafeez A, Ali B, Ercisli, S. (2023). The global dilemma of soil legacy phosphorus and its improvement strategies under recent changes in agro-ecosystem sustainability. ACS omega, 8(26), pp.23271-23282. https://doi.org/10.1021/acsomega.3c00823

Sparks DL, Page AL, Helmke PA Loeppert RH. (Eds.). (2020). "Methods of soil analysis", part 3: Chemical methods (Vol. 14). John Wiley & Sons. https://doi.org/10.2136/sssabookser5.3

Taha AA and Omar MM. (2024. Nanoparticle Applications in Plant Nutrition: A Comprehensive Review and Future Perspectives. Journal of Soil Sciences and Agricultural Engineering, 15(2), pp.25-30. https://doi.org/10.21608/jssae.2024.271443.1218

Uwingabire S, Chamshama SAO, Nduwamungu J., & Nyberg, G. (2024). French Bean Production as Influenced by Biochar and Biochar Blended Manure Application in Two Agro-Ecological Zones of Rwanda. Agronomy, 14(9), 2020. https://doi.org/10.3390/agronomy14092020

Wali F , Naveed M, Bashir MA, Asif M, Ahmad Z, Alkahtani J, Alwahibi MS, Elshikh, MS. (2020). Formulation of Biochar-Based Phosphorus Fertilizer and Its Impact on Both Soil Properties and Chickpea Growth Performance. Sustainability, 12(22), 9528. https://doi.org/10.3390/su12229528

Walinga I, Van Der Lee JJ, Houba VJ, Van Vark W, Novozamsky I. (2013). Plant analysis manual. Springer Science & Business Media. https://link.springer.com/book/10.1007/978-94-011-0203-2#accessibility-information

Yao L, Yu X, Huang L, Zhang X, Wang D, Zhao X, Guo Y. (2019). Responses of Phaseolus calcaltus to lime and biochar application in an acid soil. PeerJ, 7, 1-26. https://doi.org/10.7717/peerj.6346